North Sea Transnational Grid Evaluation of NSTG options (WP2)

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Abstract

Two scenarios for the development of a North Sea Transnational Grid for trade and connections of 52.8 GW wind energy have been evaluated. In scenario 1 the transport of wind power and traded power are integrated in an interconnected DC system. In scenario 2 wind power and trade are seperated: wind is AC connected to the onshore grid and a DC grid connects the North Sea countries. Both scenarios were developed in ten stages or phases with an approximately equal increase in wind power per stage.

Comparing the wind power connections only, the scenario 2 investment costs and average Levelised Transport Costs (LTC) are higher than for scenario 1 for all phases. When the two trade systems are compared, scenario 2 requires additional DC connections to shore and results in the highest investment and the highest average LTC per connection again. Combining wind and trade systems in a single average LTC per phase, the difference between scenario 1 and 2 increase to the detriment of scenario 2.

Based on the currently available price estimates, the integrated scenario based on DC connections is the best solution. This option is further examined in the other project work packages.

Keywords: offshore wind farm and grid electrical systems, offshore wind farm and grid economics.

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Contents

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Introduction

Work Package 2 of the North Sea Transnational Grid (NSTG) project covers the technical and economic evaluation of different solutions for the North Sea Transnational Grid. This will be based on the steady state electrical and economic calculations for the different technical options and scenarios. This report describes building and testing the EeFarm model and describes the EeFarm NSTG results.

Two scenario's will be investigated:

- North Sea Transnational Grid with interconnected wind power and trade connections (NSTG integrated scenario);
- Individual wind power connections to shore (AC connected) and a separate transnational DC trade grid (AC-DC separated scenario).

For both scenarios the development of the grid will be divided into 10 phases.

First, the choices to be made when building a large AC or DC model for the NSTG scenarios in EeFarm will be explained. Since EeFarm was built for unidirectional power flow, modelling a meshed multi-terminal DC grid requires additional control components. A description of these components and tests can be found in appendix D.

In the main part of this report, the results for the phases of the two NSTG scenarios are described and compared.

The application of EeFarm is demonstrated in a separate case study: the Cobra cable between the Netherlands and Denmark, extended with two wind farms in appendix C.

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NSTG scenarios and assumptions

2.1 NSTG scenarios

In a previous report [7] the possible locations and development phases of wind power in the North Sea have been determined, see figure 2.1. The conclusion was that the total

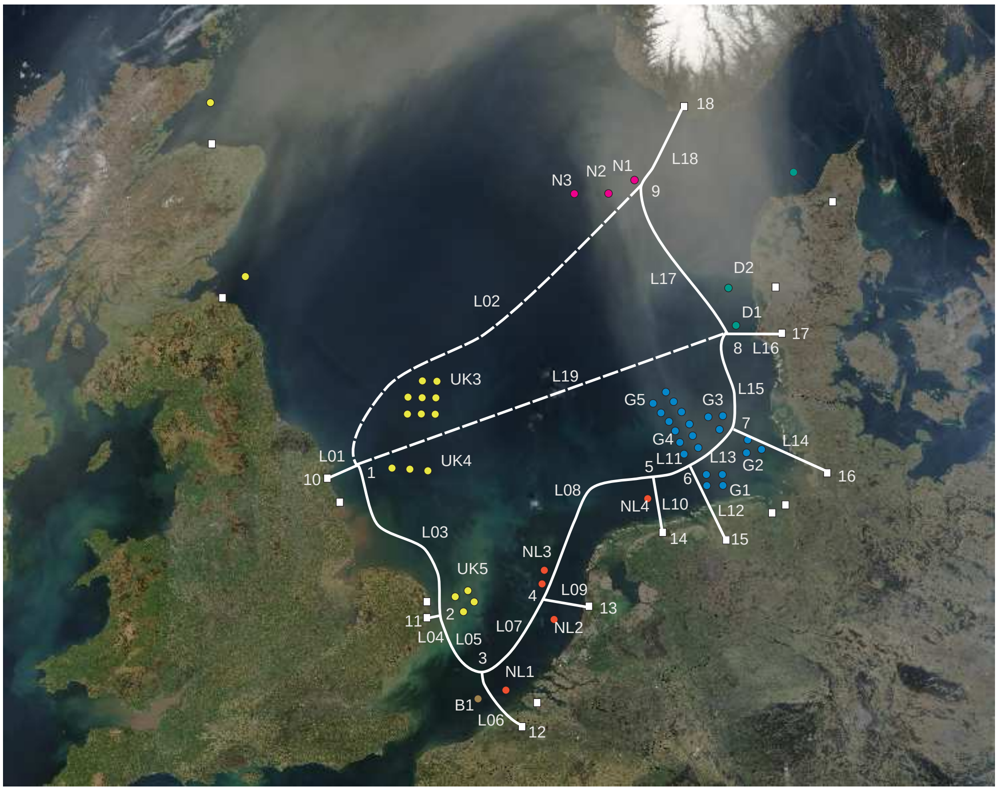

Figure 2.1: North Sea Transnational Grid and wind farm locations (photo: NASA)

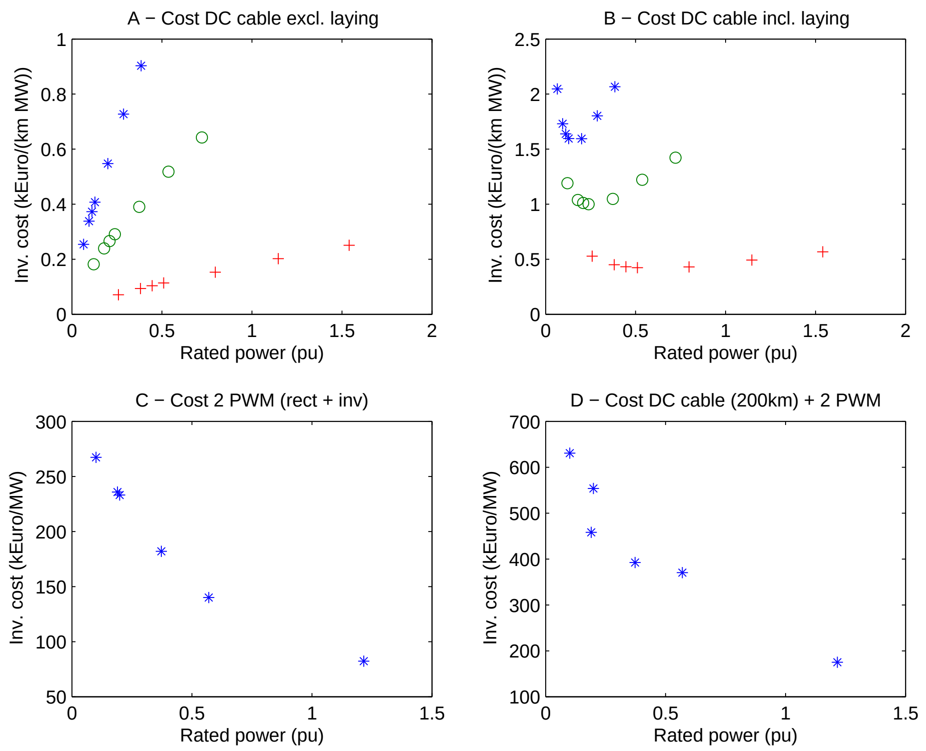

Figure 2.2: Relative costs of DC cables and PWM converters (database values 2009, P(pu)=1000MW)

amount of wind power will be 57600 MW, divided over 48 wind farms of 1200 MW each. This choice was based on the maximum size of a single DC connection (a PWM converter of 1216 MW and ±320kV combined with a DC cable of 1780 A and ±320kV). This wind farm and connection rating is also used as base case in the other work packages of the NSTG project (WP6 and WP7). The reason for this choice is that the largest available VSC-HVDC connection results in the lowest relative investment costs (Euro per installed MW).

Figure 2.2 gives the relative costs of DC cables (per km and MW) and PWM converters (per MW) as function of the rated power of the cable and converter. In figure A and B the three voltage levels (±80kV, ±150kV and ±320kV) can be recognised. In figure B the cost of laying the cable is added. Figure C gives the cost of a set of two converters (rectifier and inverter). Figure D combines cables and converters of the same voltage and power rating to compare the system price per installed MW for a cable length of 200 km. Increased system size results in lower cost per installed MW. Based on the investment costs, the 1200 MW system is the best option. The costs are based on the budget prices supplied by manufacturers in 2009. In the calculation for the NSTG cases presented in the next sections, the costs of the 1200 MW system have been updated, based on recent estimates by ENTSO-E, the IRENE-40 database and TSO inter-connector projects [5].

The two scenarios to evaluate are:

- Scenario 1 (Wind and Trade integrated): Wind power and transnational trade connections are integrated into a single North Sea Grid. Since the distances in the transnational are substantial, this will be a DC grid. All wind farms and national grids will interconnected at the DC level;

- Scenario 2 (Wind and Trade separated): Individual AC connection of wind farms to national grids and separate transnational DC connections for trade only. The maximum distance of the wind farms to shore is 180 km and all wind farms will be AC connected in this scenario. This scenario requires additional DC transnational connections to shore for trade;

The step by step wind power increase of the NSTG development plan described in [7] and the corresponding transnational grid for power trading will be evaluated. The results are compared to the development phases of separate AC grid connections for the wind farms and a separate transnational grid for power trading.

Approximate distances of the transnational grid sections are:

Table 2.1: Distances of the NSTG sections (labels of figure 2.1)

Line name	From	To	Length (km)
L01	1	10	40
L02	1	9	600
L03	1	2	250
L04	2	11	25
L05	2	3	100
L06	3	12	80
L07	3	4	125
L08	4	5	260
L09	4	13	60
L10	5	14	40
L11	5	6	40
L12	6	15	125
L13	6	7	75
L14	7	16	150
L15	7	8	50
L16	8	17	55
L17	8	9	225
L18	9	18	120
L19	1	8	500

NSTG system choice for the EeFarm calculations:

- all NSTG connections to shore have the rating of the connected wind farm(s). The wind farm to shore connections connect to the transnational DC connections intended for trade;
- the converters and cables in NSTG will be based on the largest available ABB HVDC Light system:
  - a $\pm$320 kV, 1216 MW ABB VSC converter;
  - a compatible DC bipolar ABB cable: 1x1200mm2, 320kVdc and 1146 MW.
- the transnational trade connection rating is equal to multiples of the rating of one VSC converter (1216MW). Depending on the location and phase in can be one, two or three times 1216MW;

- in the interconnected NSTG, the amount of traded power is limited by the produced amount of wind power and the capacity of the connections to shore, i.e. the wind power to be transported to shore will determine the remaining capacity for trade between the DC grid node and the shore converter. This is not the case for the scenario with separate wind and trade connections;
- the trade connections are evaluated for maximum power;
- all wind farms have a rated power of 1100 MW and consist of 220 turbines of 5 MW. This is the result of the DC cable choice (1146 MW) and the comparison to the AC connected scenario based on 200 MVA cables.

2.2 EeFarm model

EeFarm calculates the steady state value of voltage, current, active and reactive power of each electrical node in the NSTG scenarios. The electrical power of each wind farm for a given average undisturbed wind speed is the input for the calculation. The EeFarm library includes AC as well as DC components. For each electrical component the losses and the not-produced power due to component failure is calculated (assuming failure of one component at a time). This is combine with the probability of each average undisturbed wind speed and wind direction to give the total annual energy production. In combination with the investment cost the Levelised Transport Cost (the cost of transporting one kWh averaged over the economic lifetime of a connection) is calculated.

EeFarm includes a database with component prices to calculate the investment costs and the price of one kWh averaged over the wind farm life time. EeFarm makes it easy to determine the effect of different component choices (for instance an AC versus a DC connection to shore) and different control strategies on the energy production cost. EeFarm is used to determine an efficient interconnection within the wind farm, to make an accurate estimation of the wind farm electrical energy yield and to determine the optimal design the connection to shore. For more details see Appendix A.

Since EeFarm was made for calculation of wind farms with a single connection to shore, EeFarm was adapted to calculate the NSTG grid structure. The modifications and tests are listed in Appendix D.

2.3 Modelling assumptions

The evaluation will be based on the following modelling assumptions:

- the EeFarm calculations use the same power curve for all turbines and assume the same (increasing) wind speed from cut-in to cut-out for all turbines and wind farms. Also, for all wind farm locations the same wind distribution function will be used. This reduces the simulation effort considerably and ensures that maximum loading of NSTG, i.e. simultaneous maximum power production of all wind farms, is included in the evaluation. The other options would be to use:
  - individual power calculations for each wind farm;
  - individual power calculations for each turbine turbine within a wind farm.

  This will have some effect on the power production and the levelised transport cost (LTC) and secondary effects on electrical variables such as the losses but this is not critical when comparing different options since all are effected in the same way and the effect is expected to be relatively small.

- the investment costs of the wind turbines are not included in the levelised transport costs, only the electrical equipment connecting the offshore wind turbines to the onshore grid, including the cables inside the wind farm, the wind farm transfomers or power converters and platform are included;
- economic parameters: 20 yr lifetime and 7% nominal interest, 2% inflation;
- wind parameters: $V_{ave} = 9.7$ m/s and Weibul factor $S_{weib} = 2.08$.
- the voltages, currents, powers, reactive powers, losses, failure and economic performance of the NSTG cases and alternatives can be calculated by an integral or a partitioned model:
  - in the integral model includes all components, the control of the power flow is added and all is calculated in one run;
  - in the partitioned model, the system is split in sections, separate power flows are defined and the connections for these power flows are calculated separately.

