MEMORANDUM

TO	Expert meeting invitees	DATE	June 23, 2015
		REFERENCE	ONL 15-356
		FROM	Frank Wester

SUBJECT Reactive power strategy - background information

REPORT	☐
DECISION	☐

Introduction

Reactive power (MVAr) is one of the hardest subjects for ac transmission systems. We cannot do without reactive power; the ac transmission system only exists by the grace of it. Reactive power is needed to support the voltage levels through the whole ac grid. If somewhere in the grid the voltage is low, you want to have more reactive power injected there. And if the voltage is high, you want absorb reactive power from there.
To make it more complex: that same ac grid consists of components that produces and consumes reactive power. Power cables are reactive power producers; transformers are reactive power consumers. The problem is, that their production/consumption depends on the power transmitted at any moment in time.

A grid owner would like to be able to influence the reactive power throughout his grid. He cannot influence it with his cables and transformers, they are needed for the main purpose being transmission of power (MW) and the subsequently reactive power is inevitable.
The grid owner can thus only influence the reactive power in his grid by adding (extra) passive and active reactive power producers and consumers. Examples of these are:

- passive producer: capacitor banks,
- passive consumers: reactors,
- active producers/consumers: power plants, Static Var Compensators (SVCs).

A windfarm is considered as a power plant and thus needs to be able to support the reactive power. The same accounts for an offshore windfarm. Only now we are not only interested in supporting the onshore grid, but our own offshore grid as well. And that offshore grid itself is also producing and consuming reactive power (being an ac grid).
This technical note will explain the reactive power strategy for a grid connection system incl. a 350 MW offshore windfarm (one complete chain). The following steps will be described:

- requirements reactive power,
- grid connection 350 MW windfarm,
- dimensioning of components,
- loadflow calculations,
- reactive power regulation philosophy.

Requirements reactive power

In order to allow the (onshore) grid owner to influence the reactive power throughout his grid, the offshore windfarm grid connection system (being a power plant) needs to have some reactive power capabilities. Under normal operating conditions no exchange of reactive power shall take place. If needed, the grid operator can demand injection or absorption of reactive power.

The requirements of the reactive power capabilities for offshore windfarms are not set in stone, yet. Therefore, the existing requirements are used. They are shown in the document "SOC 11-175 Wind Farm Connection Requirements v5.7" (see figure 1).

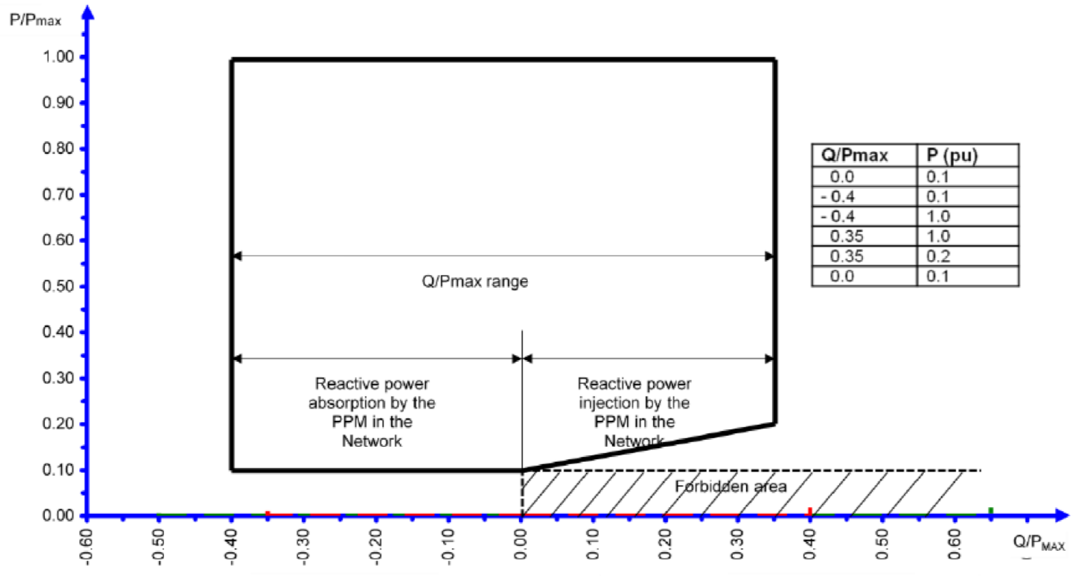


Figure 1: Reactive power capability acc. SOC 11-175

So, under normal operating conditions we must follow the (vertical) line at 0 MVAr from 0 MW (0 pu) to 350 MW (1 pu). On demand of the onshore grid owner, we must be able to absorb 140 MVAr (0,4 pu) or to inject 122,5 MVAr (0.35 pu).