  In the integral model of the NSTG cases all wind farms connect to the transnational grid and are evaluated as a single system. In the partitioned model, each wind farm only connects to its own national grid connection point and is evaluated separately. If the control of the power flow and component redundacy values (depending on the number of parallel connections) are chosen the same in both models, the results of both models are the same as well. Both models have been built and examined. The results showed that the partitioned model is much faster, it is easier to use and required less postprocessing effort. Therefore, a partitioned model of the NSTG cases is used in this report.
- the levelised transport cost is calculated per wind farm connection to the nearest grid feed-in point;
- the levelised transport cost for trade is calculated per trade grid section. To obtain the total transport costs over the complete length of the trade grid, these values have to be summed up;

3

NSTG scenario results

Scenarios and phases of development of the NSTG are calculated by evaluating each connection of a wind farm to shore and each connection between two DC nodes in the offshore transnational grid individually. A node is defined as an interface with more than two cables connected. The offshore nodes for instance are numbered 1-9 in the overviews (see figure 3.1). Each development phase adds a number of new connections to the NSTG as described in [7]. The length and the number of parallel connections depend on the location. Table 3.1 gives the wind power development phases.

Table 3.1: NSTG wind power development phases

		New 1100 MW wind farms and corresponding connections per development phase and location									
Location		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
UK3 (C)	Dog						2 (2)	1 (3)	2 (5)	1 (6)	2 (8)
UK4 (C)	Hor				2 (2)	1 (3)	(3)	(3)	(3)	(3)	(3)
UK5 (F)	Nor	1 (1)	2 (3)	1 (4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)
B1 (G)	Tho						1 (1)	(1)	(1)	(1)	(1)
NL1 (G)	Bor									1(1)	(1)
NL2 (I)	IJmA	1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
NL3 (I)	IJmB					1 (1)	(1)	1 (2)	(2)	(2)	(2)
NL4 (J)	Eem			1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
G1 (K)	Bor	2 (2)	2 (4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)
G2 (M)	Aus			2 (2)	1 (3)	(3)	(3)	(3)	(3)	(3)	(3)
G3 (M)	Amr				1	2 (3)	(3)	(3)	(3)	(3)	(3)
G4 (K)	HoS						3 (3)	2 (5)	1 (6)	(6)	(6)
G5 (K)	HoN								2 (2)	2 (4)	2 (6)
D1 (N)	HR	1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
D2 (N)	Rin						1 (1)	(1)	(1)	(1)	(1)
N1 (Q)	Lys	1 (1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
N2 (Q)	Ægi				1 (1)	(1)	(1)	(1)	(1)	(1)	(1)
N3 (Q)	Idu							1 (1)	(1)	(1)	(1)
		Total number of 1100 MW wind farms and corresponding connections per country									
UK		1	3	4	6	7	9	10	12	13	15
B							1	1	1	1	1
NL		1	1	2	2	3	3	4	4	5	5
G		2	4	6	8	10	13	15	18	20	22
D		1	1	1	1	1	2	2	2	2	2
N		1	1	1	2	2	2	3	3	3	3
Total		6	10	14	19	23	30	35	40	44	48

See figure 2.1 for the locations of the wind farm areas.

UK1, UK2 and D3 are not included in the development of NSTG due to their location.

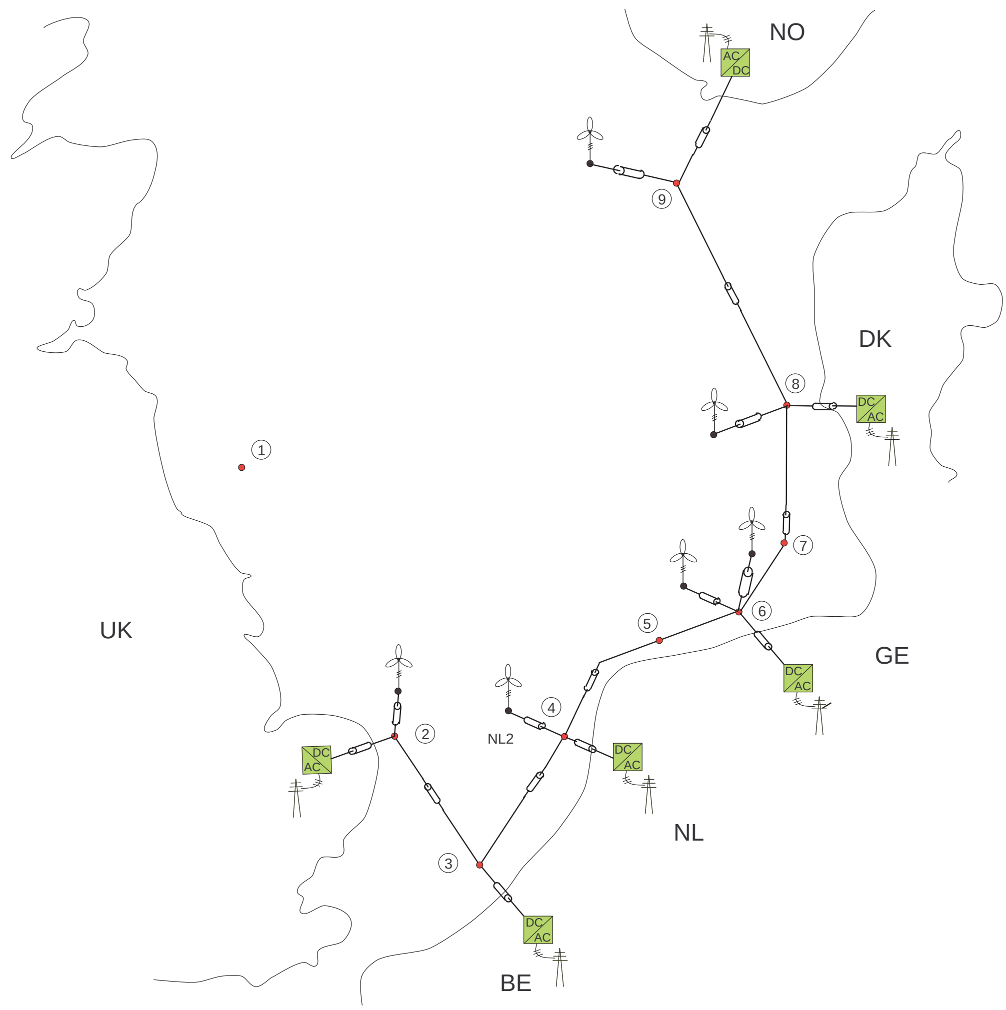

Figure 3.1: NSTG - Wind and Trade integrated (Scenario 1 - Phase 1)

Adding new connections parallel to already existing connections influences the redundancy and therefore the wind power transported by these connections during a failure. The redundancy of a connection of an individual wind farms to the DC grid node is not affected, since these are never parallel, due to different wind farm locations. The redundancy does change for connections of the NSTG DC nodes to the AC grid if an extra wind farm is connected to that DC node. The redundancy also changes for multiple connections between NSTG DC trade nodes (the grid sections connecting countries) but the effect depends on the power transported between these nodes. At full power, an extra parallel connection does not decrease the power not produced due to failure of a component. For the wind farm to shore connections redundancy is useful, since most of the time the wind farms operate below rated power.

3.1 Scenario 1 - Wind and Trade integrated - Part 1 : Wind DC to shore

In the NSTG integrated scenario all connections are of the same type: 1200MW, 320kV DC and VSC. Figure 3.1 shows the first phase of the NSTG development. In this phase, the DC connection between UK, Belgium, Netherlands, Germany, Denmark and Norway is

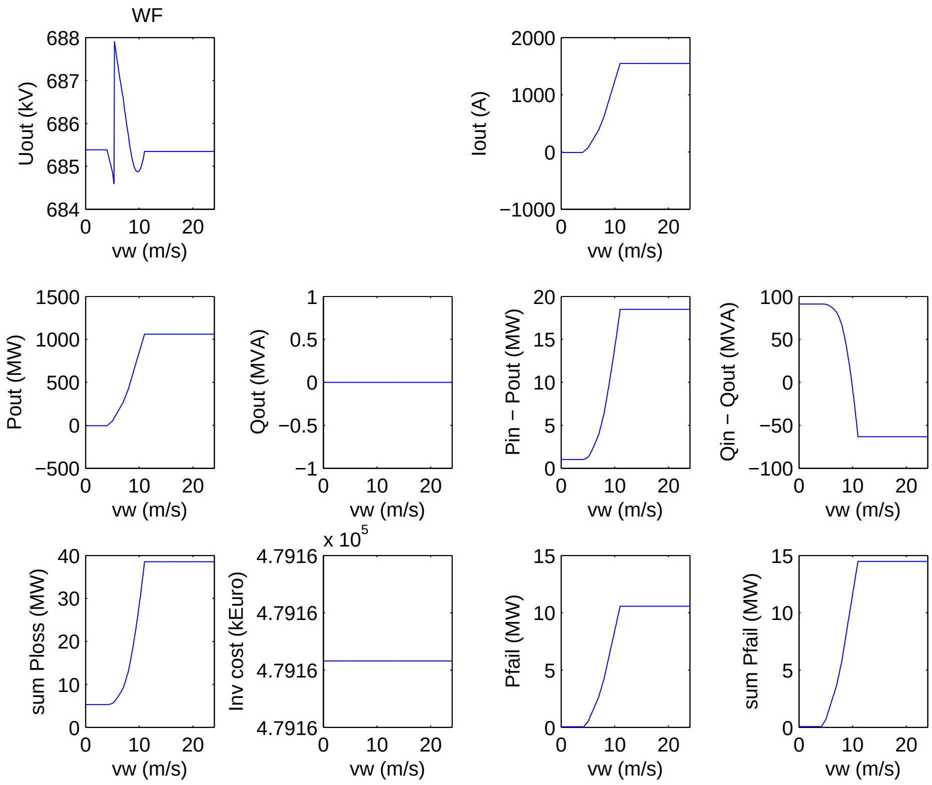

Figure 3.2: Wind Farm DC connected to shore: DC connection point after Wind Farm rectifier at WF platform

already installed. The number of wind farms in this phase is 6.

In this section, the DC connections of the wind farm to shore are evaluted. Figure 3.2 shows the voltage, current, power, reactive power, losses and not produced power due to failure as function of the wind speed for the DC side of the wind farm rectifier. The rectifier supplies the reactive power for the wind farm Q_{in}, which changes from 100 MVA to -50 MVA. The change is cause by the leakage inductance of the wind farm transformers. The turbine generator is a doubly fed induction machine and it is operating at power factor 1. The variables labelled *out* are immediately after the component in the direction to shore. For the rectifier this is DC side. The reactive power flow in the wind farm was not optimized for minimal losses since this is outside the scope of this study (all reactive power is supplied by the rectifier). The power loss $P_{in} - P_{out}$, the reactive power difference $Q_{in} - Q_{out}$ and the not produced power due to failure P_{fail} only concern the last component in the connection, in figure 3.2 this is the rectifier. The investment costs $Invcost$ and $sumP_{loss}$, $sumP_{fail}$ are added over all components starting from the wind farm until and including the component in the figure. The wind turbine costs are not included in the investment costs.

Figure 3.3 is an example of the values calculated at the point of connection of the NSTG to the onshore grid. At node 11 wind farm UK5 connects to the UK HVAC grid. Each wind farm to shore connection consists of AC cables in the wind farm, transformers, a set of PWM converters and DC cables. As before, the independent variable is the wind speed. Since the variables are AC now, the voltage and current angles w.r.t. a common reference (the voltage at the wind turbine) are now included. At low windspeeds the wind power

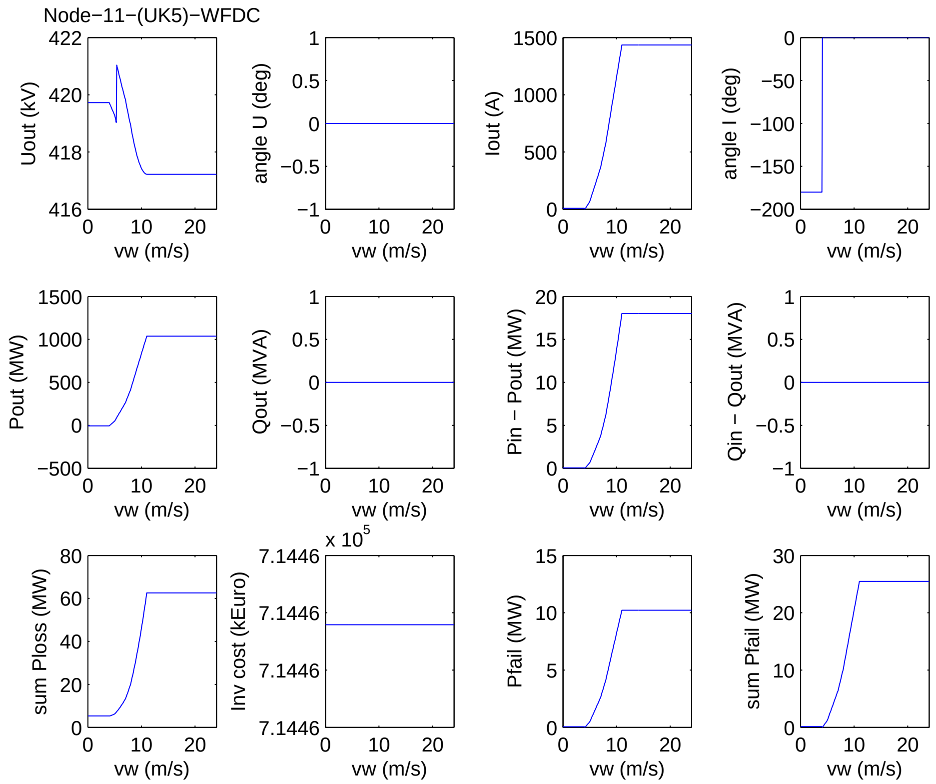

Figure 3.3: WF UK5 DC connected to Node 11 (UK): inverter variables at connection to AC HV grid (Phase 1)

production is zero and the losses of the rectifier lead to a initial current angle close to -180 degrees. The angle changes to almost zero when the farms starts producion. The reactive power of the inverter is set to zero. Losses and not produced power due to failure depend on the transported power, i.e. the wind speed. The total losses at maximum power are about 6% and the total not produced power due to failure is about 2.5%. The investment cost for the total transport connection is also included, summed from the wind turbine up to the inverter. A transformer connecting the inverter to the grid is not included. A grid side transformer is not included in the AC connected wind farms either.

Table 3.2: Scenario 1, Phase 1: DC connections Wind to Shore, variables at the onshore grid at maximum power

Wind Farm DC connection	U (kV)	I (A)	Pout (MW)	Qout (MVA)	Inv (MEuro)	PlossTot (MW)	Pfail (MW)	PfailTot (MW)
11-UK5	417.2	1435.0	1037.0	0.0	714.5	62.6	10.2	25.5
13-NL2	416.1	1435.0	1034.1	0.0	765.9	65.5	10.2	25.8
15-G1	413.9	1434.9	1028.8	0.0	861.5	70.8	4.1	19.7
17-D1	416.2	1435.0	1034.5	0.0	758.6	65.1	10.2	25.8
18-N1	414.1	1434.9	1029.2	0.0	854.2	70.4	10.1	26.4

Table 3.2 list the main parameters of one of the six wind farm connections to shore of phase 1 at the output of the inverter.

In figure 3.4 and 3.5 the total losses, investment costs and failure for the connection of wind farm UK5 to the UK grid node 11 are indicated per component type. The PWM rectifier and inverter play an important role in all three but especially in the not produced

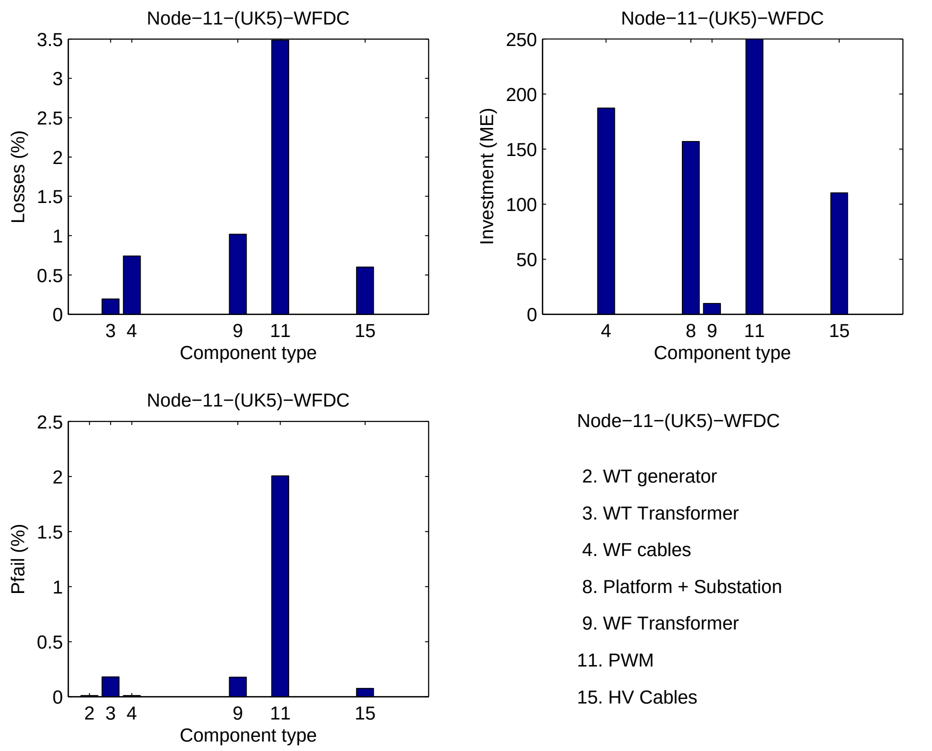

Figure 3.4: Wind Farm UK5 DC connected to Node 11 (Phase 1): total losses, failure (at full power) and the investment per component type

power due to component failure. For the other DC connected wind farms the results are similar: the relative contributions change a bit due to the different cable lengths and the number of parallel connections.

Table 3.3 list the variable for all individual wind farm connections in the phase 10. For connection 11-UK5 the not produced power due to failure now is 16.3 MW (1.2 MW for the inverter only) compared to 25.5 MW (10.2 for the inverter only) in phase 1. This shows the effect of multiple connections from DC node 2 to shore node 11.

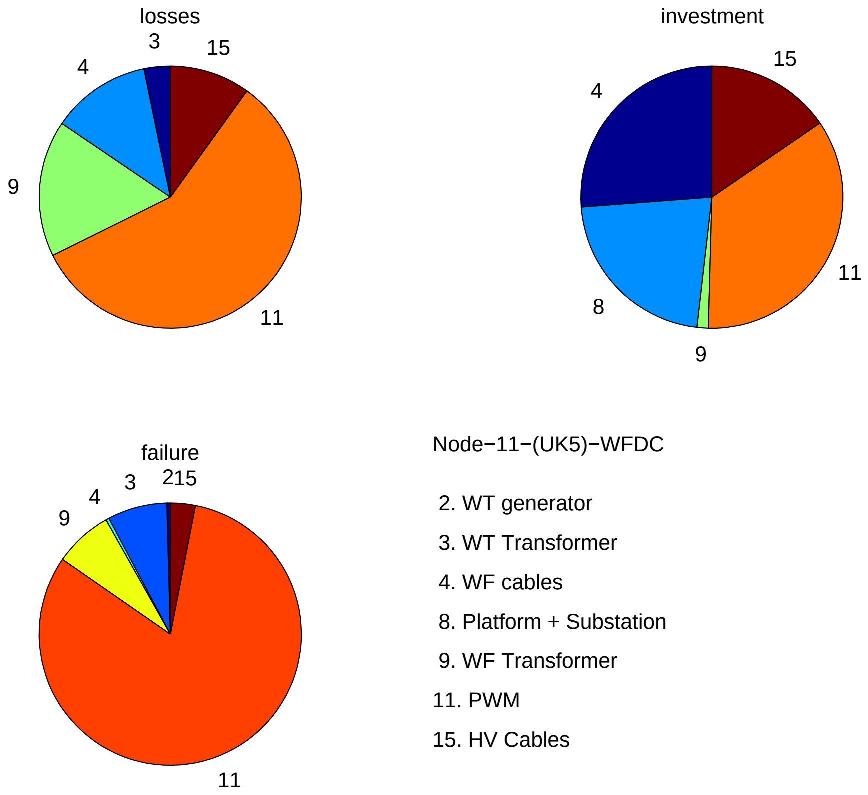

Figure 3.5: WF UK5 DC connected to Node 11 (UK) total losses and failure at full power and the investment per component type (Phase 1)

Table 3.3: NSTG Phase 10: DC connection Wind to Shore, variables at the connection to the grid on shore per 1200 MW connection at maximum power

Wind Farm DC connection	U (kV)	I (A)	Pout (MW)	Qout (MVA)	Inv (MEuro)	PlossTot (MW)	Pfail (MW)	PfailTot (MW)
10-UK3	415.1	1434.9	1031.7	0.0	810.0	68.1	0.0	15.5
10-UK4	416.7	1435.0	1035.8	0.0	736.5	63.8	2.2	17.3
11-UK5	417.2	1435.0	1037.0	0.0	714.5	62.6	1.2	16.3
12-B1	415.4	1435.0	1032.5	0.0	795.3	67.1	10.2	26.0
12-NL1	415.4	1435.0	1032.5	0.0	795.3	67.1	10.2	26.0
13-NL2	416.1	1435.0	1034.1	0.0	765.9	65.5	10.2	25.8
13-NL3	416.1	1435.0	1034.1	0.0	765.9	65.5	4.2	19.5
14-NL4	416.7	1435.0	1035.8	0.0	736.5	63.8	10.2	25.6
15-G1	413.9	1434.9	1028.8	0.0	861.5	70.8	1.1	16.3
16-G2	413.1	1434.9	1026.7	0.0	898.3	72.9	2.1	17.5
16-G3	413.1	1434.9	1026.7	0.0	898.3	72.9	2.1	17.5
15-G4	413.9	1434.9	1028.8	0.0	861.5	70.8	0.1	15.2
15-G5	412.3	1434.9	1024.7	0.0	935.1	74.9	0.1	15.6
17-D1	416.2	1435.0	1034.5	0.0	758.6	65.1	10.2	25.8
17-D2	414.6	1434.9	1030.4	0.0	832.1	69.2	10.1	26.2
18-N1	414.1	1434.9	1029.2	0.0	854.2	70.4	10.1	26.4
18-N2	414.1	1434.9	1029.2	0.0	854.2	70.4	10.1	26.4
18-N3	414.1	1434.9	1029.2	0.0	854.2	70.4	10.1	26.4

Tables 3.4, 3.5 and 3.6 list the results for each wind farm to shore connection in each of the 10 phases of the NSTG. Since the rating of all connections is the same (1200 MW and 320kV DC), the main difference is the length of the cable, determined by the location of wind farm and AC grid feed-in point. This explains the differences in investment costs and losses. The results also show the effect of multiple connections: the power not produced

due to failure decreases. Since failure values are not that big (typically a few percent of the total transported energy), the effect of multiple connections on the overall performance (Levelised Transport Costs LTC) is small.

Table 3.4: NSTG Phase 1—2—3—4: DC connection Wind to Shore

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
11-UK5	714.5	1037.0	62.6	25.5	6.0	2.5	0.0113
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
15-G1	861.5	1028.8	70.8	19.7	6.9	1.9	0.0136
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

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15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
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13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	19.8	7.1	1.9	0.0142
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK4	736.5	1035.8	63.8	19.4	6.2	1.9	0.0116
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	26.7	7.1	2.6	0.0143
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

DC connections according to figure 2.1.

InvTot	investment cost (MEuro)
PoutMax	maximum output power at node (MW)
PlossTot	electrical losses at maximum output power at node (MW)
PfailTot	not produced electrical power at maximum output power at node (MW)
PlossRel	100*PlossTot/PoutMax (%)
PfailRel	100*PfailTot/PoutMax (%)
LTC	Levelised Transport Cost (Euro/kWh), see appendix B

Table 3.5: NSTG Phase 5—6—7: DC connection Wind to Shore

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK4	736.5	1035.8	63.8	17.3	6.2	1.7	0.0115
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
13-NL3	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK3	810.0	1031.7	68.0	19.9	6.6	1.9	0.0128
10-UK4	736.5	1035.8	63.8	17.3	6.2	1.7	0.0115
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
12-B1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
13-NL3	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
15-G4	861.5	1028.8	70.8	17.4	6.9	1.7	0.0136
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
17-D2	832.1	1030.4	69.2	26.2	6.7	2.5	0.0132
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK3	810.0	1031.7	68.0	17.8	6.6	1.7	0.0127
10-UK4	736.5	1035.8	63.8	17.3	6.2	1.7	0.0115
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
12-B1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
13-NL3	765.9	1034.1	65.5	19.5	6.3	1.9	0.0120
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
15-G4	861.5	1028.8	70.8	15.6	6.9	1.5	0.0136
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
17-D2	832.1	1030.4	69.2	26.2	6.7	2.5	0.0132
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N3	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

DC connections according to figure 2.1.

Table 3.6: NSTG Phase 8—9—10: DC connection Wind to Shore

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK3	810.0	1031.7	68.0	16.1	6.6	1.6	0.0127
10-UK4	736.5	1035.8	63.8	17.3	6.2	1.7	0.0115
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
12-B1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
13-NL3	765.9	1034.1	65.5	19.5	6.3	1.9	0.0120
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
15-G4	861.5	1028.8	70.8	15.2	6.9	1.5	0.0136
15-G5	935.1	1024.7	74.9	20.1	7.3	2.0	0.0148
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
17-D2	832.1	1030.4	69.2	26.2	6.7	2.5	0.0132
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N3	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK3	810.0	1031.7	68.0	15.7	6.6	1.5	0.0127
10-UK4	736.5	1035.8	63.8	17.3	6.2	1.7	0.0115
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
12-B1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
12-NL1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
13-NL3	765.9	1034.1	65.5	19.5	6.3	1.9	0.0120
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
15-G4	861.5	1028.8	70.8	15.2	6.9	1.5	0.0136
15-G5	935.1	1024.7	74.9	16.8	7.3	1.6	0.0148
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
17-D2	832.1	1030.4	69.2	26.2	6.7	2.5	0.0132
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N3	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

Wind Farm DC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
10-UK3	810.0	1031.7	68.1	15.5	6.6	1.5	0.0127
10-UK4	736.5	1035.8	63.8	17.3	6.2	1.7	0.0115
11-UK5	714.5	1037.0	62.6	16.3	6.0	1.6	0.0112
12-B1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
12-NL1	795.3	1032.5	67.1	26.0	6.5	2.5	0.0126
13-NL2	765.9	1034.1	65.5	25.8	6.3	2.5	0.0121
13-NL3	765.9	1034.1	65.5	19.5	6.3	1.9	0.0120
14-NL4	736.5	1035.8	63.8	25.6	6.2	2.5	0.0116
15-G1	861.5	1028.8	70.8	16.3	6.9	1.6	0.0136
16-G2	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
16-G3	898.3	1026.7	72.9	17.5	7.1	1.7	0.0142
15-G4	861.5	1028.8	70.8	15.2	6.9	1.5	0.0136
15-G5	935.1	1024.7	74.9	15.6	7.3	1.5	0.0148
17-D1	758.6	1034.5	65.1	25.8	6.3	2.5	0.0120
17-D2	832.1	1030.4	69.2	26.2	6.7	2.5	0.0132
18-N1	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N2	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136
18-N3	854.2	1029.2	70.4	26.4	6.8	2.6	0.0136

DC connections according to figure 2.1.