These requirements or reactive power capabilities are not only valid for the onshore grid connection (connection of TenneT Offshore to TenneT TSO grid). They are also applicable for the offshore windfarm connection at the Point of Common Coupling (PCC) i.e. the 66 kV busbar on the offshore platform (connection point of OWP to TenneT Offshore).
Stating that, immediately the first problem occurs:

> Under normal operating conditions the reactive power exchange shall be 0 MVAr for all wind power productions (MWs). One can never comply to that onshore as well as offshore at the same time since the offshore grid itself is also injecting and absorbing reactive power depending on the MWs transmitted.

For this reason the offshore reactive power shall be within the range of –0,1 pu and +0,1 pu under normal operating conditions. This same range will be needed for reactive power regulation (explained underneath).
The onshore requirement remains the same.

Grid connection 350 MW windfarm

The TenneT Offshore platforms are dimensioned in such way that a total of 700 MW (2x 350 MW) wind farm power production can be connected and transmitted to the onshore TenneT TSO grid. For each OWP a 350 MW grid connection "chain" is designed. These 2 chains can be connected at 66 kV level.
In terms of reactive power strategy, these 2 chains will be handled separately (no interconnection). For one complete chain reference is made to figure 2.

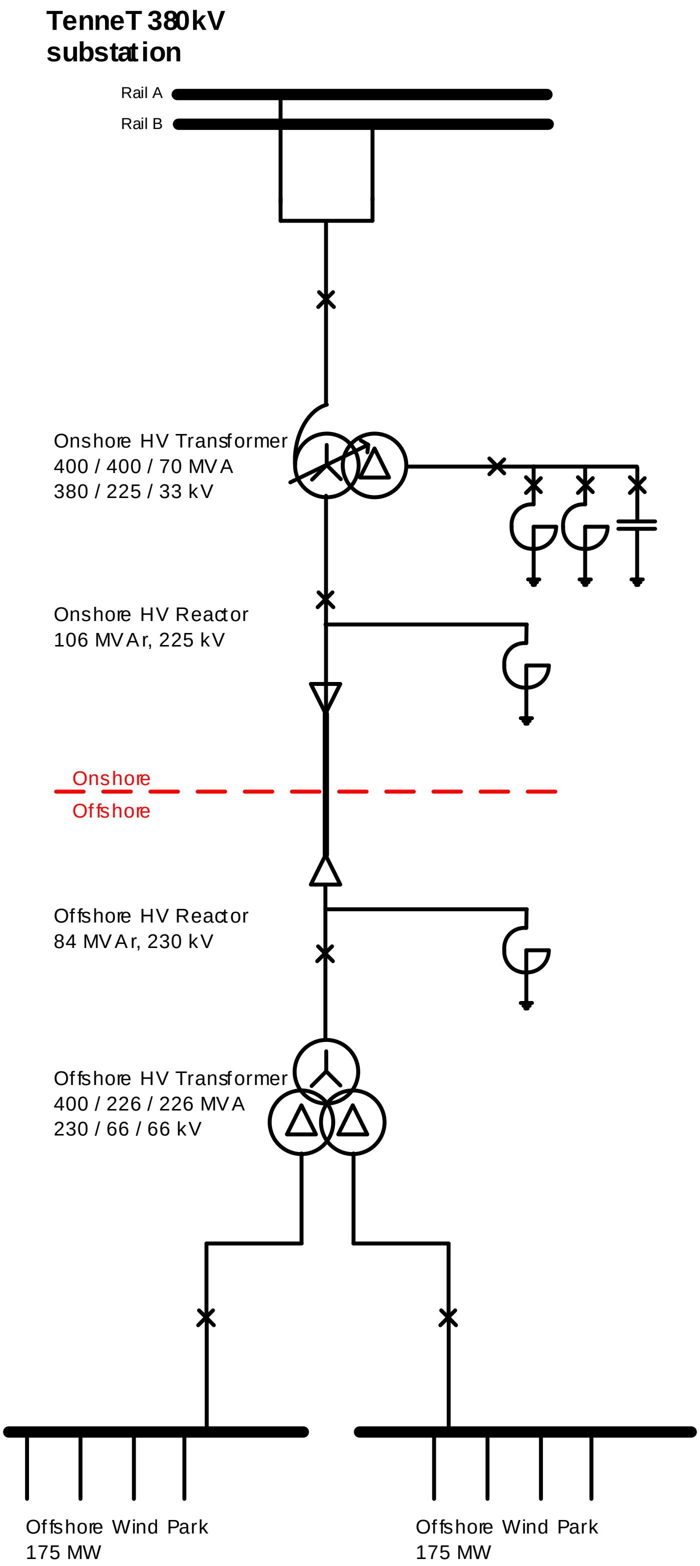


Figure 2: Single line of grid connection system

Dimensioning of components

The first step is determining the operating voltage levels. The limiting component in the 220 kV grid is the export cable. To increase the transmission power the voltage level is chosen as high as reasonably possible. The 220 kV will be regulated onshore at 225 kV. This means that the offshore voltage will be 230 kV (at full load) and well within the upper limit of all equipment being 245 kV.
There are no constraints for choosing the operating voltage of the 66 kV grid. Therefore it will be regulated in the offshore platform at 66 kV. Further down the infield grid the voltage level can be something like 68-70 kV.

Offshore transformer
The offshore transformer will be a 3-winding transformer: 1 primary winding 230 kV and 2 secondary windings 66 kV. Main reason for double secondary windings is the current rating. With 1 winding the current will be 3400 A; with 2 windings the current will be 1700 A which is a common current rating for windings, cables and GIS equipment.
The power rating of the secondary windings is based on the worst case distribution of wind power over the 2 windings. This worst case would be to have 5 strings of 70 MW. Then it will be split in 3 strings for 1 winding and 2 strings for the other. So, 1 winding should be able to transmit 3x70 = 210 MW. Considering the extreme cases of reactive power injection and absorption the rating of the secondary windings should be 226 MVA.