Table 3.7: Wind Farms DC connected: all NSTG phases total sums and averages

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	4816.2	7968.1	11215.7	15339.5	18638.5
Pmax (MW)	6049.6	10128.9	14176.7	19226.2	23284.8
Etotal (GWh/y)	30170.8	50513.5	70704.5	95892.8	116141.5
Elosses (GWh/y)	1973.6	3276.4	4601.4	6272.8	7610.4
Elosses (%)	6.5	6.5	6.5	6.5	6.6
Efail (GWh/y)	699.8	951.7	1332.3	1843.1	2153.8
Efail (%)	2.3	1.9	1.9	1.9	1.9
Inv per MW (MEuro/MW)	0.7961	0.7867	0.7911	0.7978	0.8005
LTC ave (Euro/kWh)	0.01270	0.01256	0.01263	0.01273	0.01277
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	24470.6	28623.8	32975.6	36451.1	39941.3
Pmax (MW)	30353.1	35426.6	40487.6	44534.6	48590.4
Etotal (GWh/y)	151409.4	176713.7	201960.3	222141.2	242363.4
Elosses (GWh/y)	9964.5	11643.7	13370.5	14750.5	16138.9
Elosses (%)	6.6	6.6	6.6	6.6	6.7
Efail (GWh/y)	2850.6	3238.4	3636.4	3972.6	4264.0
Efail (%)	1.9	1.8	1.8	1.8	1.8
Inv per MW (MEuro/MW)	0.8062	0.8080	0.8145	0.8185	0.8220
LTC ave (Euro/kWh)	0.01286	0.01289	0.01300	0.01306	0.01312

LTC ave: average LTC determined by the sum of the LTCs divided by the number of connections

Table 3.7 summarizes the results for the wind farm to shore connections of all ten NSTG Scenario 1 phases. The investment cost increase from 4816 to 39941 Million Euro while the annually transported energy increases from 30170 GWh/y to 242363 GWh/y. The effect on the average Levelised Transport Cost in not that big however: an increase from 0.0127 to 0.0131. Figure 3.6 shows that the transported energy and investment costs increase almost linearly with the increasing number of wind farms. The trade connections are not included in these results yet, these will be evaluated in the next section.

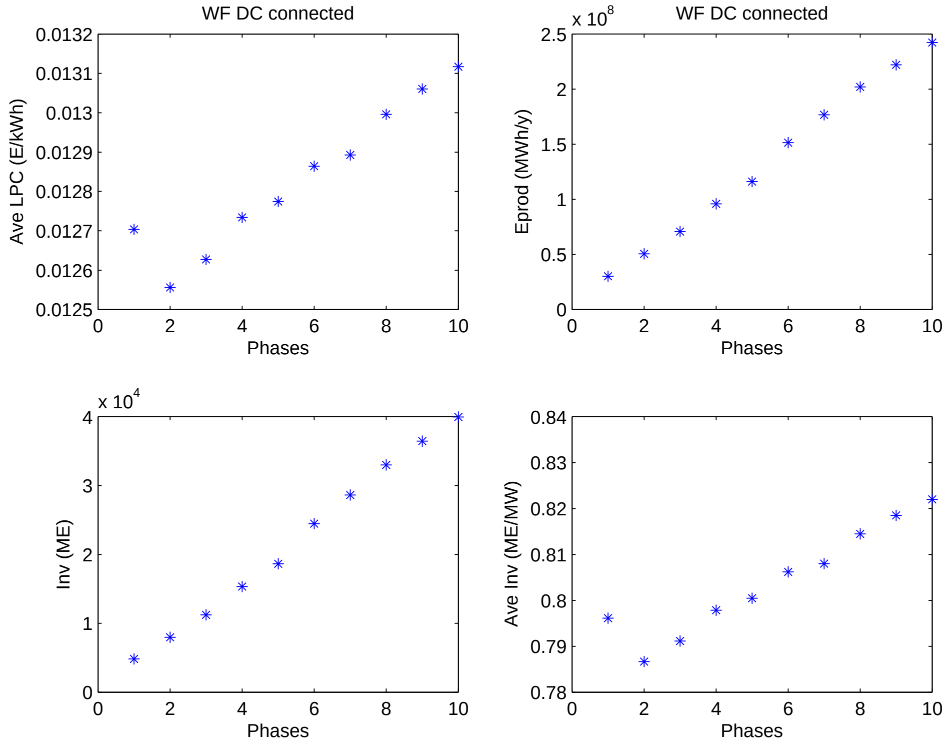

Figure 3.6: Wind Farms DC connected: all NSTG phases

3.2 Scenario 1 - Wind and Trade integrated - Part 2 : Trade connections

The second part of NSTG scenario 1 consists of the DC cables connecting the offshore nodes 1-9, see figure 3.1. These connections will only be used for trade and the location and number of connections depends on the development phase of NSTG. Table 3.8 list the number of the trade connections in each phase of NSTG under — B — Country to country. The connection of the DC offshore nodes to shore are either the wind farm to shore connections (— A — Wind farm to shore) or in case of individually AC connected wind farms separate DC connections listed under — C — Trade only to shore. This section only considers the connection under — B — Country to country. These connections will also be part of scenario 2.

Table 3.8: North Sea HVDC grid development phases

Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
— A — Wind farm to shore											
Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
L01	UK				2	3	5	6	8	9	11
L04	UK	1	3	4	4	4	4	4	4	4	4
L06	B						1	1	1	2	2
L09	NL	1	1	1	1	2	2	3	3	3	3
L10	NL			1	1	1	1	1	1	1	1
L12	G	2	4	4	4	4	7	9	11	14	16
L14	G			2	4	6	6	6	6	6	6
L16	DK	1	1	1	1	1	2	2	2	2	2
L18	N	1	1	1	2	2	2	3	3	3	3
Total		6	10	14	19	23	30	35	40	44	48
— B — Country to country											
Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
L03	UK				1	1	1	1	1	1	1
L05	UK-B	1	1	1	2	2	2	2	3	3	3
L07	B-NL	1	1	1	1	1	2	2	2	2	2
L08	NL-NL	1	1	1	1	1	2	2	2	2	2
L11	NL-G	1	1	2	2	2	2	2	2	2	2
L13	G-G	1	1	2	2	2	2	2	2	2	2
L15	G-DK	1	1	1	1	2	2	2	2	2	2
L17	DK-N	1	1	1	1	2	2	2	2	2	2
L02	N-UK						1	1	2	2	2
L19	D-UK					1	1	1	1	1	1
Total		7	7	9	11	14	17	17	19	19	19
— C — Trade only to shore											
Grid section		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
L01	UK				1	2	3	3	3	3	3
L04	UK	1	1	1	2	2	2	2	2	2	2
L06	B		1	1	1	1	1	1	1	1	1
L09	NL	1	1	1	1	1	1	1	2	2	2
L10	NL			1	1	1	1	1	1	1	1
L12	G	1	1	1	1	1	1	2	2	2	2
L14	G			1	1	1	1	1	1	1	2
L16	DK		1	1	1	2	2	2	2	2	2
L18	N	1	1	1	1	1	2	2	2	2	2
Total		4	6	8	10	12	14	15	16	16	17

The values in table 3.8 represent the number of 1200MW DC connections. See figure 2.1 for the grid node letters and numbers.

The trade connections have the same rating as the wind farm connections in the previous section: 1200MW and 320kV DC. The trade connections are calculated for maximum power, independant of the windspeed.

Figure 3.7 gives an example of a trade connection: section L03 connecting node 1 to node 2. The loss in this section is about 30.4 MW at a transported power of about 1169.5 MW. Since no converters are included, the not produced power due to failure is relatively low: about 0.5 MW.

Table 3.9 lists the variables for all trade connections. The number of connections depends on the phase and can vary from 0 (no connection installed yet) to 3 (see table 3.8). The number of parallel connections does not have an effect on the not produced power due to failure since the connections are evaluated for rated power. Therefore, a failure can not be partly compensated by sending more power over the remaining connections.

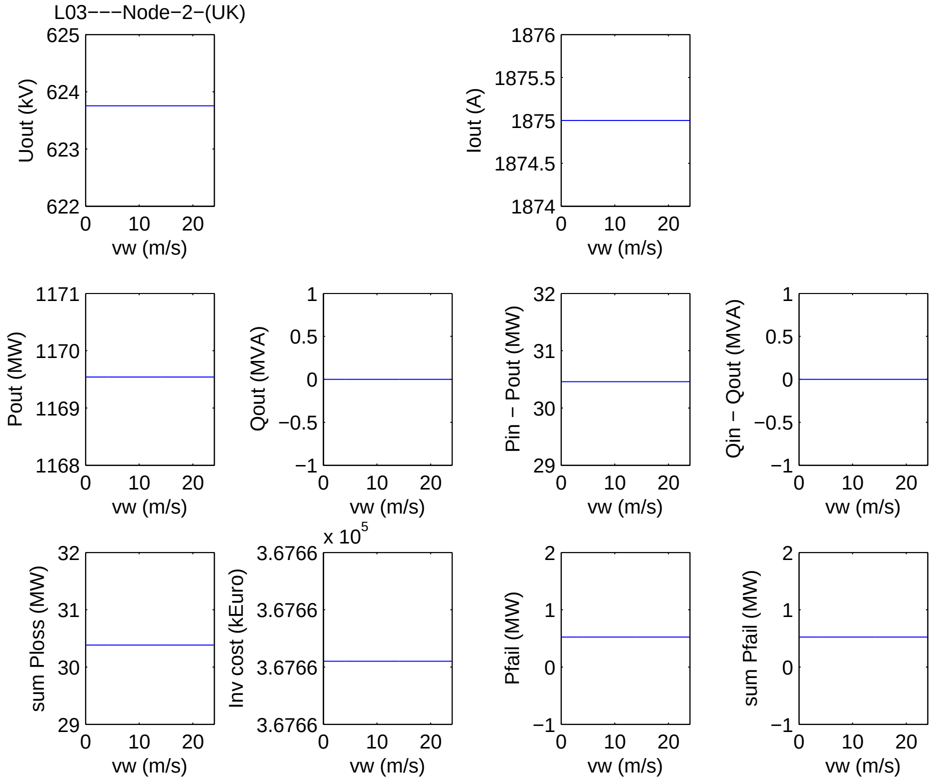

Figure 3.7: NSTG DC Ring - Country to country section L03 at Node 2 operating at rated power independant of wind speed

Table 3.9: NSTG DC Ring - Country to country sections variables at rated power

Trade Grid section	U (kV)	I (kA)	Pout (MW)	Qout (MVA)	Inv (MEuro)	sumPloss (MW)	Pfail (MW)	sumPfail (MW)
L03—Node-2-(UK)	623.8	1.9	1169.5	0.0	367.7	30.4	2.9	2.9
L05—Node-3-(BE)	633.5	1.9	1187.8	0.0	147.1	12.2	1.2	1.2
L07—Node-4-(NL)	631.9	1.9	1184.8	0.0	183.8	15.2	1.5	1.5
L08—Node-5-(NL)	623.1	1.9	1168.3	0.0	382.4	31.6	3.0	3.0
L11—Node-6-(GE)	637.4	1.9	1195.1	0.0	58.8	4.9	0.5	0.5
L13—Node-7-(GE)	635.1	1.9	1190.9	0.0	110.3	9.1	0.9	0.9
L15—Node-8-(DK)	636.8	1.9	1193.9	0.0	73.5	6.1	0.6	0.6
L17—Node-9-(NO)	625.4	1.9	1172.6	0.0	330.9	27.4	2.6	2.6
L19—Node-8-(DK-UK)	607.5	1.9	1139.1	0.0	735.3	60.6	5.7	5.7
L02—Node-9-(NO-UK)	601.0	1.9	1126.9	0.0	882.4	72.7	6.8	6.8

Table 3.10: NSTG DC Ring - Country to country sections operating at rated power

Trade Grid section	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
L03—Node-2-(UK)	367.7	1169.5	30.4	2.9	2.6	0.2	0.0029
L05—Node-3-(BE)	147.1	1187.8	12.2	1.2	1.0	0.1	0.0011
L07—Node-4-(NL)	183.8	1184.8	15.2	1.5	1.3	0.1	0.0014
L08—Node-5-(NL)	382.4	1168.3	31.6	3.0	2.7	0.3	0.0030
L11—Node-6-(GE)	58.8	1195.1	4.9	0.5	0.4	0.0	0.0005
L13—Node-7-(GE)	110.3	1190.9	9.1	0.9	0.8	0.1	0.0008
L15—Node-8-(DK)	73.5	1193.9	6.1	0.6	0.5	0.1	0.0006
L17—Node-9-(NO)	330.9	1172.6	27.4	2.6	2.3	0.2	0.0026
L19—Node-8-(DK-UK)	735.3	1139.1	60.6	5.7	5.3	0.5	0.0059
L02—Node-9-(NO-UK)	882.4	1126.9	72.7	6.8	6.4	0.6	0.0072

Table 3.10 list the overall results for all trade sections, independent of the number of parallel connections.

Table 3.11: NSTG DC Ring - Country to country sections: all development phases

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	1286.8	1286.8	1455.9	1970.7	3110.4
Pmax (MW)	8283.1	8283.1	10667.7	13020.9	16517.6
Etotal (GWh/y)	72107.1	72107.1	92866.1	113351.9	143791.4
Elosses (GWh/y)	926.6	926.6	1048.6	1419.1	2238.1
Elosses (%)	1.3	1.3	1.1	1.3	1.6
Efail (GWh/y)	89.8	89.8	101.7	137.5	215.3
Efail (%)	0.1	0.1	0.1	0.1	0.1
Inv per MW (MEuro/MW)	0.1554	0.1554	0.1365	0.1513	0.1883
LTC ave (Euro/kWh)	0.00143	0.00143	0.00126	0.00139	0.00174
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	4559.0	4559.0	5588.5	5588.5	5588.5
Pmax (MW)	19986.3	19986.3	22293.0	22293.0	22293.0
Etotal (GWh/y)	173987.8	173987.8	194069.0	194069.0	194069.0
Elosses (GWh/y)	3278.3	3278.3	4017.0	4017.0	4017.0
Elosses (%)	1.9	1.9	2.1	2.1	2.1
Efail (GWh/y)	313.4	313.4	382.6	382.6	382.6
Efail (%)	0.2	0.2	0.2	0.2	0.2
Inv per MW (MEuro/MW)	0.2281	0.2281	0.2507	0.2507	0.2507
LTC ave (Euro/kWh)	0.00212	0.00212	0.00233	0.00233	0.00233

Table 3.12 summarizes the total results for the trade sections connections for each development phase. The number of connections increases from 7 in phase 1 to 19 in phase 10. The investment costs increase from 1286 MEuro to 5588 MEuro. If the transported power per section are added, the total maximum power increases from 8283 MW to 22293 MW. The average Levelized Transport Costs LTC, which is defined as the sum of LTCs of all connections divided by the number of connections, varies between 0.00126 and 0.00233 Euro/kWh. In figure 3.8 the results in table 3.12 are plotted.

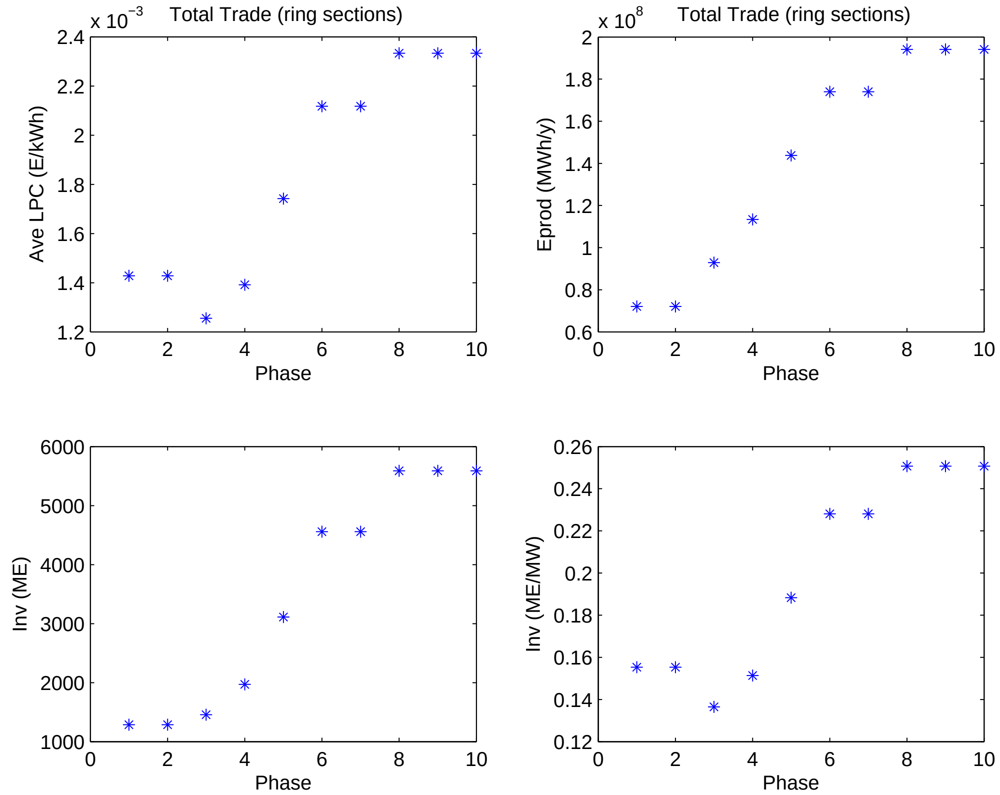

Figure 3.8: DC Ring - all phases at maximum possible trade

3.3 Scenario 2 - Wind and Trade Separate - Part 1 : Wind AC to shore

In Scenario 2 the wind farm and trade connections will not be integrated. The wind farms will be connected to shore by AC cables. For the 1100 MW wind farms, an AC cable with a high rated power is required. The EeFarm database limits the choice to 6 HVAC cables with voltages of 138, 150 and 245 kV, see figure 3.9. In general, a higher voltage requires more reactive power compensation and this reduces the remaining power transport capability, especially at longer distances. Decreasing the voltage reduces the rated power for the same rated current and increases the relative losses but reduces the required reactive power. A 150 kV cable with a rating of 200 MVA was chosen. The price of this cable is at the lower end of the range of price indications supplied by ENTSO-E [6]. The cable with the lowest cost per MW in the database was a 132kV cable. The rated power of this cable is relatively low however, requiring an even higher number of cables for the 1100MW wind farm. Secondly, the price was far below the range indicated by ENTSO-E (2.6 - 4 kEuro/(km.MW) excl. laying) and therefore considered not realistic. A 245 kV cable was also considered but the investment cost including laying was higher and the reactive power compensation for this cable was much higher.

The wind farm rated power and the distance to shore will determine the number of parallel cables, see figure 3.10. Below a distance of 110 km, the number of AC cables to connect a 1100 MW wind farm is 6 if reactive power is supplied from both sides of the cable. At the maximum distance of 180 km, 7 parallel AC cables result in a maximum transport capability of 1080 MW, sufficient to connect the wind farm. This AC connection can be

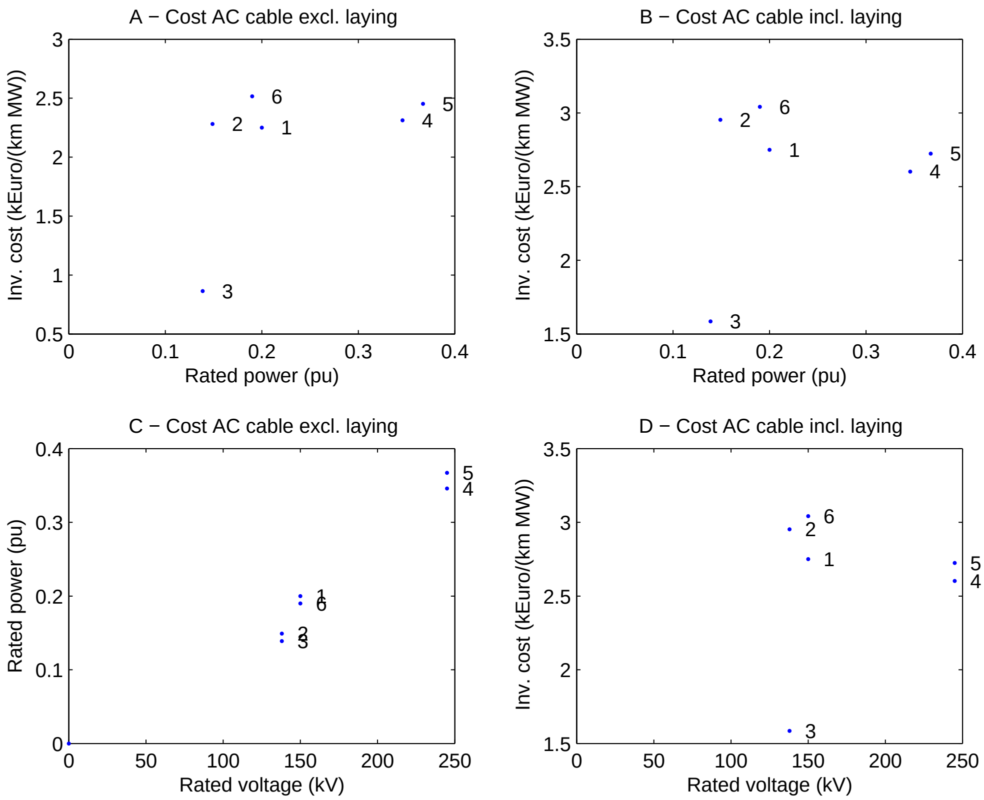

Figure 3.9: AC cable costs (P(pu)=1000MW)

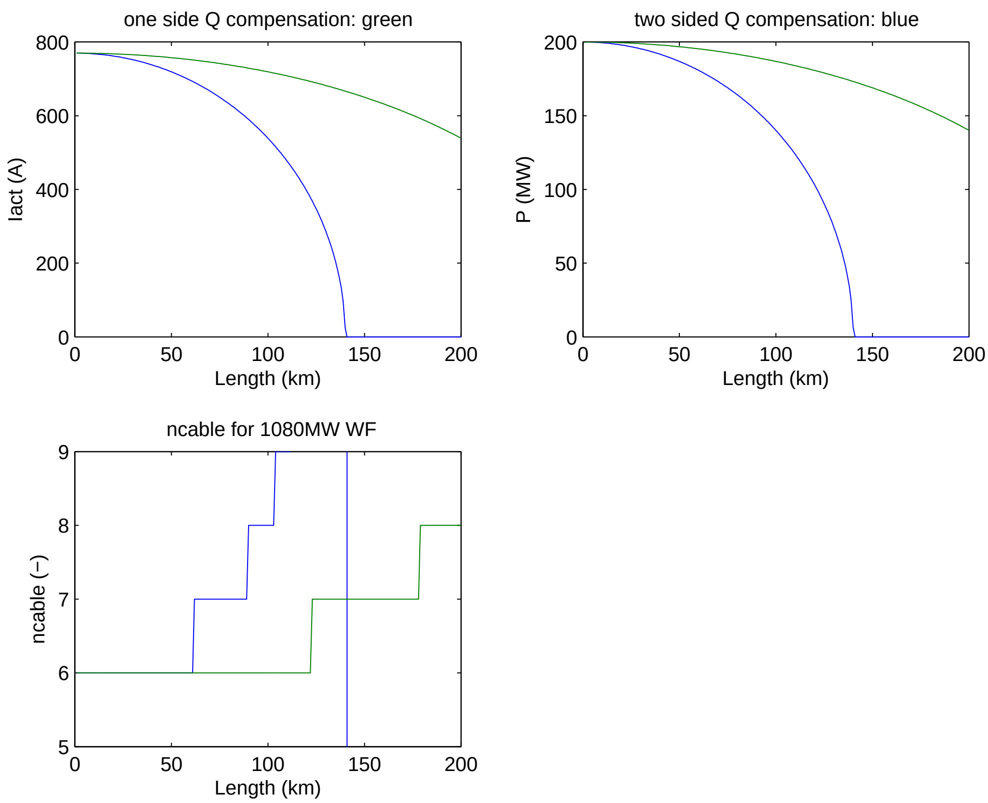

Figure 3.10: Number of 150 kV, 200 MVA AC cables for a 1100 MW wind farm with one (blue) and two sided reactive power compensation (green)

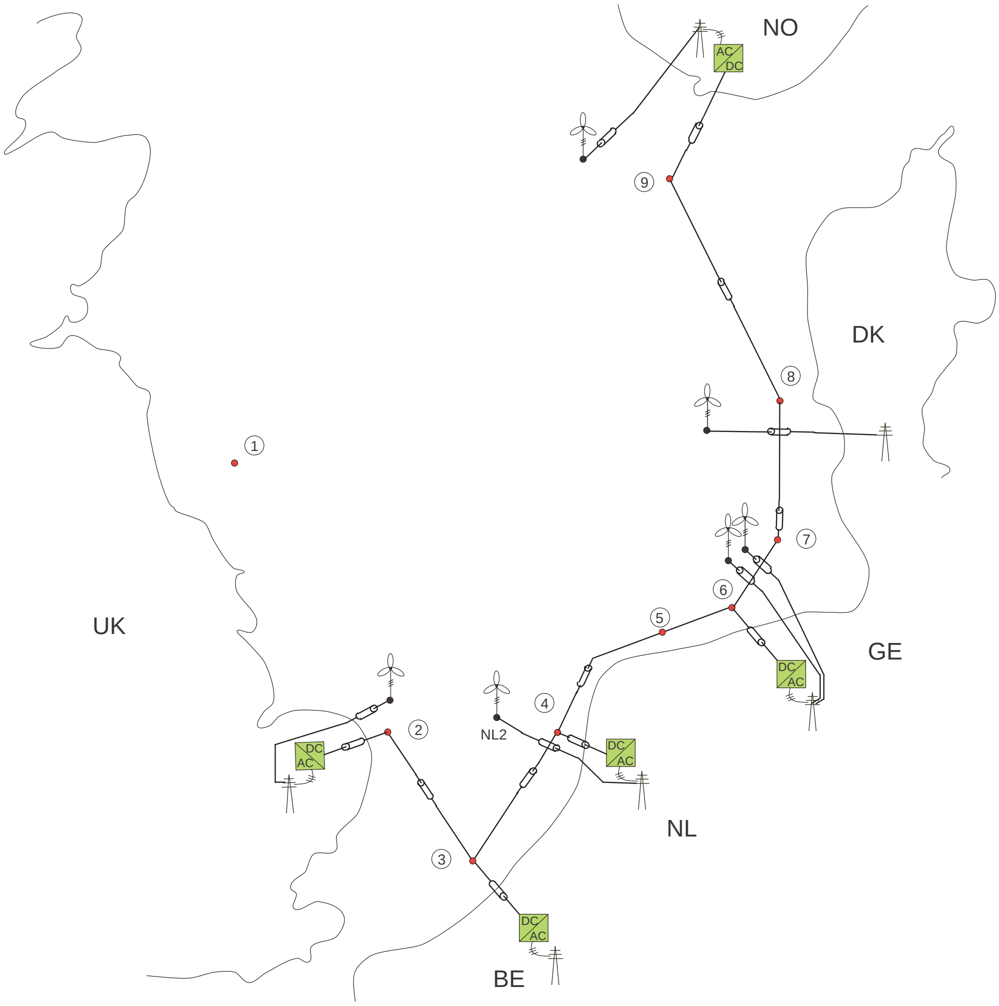

Figure 3.11: Wind and Trade separate (Scenario 2 - Phase 1)

used for all wind farms in the Wind and Trade Separate scenario. Table 3.12 summarizes the result per wind farm location.