The power rating of the primary windings need not to be the summation of both secondary windings. In this case it is very sure that 350 MW will not be exceeded. The primary winding is thus based on 350 MW taking into account again the extreme cases of reactive power injection and absorption but also the transformers own reactive power absorption. The rating of the primary winding will be 400 MVA.
Under normal operating conditions (no exchange of reactive power) this rating also covers overplanting.
The reactive power behaviour of such transformer will be an absorption of 0 MVAr (no load) to 32 MVAr (full load).

Export cable
The export cable is rated for 350 MW. This rating is the maximum rating available on the market. The reactive power behaviour of the export cable very much depends on the exact cable length and the cable supplier. Both are unknown.
The reactive power calculations are based on the worst case cable. If we can cover the highest reactive power injected by the export cable, we for sure can cover all situations (all cable lengths, all suppliers).
The reactive power behaviour of the (worst) export cable will be an injection of 237 MVAr (no load) to 228 MVAr (full load).

Offshore reactor
The main driver for dimensioning the offshore (and onshore) reactor is the injected reactive power by the export cable. To exploit the MW transmission capability of the export cable to the max, the reactive power injected by this cable should be absorbed at both ends equally. The easiest way to achieve that is to have "50% reactors" placed at either end of the cable. However, 100% reactive power compensation will introduce the problem of "zero-missing-phenomenon": if you energize a faulty cable, it will never be switch off because the short circuit current through the cable does not have a zero crossing. Rule of thumb is to have 2x 40% reactors placed at both ends.
The positive effect of the offshore transformer is its reactive power absorption at full load conditions (approx. 32 MVAr). Using that, we can achieve 50% offshore with a reactor of 82 MVAr (228/2–32) and stay under the zero-missing-limit of 40% (i.e. 0,4*228 = 91 MVAr).

The reactive power behaviour of the offshore reactor will be an absorption of 82 MVAr.

Onshore transformer
The 380/225 kV onshore transformer will be an auto-transformer with an extra "tertiary" winding for connecting extra reactive power compensation at 33 kV.
The power rating is again based on 350 MW taking into account the extreme cases of reactive power injection and absorption. Also the reactive power absorbed/injected at 33 kV level (tertiary winding) is taken into account. This will be maximum 70 MVAr, because that would mean reasonable current ratings at 33 kV level (<1250 A).
The primary/secondary winding is rated 400 MVA.