Table 3.12: AC connected wind farms in Wind and Trade Separate scenario

UK4, UK5, B1, NL1, NL2, NL3, NL4, G1, G2, D1, D2	6 parallel AC cables
UK3, G3, G4, G5, N1,2,3	7 parallel AC cables

Figure 3.11 shows the first phase of the Wind and Trade Separate scenario, consisting of 6 wind farms, 7 trade sections (between the nodes 2-9) and 4 trade connections to shore. The wind farm voltage, current, power, reactive power, losses and not produced power due to failure are plotted as a function of the wind speed in figure 3.12.

Figure 3.13 shows the variables for wind farm UK3 connected to Node 10 at the point of connection to the onshore grid. The total output of the AC cables is shown. About half of the reactive power required by the cables is supplied from the shore side: between

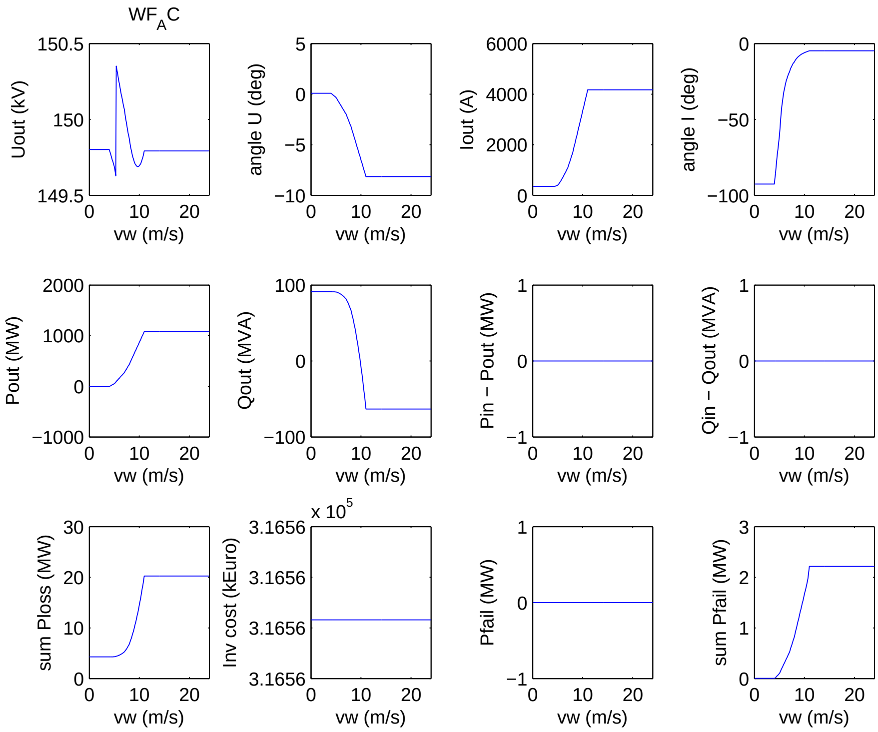

Figure 3.12: Wind Farm AC connected to shore: AC connection point after trafo at wind farm platform

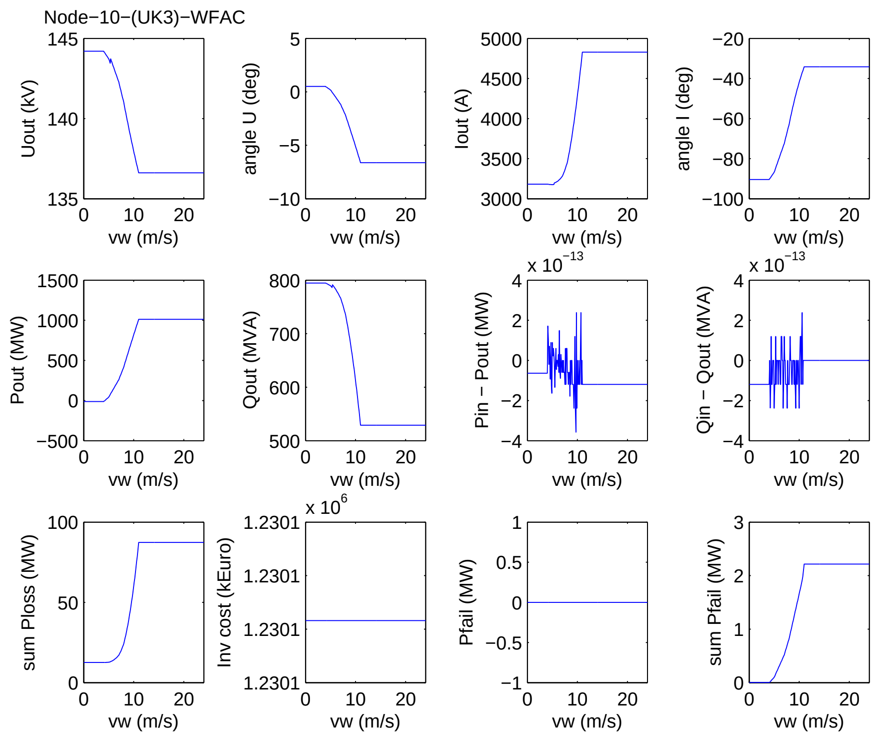

Figure 3.13: Wind Farm UK3 AC connected to Node 10 (UK) at point of connection to onshore grid

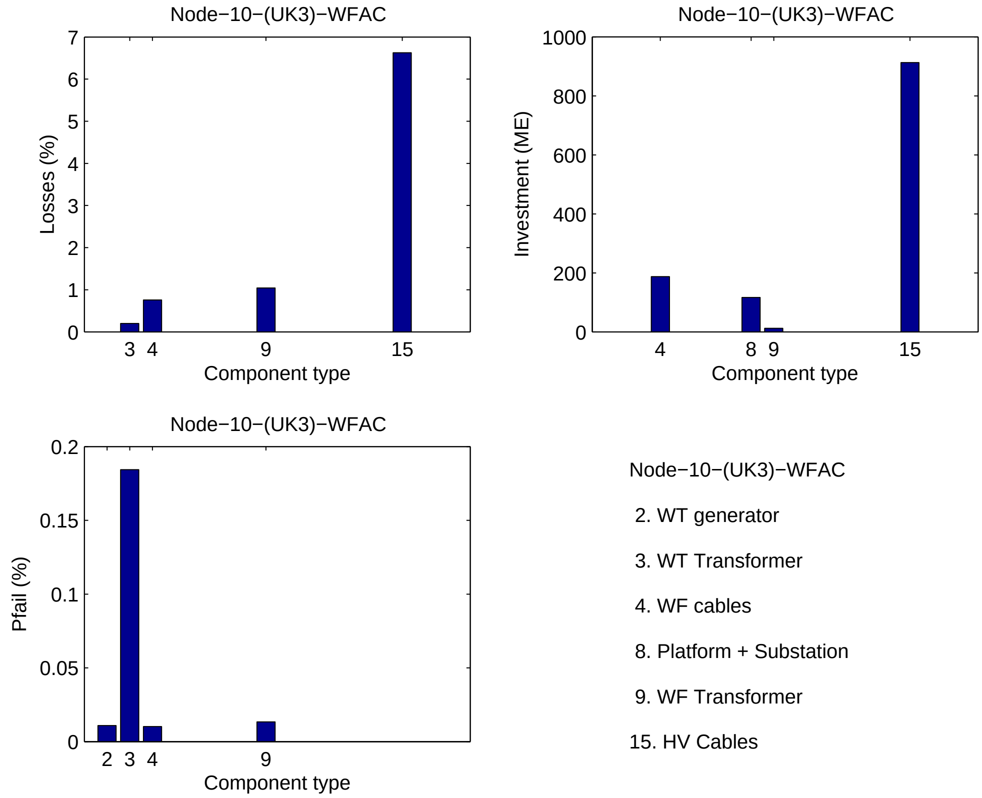

Figure 3.14: Wind Farm UK3 AC connected to Node 10 (UK): total losses, investment and failure per component type

530 and 800 MVA. The change in phase angle corresponds to the increased power and reduced reactive power. $P_{in} - P_{out}$ and $Q_{in} - Q_{out}$ are zero since the last component is a lossless node connecting all cables.

In figures 3.14 and 3.15 the total losses, investment costs and failure of the AC connection of wind farm UK3 to the onshore grid at node 10 are presented per component type. In the losses and investment costs the AC cables are dominant. The cables are not present in the not transported due to failure due to the number of parallel connections: seven. In the failure figures the turbine transformers are dominant and not the wind farm transformers because the number of wind farm transformers equals the number of cables and operate in parallel.

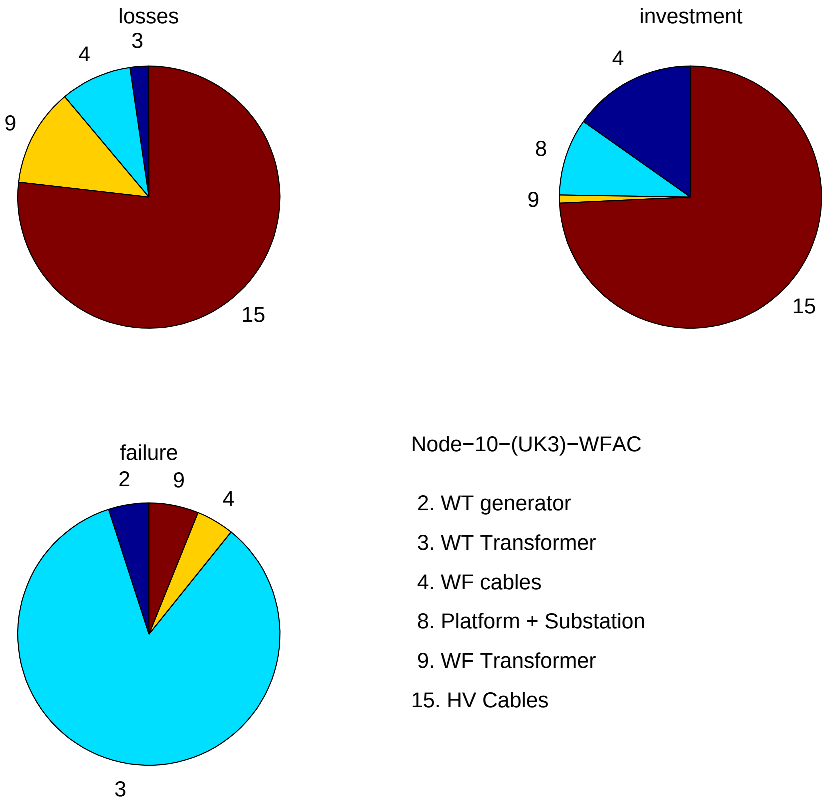

Figure 3.15: WF UK3 AC connected to Node 10 (UK) total losses, investment and failure per component type

Table 3.13: AC connected wind farms: variables at maximum power

Wind farm AC connection	U (kV)	I (kA)	Pout (MW)	Qout (MVA)	Inv (MEuro)	PlossTot (MW)	Pfail (MW)	PfailTot (MW)
–WF-AC–	149.8	4168.8	1079.7	-63.3	316.6	20.3	0.0	2.2
Node-10-UK3	136.6	4828.3	1012.6	529.0	1230.1	87.4	0.0	2.2
Node-10-UK4	138.5	4473.7	1032.3	292.6	819.9	67.7	0.0	2.3
Node-11-UK5	139.5	4416.9	1040.5	237.1	736.0	59.5	0.0	2.3
Node-12-B1	140.5	4371.4	1048.5	180.1	652.1	51.4	0.0	2.3
Node-12-NL1	140.5	4371.4	1048.5	180.1	652.1	51.4	0.0	2.3
Node-13-NL2	140.5	4371.4	1048.5	180.1	652.1	51.4	0.0	2.3
Node-13-NL3	137.9	4494.5	1026.7	312.5	875.8	73.2	0.0	2.3
Node-14-NL4	140.5	4371.4	1048.5	180.1	652.1	51.4	0.0	2.3
Node-15-G1	137.9	4494.5	1026.7	312.5	875.8	73.2	0.0	2.3
Node-16-G2	137.9	4494.5	1026.7	312.5	875.8	73.2	0.0	2.3
Node-16-G3	135.8	4999.7	1007.0	607.5	1295.3	93.0	0.0	2.2
Node-15-G4	135.8	4999.7	1007.0	607.5	1295.3	93.0	0.0	2.2
Node-15-G5	133.9	5335.3	988.9	743.8	1491.1	111.1	0.0	2.3
Node-17-D1	139.5	4416.9	1040.5	237.1	736.0	59.5	0.0	2.3
Node-17-D2	139.5	4416.9	1040.5	237.1	736.0	59.5	0.0	2.3
Node-18-N1	135.8	4999.7	1007.0	607.5	1295.3	93.0	0.0	2.2
Node-18-N2	135.8	4999.7	1007.0	607.5	1295.3	93.0	0.0	2.2
Node-18-N3	135.8	4999.7	1007.0	607.5	1295.3	93.0	0.0	2.2

Table 3.13 lists the main variables for all AC wind farm connections to shore at maximum power. Table 3.14 summarizes the result determining the economic performance of the AC wind farm connections. In table 3.15 the results per connection are added to find the overall results of the ten development phases. In figure 3.16 the main results are plotted.