Offshore reactors and capacitors banks
Based on the offshore components, the onshore components need to be designed in such a way that:

- under full load the cos(phi) on PCC 380 kV will be equal to 1, without making (too much) use of the reactive capabilities of the WTGs,
- by switching compensation components on the tertiary winding of the onshore transformer, the full reactive capability can be reached making use of the reactive power capabilities of the WTGs,
- by switching compensation components on the tertiary winding of the onshore transformer, the full power sweep (P=0 to P=350 MW) can be made, while the offshore windfarms are never needed to go exceed the +/- 0,1 pu reactive power bandwidth during normal operation,
- preferably the tertiary winding of the onshore transformer is limited to 1250 A (72 MVAr),
- preferably the number of reactor/capacitor switches in normal operation is limited.

The reactive power behaviour of the 220 kV onshore reactor will be an absorption of 106 MVAr.
At 33 kV level additional reactors and capacitor banks will be installed: 2 reactors rated 31,5 MVAr and 1 capacitor bank rated 31,5 MVAr.

Loadflow calculations

The results of the loadflow calculations of the normal operating condition are presented in figure 3.
Figure 3 shows the (banana-shaped) areas corresponding with the 33 kV onshore reactors and capacitor switched on/off. The width of these areas are corresponding with the 0,1 pu regulating band at the offshore PCC. With every switching of these 33 kV reactors/capacitor the "banana-shape" is shifted to the right or left. This way the 0 MVAr at the onshore grid connection can be obtained throughout the power sweep from 0 MW to 350 MW.
No reactive power exchange at the onshore grid connection over the full power range can be covered this way.

The results of the loadflow calculations of the extreme reactive power injection/absorption are presented in figure 4.
Figure 4 shows similar (banana-shaped) areas also corresponding with the 33 kV onshore reactors and capacitor switched on/off. Only now the width of these areas are corresponding with the –0,35 pu resp. 0,4 pu requirement at the offshore PCC. In the background of the figure the SOC 11-175 requirement is shown. It can be fully covered by the reactive power capabilities of the complete offshore grid connection system.