Table 3.14: AC connected wind farms overview (single as well as multiple connections)

Wind farm AC connection	InvTot (ME)	PoutMax (MW)	PlossTot (MW)	PfailTot (MW)	PlossRel (percent)	PfailRel (percent)	LTC (E/kWh)
–WF-AC–	316.6	1079.7	20.3	2.2	1.9	0.2	0.0047
Node-10-UK3	1230.1	1012.6	87.4	2.2	8.6	0.2	0.0194
Node-10-UK4	819.9	1032.3	67.7	2.3	6.6	0.2	0.0127
Node-11-UK5	736.0	1040.5	59.5	2.3	5.7	0.2	0.0113
Node-12-B1	652.1	1048.5	51.4	2.3	4.9	0.2	0.0099
Node-12-NL1	652.1	1048.5	51.4	2.3	4.9	0.2	0.0099
Node-13-NL2	652.1	1048.5	51.4	2.3	4.9	0.2	0.0099
Node-13-NL3	875.8	1026.7	73.2	2.3	7.1	0.2	0.0136
Node-14-NL4	652.1	1048.5	51.4	2.3	4.9	0.2	0.0099
Node-15-G1	875.8	1026.7	73.2	2.3	7.1	0.2	0.0136
Node-16-G2	875.8	1026.7	73.2	2.3	7.1	0.2	0.0136
Node-16-G3	1295.3	1007.0	93.0	2.2	9.2	0.2	0.0206
Node-15-G4	1295.3	1007.0	93.0	2.2	9.2	0.2	0.0206
Node-15-G5	1491.1	988.9	111.1	2.3	11.2	0.2	0.0242
Node-17-D1	736.0	1040.5	59.5	2.3	5.7	0.2	0.0113
Node-17-D2	736.0	1040.5	59.5	2.3	5.7	0.2	0.0113
Node-18-N1	1295.3	1007.0	93.0	2.2	9.2	0.2	0.0206
Node-18-N2	1295.3	1007.0	93.0	2.2	9.2	0.2	0.0206
Node-18-N3	1295.3	1007.0	93.0	2.2	9.2	0.2	0.0206

Table 3.15: Wind Farms AC connected: all phases

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	5171.2	8394.9	11534.8	16641.1	20927.4
Pmax (MW)	6176.2	10301.4	14434.6	19528.4	23592.2
Etotal (GWh/y)	30848.3	51462.4	72113.0	97553.6	117846.9
Elosses (GWh/y)	1956.7	3206.9	4419.9	6330.5	7922.3
Elosses (%)	6.3	6.2	6.1	6.5	6.7
Efail (GWh/y)	66.3	110.8	155.2	210.2	254.1
Efail (%)	0.2	0.2	0.2	0.2	0.2
Inv per MW (MEuro/MW)	0.8373	0.8149	0.7991	0.8521	0.8870
LTC ave (Euro/kWh)	0.01339	0.01301	0.01275	0.01361	0.01418
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	28661.6	34653.5	41391.0	46255.3	51697.6
Pmax (MW)	30711.7	35760.6	40759.3	44789.2	48783.2
Etotal (GWh/y)	153380.5	178583.4	203504.1	223589.8	243498.3
Elosses (GWh/y)	10692.6	12857.4	15329.5	17152.4	19160.8
Elosses (%)	7.0	7.2	7.5	7.7	7.9
Efail (GWh/y)	330.2	384.6	438.8	482.5	525.9
Efail (%)	0.2	0.2	0.2	0.2	0.2
Inv per MW (MEuro/MW)	0.9332	0.9690	1.0155	1.0327	1.0597
LTC ave (Euro/kWh)	0.01493	0.01550	0.01626	0.01654	0.01698

3.4 Scenario 2 - Wind and Trade Separate - Part 2 : Trade connections

To complete the Wind and Trade Separate scenario, the trade connections have to be added to this scenario:

- the trade sections between the offshore nodes 1-9 (the ring);
- the connections of the ring to shore (labelled L01, L04, L06, L09, L10, L12, L14, L16 and L18 in figure 2.1).

The connections between the offshore nodes 1-9 are the same as in the integrated case and have been presented in section 3.2.

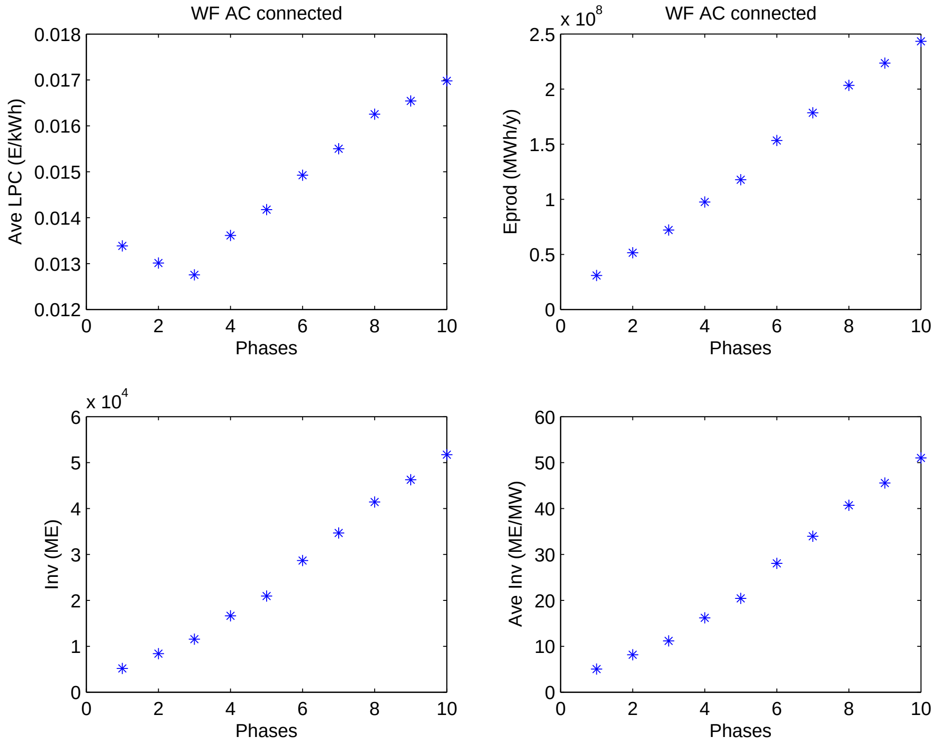

Figure 3.16: Wind Farms AC connected: all phases

In the Wind and Trade Integrated scenario, the DC connections of the individual wind farms are used to transport wind power and trade. For the Wind and Trade Separate scenario with AC connected wind farms this is not possible and additional DC connections of the offshore nodes 1-9 to the onshore grid are required.

Table 3.8 section — *B* — *Country to county* and section — *C* — *Trade only to shore* present the trade connections in scenario 2 per development phase. The number of trade connections to shore is much lower than the number of wind connections to shore: in Phase 10 the number of wind farm connections is 48 compared to 17 trade connections to shore. As before, it is assumed that the trade connections operate at maximum power independent of the wind speed, see figure 3.17.

Figure 3.17 gives an example of a trade connection to shore. The variables are plotted for the connection point to the onshore grid.

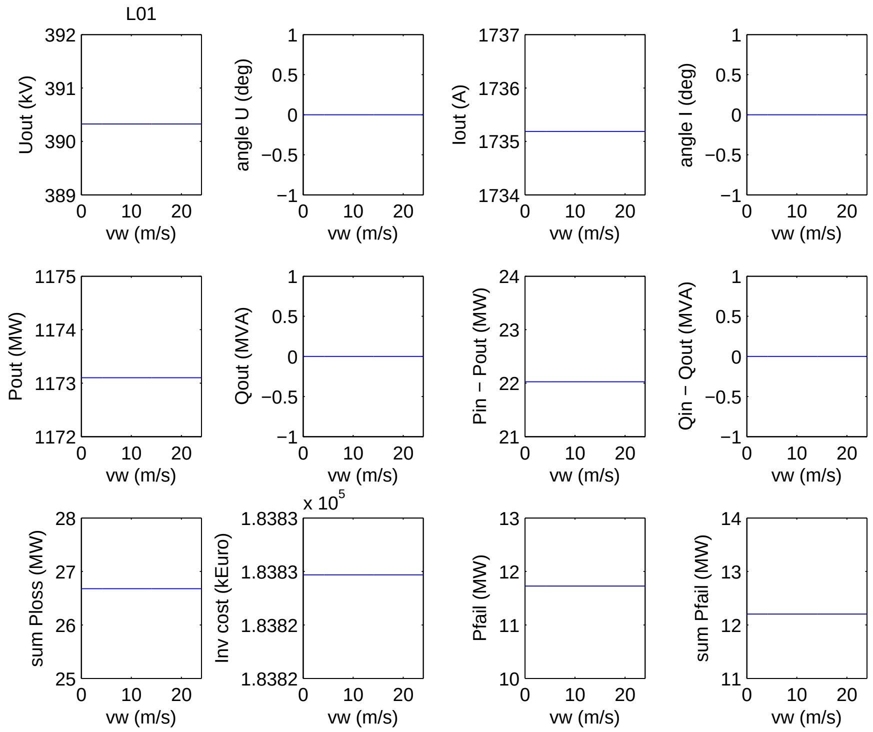

Figure 3.17: Trade connection to shore section L01 operating at rated power

Table 3.16: Trade connections to shore connections: variables at grid connection point

Grid section	U	I	Pout	Qout	Inv	sumPloss	Pfail	sumPfail
Ring to shore	(kV)	(kA)	(MW)	(MVA)	(MEuro)	(MW)	(MW)	(MW)
L01	390.3	1735.2	1173.1	0.0	183.8	26.7	11.7	12.2
L04	390.9	1735.2	1174.9	0.0	161.8	24.9	11.7	12.0
L06	388.7	1735.1	1168.3	0.0	242.7	31.5	11.7	12.6
L09	389.5	1735.2	1170.7	0.0	213.2	29.1	11.7	12.4
L10	390.3	1735.2	1173.1	0.0	183.8	26.7	11.7	12.2
L12	386.9	1735.1	1162.9	0.0	308.8	36.9	11.6	13.1
L14	385.9	1735.0	1159.8	0.0	345.6	39.9	11.6	13.4
L16	389.7	1735.2	1171.3	0.0	205.9	28.5	11.7	12.4
L18	387.1	1735.1	1163.5	0.0	301.5	36.3	11.6	13.0

Table 3.17: Trade connections to shore: results per connection for all phases

Grid section	InvTot	PoutMax	PlossTot	PfailTot	PlossRel	PfailRel	LTC
Ring to shore	(ME)	(MW)	(MW)	(MW)	(percent)	(percent)	(E/kWh)
L01	183.8	1173.1	26.7	12.2	2.3	1.0	0.0014
L04	161.8	1174.9	24.9	12.0	2.1	1.0	0.0013
L06	242.7	1168.3	31.5	12.6	2.7	1.1	0.0019
L09	213.2	1170.7	29.1	12.4	2.5	1.1	0.0017
L10	183.8	1173.1	26.7	12.2	2.3	1.0	0.0014
L12	308.8	1162.9	36.9	13.1	3.2	1.1	0.0025
L14	345.6	1159.8	39.9	13.4	3.4	1.2	0.0028
L16	205.9	1171.3	28.5	12.4	2.4	1.1	0.0016
L18	301.5	1163.5	36.3	13.0	3.1	1.1	0.0024

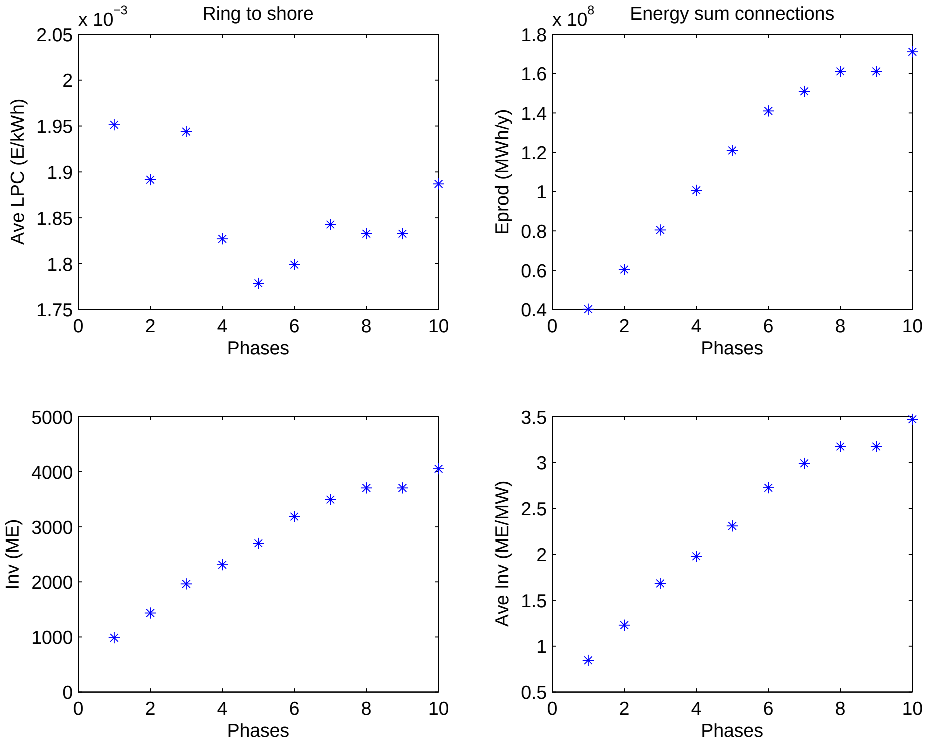

Figure 3.18: Trade connections to shore all phases: results per phase

Table 3.16 and 3.17 list the main variables and the economic results for all trade to shore connections. The results are independent of the number of parallel connections since operation at maximum power leaves not room for redundancy.