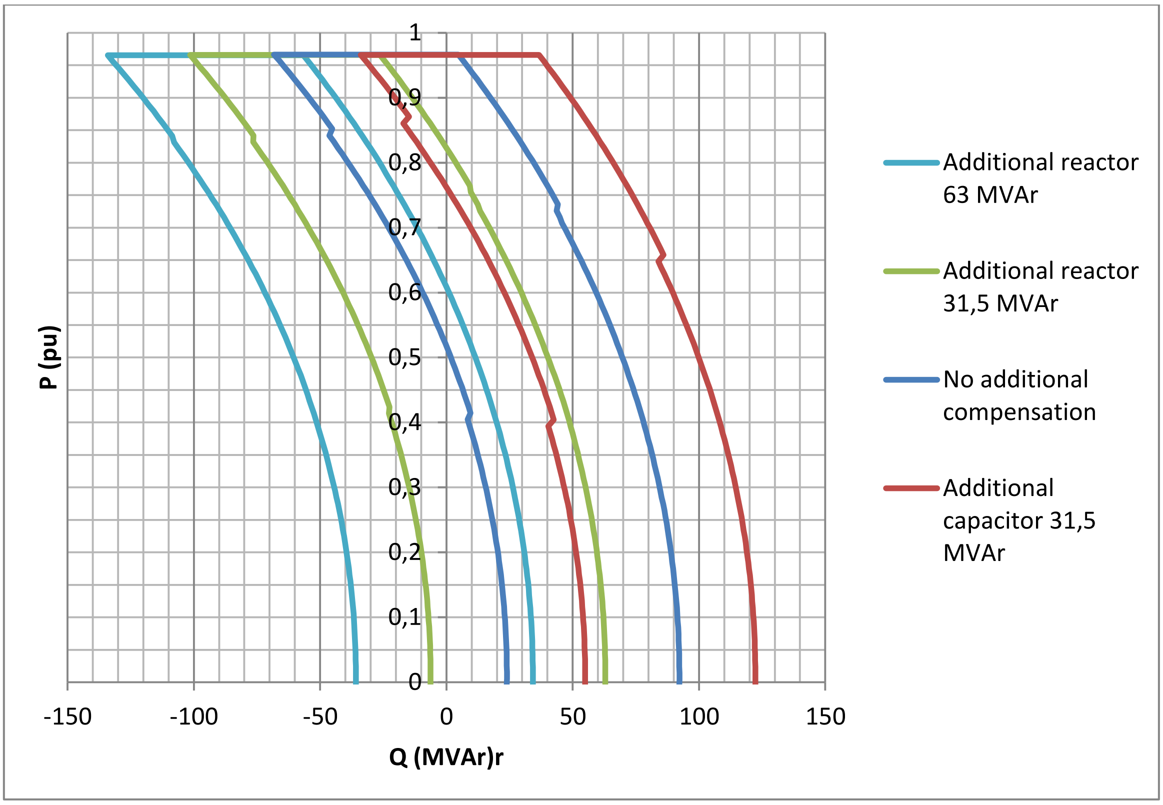


Figure 3: Loadflow calculation normal operating condition

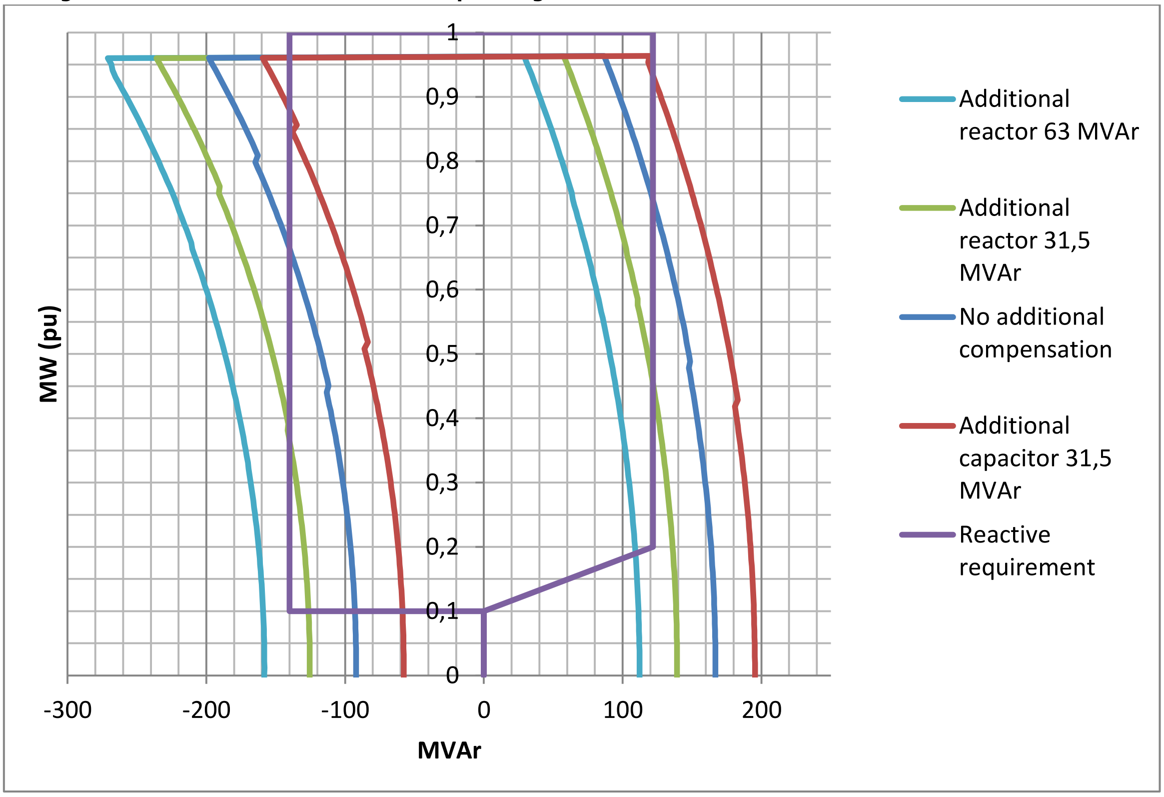


Figure 4: Loadflow calculation extreme reactive power injection/absorption

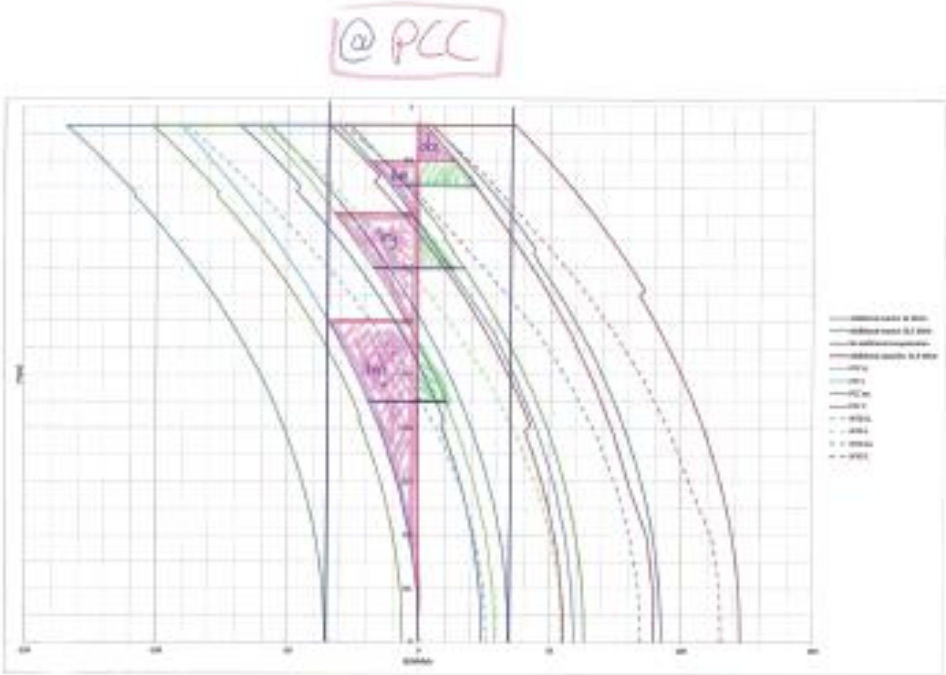
Reactive power regulation philosophy

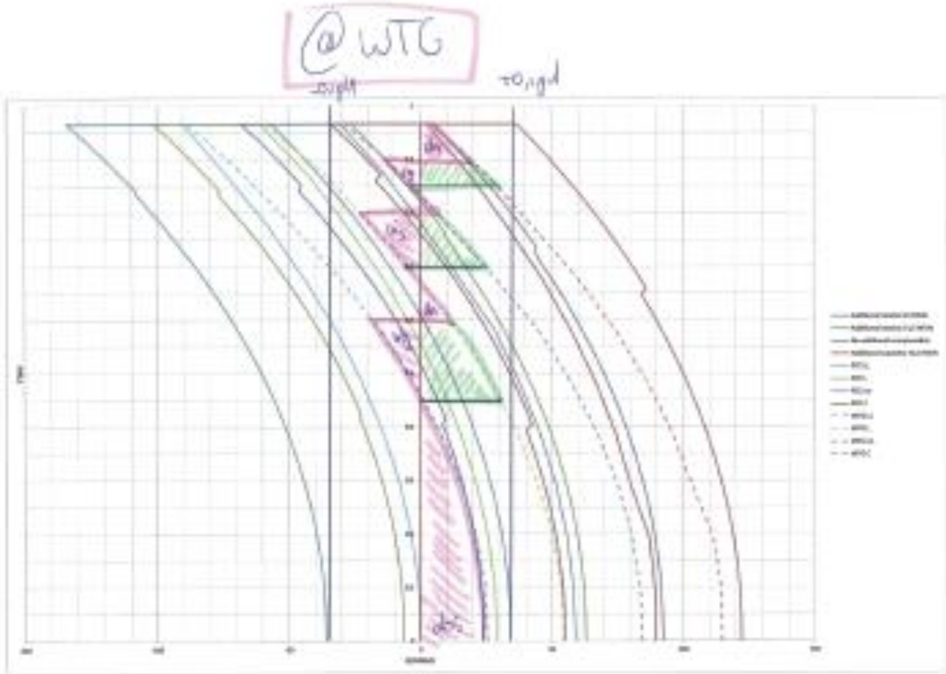
The normal operation requirement 0 MVAr exchange at the onshore connection point will be obtained by switching on and off the 33 kV onshore reactors/capacitor together with the reactive power capability of the WTGs (within the 0,1 pu band). Not only the band at 66 kV PCC is respected, but also at the WTG converters the same limit of 0,1 pu shall be respected. The reactive power contribution by the OWP at PCC as well as WTG converter is shown in the attachment.

At PCC
Starting at 0 MW and increasing the wind power the need for reactive power injection by the OWP increases. When the 0,1 pu boundary is reached, 1 reactor will be switched off (jump to the next curve). This continues up to 350 MW.
The downward slope is similar; only the switching points differ because of the needed hysteresis. The hysteresis is needed for a stable regulation.

At WTG
The curves at the WTGs is the same as at PCC only they are shifted to the right. Also these slopes up and down stay within the 0,1 pu regulation band.

Reactive power capabilities at 0 MW
If the reactive power capabilities of the WTGs are limited at very low loads, the curves can be shifted more to the left by adjusting the onshore reactor sizes. To prevent exceeding the 0,1 pu band at PCC, maybe an extra reactor switching point is needed.
Appendix A:


@ PCC


@ WTG