Table 3.18: Trade connections to shore all phases: results per phase

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	985.3	1433.9	1963.3	2308.9	2698.6
Pmax (MW)	4621.3	6935.9	9243.3	11567.0	13886.9
Etotal (GWh/y)	40230.2	60379.4	80466.0	100695.2	120890.1
Elosses (GWh/y)	1107.3	1629.5	2209.3	2658.2	3138.5
Elosses (%)	2.8	2.7	2.7	2.6	2.6
Efail (GWh/y)	440.5	658.0	880.5	1091.6	1305.5
Efail (%)	1.1	1.1	1.1	1.1	1.1
Inv per MW (MEuro/MW)	0.2132	0.2067	0.2124	0.1996	0.1943
LTC ave (Euro/kWh)	0.00195	0.00189	0.00194	0.00183	0.00178
	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	3183.9	3492.7	3706.0	3706.0	4051.5
Pmax (MW)	16198.2	17347.9	18506.2	18506.2	19652.7
Etotal (GWh/y)	141010.8	151019.9	161103.1	161103.1	171083.7
Elosses (GWh/y)	3686.9	4008.2	4261.5	4261.5	4609.0
Elosses (%)	2.6	2.7	2.6	2.6	2.7
Efail (GWh/y)	1525.2	1639.2	1747.3	1747.3	1863.6
Efail (%)	1.1	1.1	1.1	1.1	1.1
Inv per MW (MEuro/MW)	0.1966	0.2013	0.2003	0.2003	0.2062
LTC ave (Euro/kWh)	0.00180	0.00184	0.00183	0.00183	0.00189

The total results for the ten development phases for the trade connections to shore in scenario 2 is presented in table 3.18 and figure 3.18.

3.5 Comparison of scenarios

This section summarizes the results presented in the previous sections by comparing the cost of energy transport of the two scenarios. The wind farm connection and the additional trade connections are compared separately as well as combined. As described in section 1 scenario 1 integrates wind power and trade and both use DC systems. In scenario 2 wind power and trade use separate grids, wind power is AC connected and a transnational DC grid is built for trade purpose only. The number, the length and the rated power of the individual connections in both scenarios is the same, except for the additional trade connections to shore required in scenario 2.

Table 3.19: Scenario 1 and 2: Wind connections only

Scenario 1: Wind DC	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of WF	6	10	14	19	23
Inv (MEuro)	4816.2	7968.1	11215.7	15339.5	18638.5
LTC ave (Euro/kWh)	0.01270	0.01256	0.01263	0.01273	0.01277
Scenario 2: Wind AC	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of WF	6	10	14	19	23
Inv (MEuro)	5171.2	8394.9	11534.8	16641.1	20927.4
LTC ave (Euro/kWh)	0.01339	0.01301	0.01275	0.01361	0.01418

Scenario 1: Wind DC	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of WF	30	35	40	44	48
Inv (MEuro)	24470.6	28623.8	32975.6	36451.1	39941.3
LTC ave (Euro/kWh)	0.01286	0.01289	0.01300	0.01306	0.01312
Scenario 2: Wind AC	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of WF	30	35	40	44	48
Inv (MEuro)	28661.6	34653.5	41391.0	46255.3	51697.6
LTC ave (Euro/kWh)	0.01493	0.01550	0.01626	0.01654	0.01698

Table 3.19 compares the wind connection investment costs and the average LTC per connection for both scenarios. The LTC for a wind farm connection is based on the transported wind power only, using the connection for trade is not taken into account in these LTC. The investment costs and average LTCs are higher for the AC connected scenario than for the DC connections. Figure 3.19 A shows that the difference between the LTC values for wind only increases after phase 3.

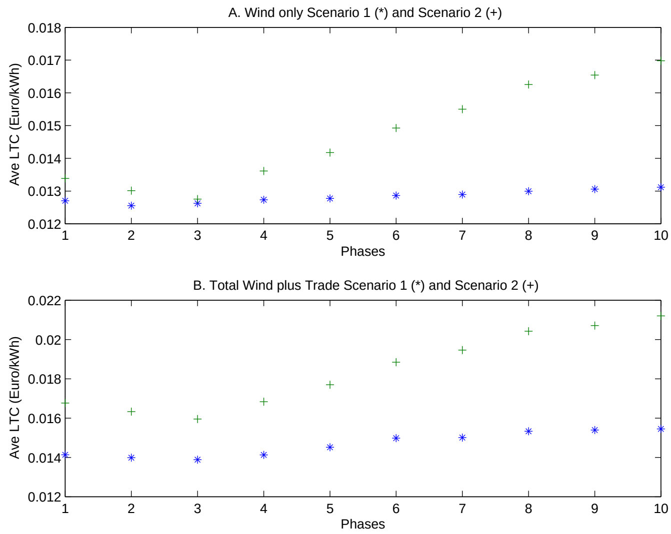

Figure 3.19: Average Levelized Transport Costs per connection and phase

Table 3.20: Trade connections only in Scenario 1 and 2 per phase

Scenario 1 and 2: Ring (Trade)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of trade connections	7	7	9	11	14
Inv (MEuro)	1286.8	1286.8	1455.9	1970.7	3110.4
LTC ave (Euro/kWh)	0.00143	0.00143	0.00126	0.00139	0.00174
Scenario 2: Trade to Shore	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
number of trade connections to shore	4	6	8	10	12
Inv (MEuro)	985.3	1433.9	1963.3	2308.9	2698.6
LTC ave (Euro/kWh)	0.00195	0.00189	0.00194	0.00183	0.00178

Scenario 1 and 2: Ring (Trade)	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of trade connections	17	17	19	19	19
Inv (MEuro)	4559.0	4559.0	5588.5	5588.5	5588.5
LTC ave (Euro/kWh)	0.00212	0.00212	0.00233	0.00233	0.00233
Scenario 2: Trade to Shore	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
number of trade connections to shore	14	15	16	16	17
Inv (MEuro)	3183.9	3492.7	3706.0	3706.0	4051.5
LTC ave (Euro/kWh)	0.00180	0.00184	0.00183	0.00183	0.00189

Table 3.20 list the trade connection total investment costs and the average LTC per connection for both scenarios. The ring connections are present in both scenarios. In scenario 1, the power trade may be limited by the capacity of the connections of an offshore node to shore. This effect is reduced by the relatively large number of wind farm connections (48 in phase 10) to the number of transnational connections (19 in phase 10). The trade to shore connections are only required for scenario 2. The LTC for a trade connection is based on permanent use at maximum power.

Figure 3.19 B shows the total LTC values of wind and trade in both scenarios. Compared to figure 3.19 A, the increase represents the cost of transporting traded power between countries assuming full use of all trade connections all the time in both scenarios. The LTC increases most in scenario 2 due to the additional connections to shore.

4

Summary and conclusions

Two scenarios for the development of a North Sea Transnational Grid for trade and connections of 52.8 GW wind energy have been evaluated. In scenario 1 the transport of wind power and traded power are integrated in an interconnected DC system. In scenario 2 wind power and trade are seperated: wind is AC connected and a DC grid connects the North Sea countries.

Both scenarios consist of the same cable routes with the exception of a number of extra cable routes in the wind and trade separate scenario 2 necessary to connect the ring shaped trade grid to the onshore grid. The scenarios are compared on a level of individual connections as well as in total. The EeFarm program was used to calculate electrical variables, losses, not produced power due to failure, investment costs and the transport costs averaged over the economic life time of the systems (LTC).

Both scenarios were developed in ten stages or phases with an approximately equal increase in wind power per stage.

Table 4.1: Scenario 1 and 2: Wind and Trade Total (Electrical system only, wind turbines not included)

Scenario 1: Wind DC + Trade	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	6103.0	9255.0	12671.6	17310.1	21748.9
LTC ave (Euro/kWh)	0.01413	0.01398	0.01388	0.01413	0.01452
Scenario 2: Wind AC + Trade	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Inv (MEuro)	7443.3	11115.6	14954.0	20920.6	26736.4
LTC ave (Euro/kWh)	0.01676	0.01633	0.01595	0.01683	0.01770

Scenario 1: Wind DC + Trade	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	29029.6	33182.8	38564.0	42039.5	45529.7
LTC ave (Euro/kWh)	0.01498	0.01501	0.01533	0.01539	0.01545
Scenario 2: Wind AC + Trade	Phase 6	Phase 7	Phase 8	Phase 9	Phase 10
Inv (MEuro)	36404.5	42705.2	50685.4	55549.7	61337.6
LTC ave (Euro/kWh)	0.01884	0.01946	0.02042	0.02071	0.02120

The scenarios are compared in three way: connection of wind power only, connection of power trade only and the total of wind and trade. The scenarios are compared by calculating the average levelized transport cost of the system, i.e. the average LTC per connection. Since the cable routes are the same (with the mentioned exception, which is treated separately) this is a clear comparison which also shows the development between one phase and the next.

The results in section 3.5 and table 4.1 show that the investment costs play a dominant role in the comparison of the scenarios. The transport cost follow the trend in the invesment costs. The investment cost are based on the EeFarm database and have been compared to recent literature.

Comparing the wind power connestions only, the scenario 2 investment costs and average LTC are higher than for scenario 1 for all phases. The difference increases in next phases due to longer distances, which are a disanvantage for an AC system due to the relatively increasing weight of the cable costs and to a lesser extent the losses.

The AC solution requires a relatively larger number of parallel connections, while the DC solution is based on a single connection. The losses for the 10 shortest AC connections are below the DC system losses and for the remaining 6 above the DC losses. Due to the relatively larger number of parallel connections, the not produced power due to failure is negligable for the AC solutions (about 0.2%). For the single DC connection including two converters this is about 1.8-2.5%. This does not reverse the investment cost disadvantage of the AC system however.

Secondly, the two trade systems are compared. Since scenario 2 requires additional DC connections to shore, it requires the highest investment again and results in the highest average LTC per connection. Scenario 2 has the relative advantage of full availability for trade of the connections to shore but this may not be very decisive since there are relatively many wind connections to shore in scenario 1, which are most of the time only partly used.

When wind and trade systems are combined in a single average LTC per phase, the difference between scenario 1 and 2 increase to the detriment of scenario 2.

The critical factor determining the results in this study was the investment cost of the systems. The manufacturer supplied component prices in the EeFarm database were compared to recent ETSO-E data and for the DC system partly updated in an upward direction. When comparing AC and DC options, there appears to be more room for technical improvement (for instance loss reduction) and subsequent price reduction (due to increasing experience in design and operation) for the DC option.

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A

EeFarm-II model and database description

EeFarm-II calculates the output voltage and current phasor (AC) or voltage and current value (DC) of each wind farm component based on the input voltage and current and the component parameters. This is repeated for each wind speed bin, i.e. for the complete range of operation of the wind farm. From the output power for each wind speed bin and the wind speed distribution, the annual energy losses and the annually produced energy are determined. The Levelised Production Costs (LPC), i.e. the average production costs over the lifetime of the wind farm, are based on the investment cost, the produced energy and a number of economic parameters. Figure A.2 gives an overview of the different steps in the calculation of the Levelised Production Costs.

EeFarm-II is programmed in Matlab-Simulink, which may seem an a bit odd choice because stepping through a wind farm power curve and calculating the output of a wind farm is not a dynamic simulation, the task for which Simulink was designed. On the other hand, Matlab-Simulink has a lot of advantages, also for these kind of steady state calculations:

- *the graphical user interface and library facility, which makes setting up a new wind farm model from an existing set of component models very easy and transparant;*
- *the Simulink bus signal, which results in simple and error free connection of component models in the wind farm model;*
- *the Matlab data structure, which simplifies the transfer of component parameters to the wind farm model: complete sets of parameters are assigned by a single command.*

An advantage of EeFarm-II is that it can handle AC as well as DC components, standard load flow models can only handle AC components. The core of EeFarm-II consists of steady state models of wind farm electrical components. The EeFarm-II component models reside in a Simulink model library, see figure A.1. A wind farm model is built by copying the model blocs to a Simulink model and connecting the blocks. The electrical model blocs have one input and one output, which is a Simulink bus. The content of a bus for all AC and for all DC blocks is the same, see table A.1 for the AC bus. The component blocks are arranged and connected from the individual wind turbines in the direction of the point of common coupling (PPC: the connection of the wind farm to the HV grid). So, for example, the cable end connected to the turbine generator is input and the cable end connected to the turbine transformer is output. The signal direction also gives the order in which the model blocks are evaluated, starting at the turbines and ending at the HV transformer at the PCC. The voltage at each wind turbine generator is set by the user and is assumed to be constant, all other voltages are calculated by the programme. If two outputs need to be joined, for instance two cables comming from two turbines, a node block is used. Table A.2 gives an overview of the components in the library of EeFarm-II.

The AC component models are the well known equivalent circuit diagrams for generators (induction, doubly fed and full converter), cables and transformers. For the PWM converter three different models representing the switching and conduction losses can be chosen. EeFarm-II does not solve the load flow in the classical way because this would make it difficult to include DC components. Instead, it determines an average solution which is sufficiently accurate to determine the losses and the produced power, due to the small voltage drops and the small voltage angle differences in a wind farm. For a detailed description of EeFarm-II is referred to [9].

The independent variable in the EeFarm calculation is the wind speed. The wind turbine power curve specified by the turbine manufacturer is used to determine the turbine electric power. Alternatively, the electric power of each individual wind turbine in the farm, calculated by a wind farm wake program (for instance the ECN program FarmFlow) can be used. The turbine generator and turbine transformer model are only required if the reactive power produced by the turbine has to be determined. The losses in these components are set to zero, since already included in the power curve.

Table A.1: AC bus signals

$U_{line,out}$	line voltage phasor (RMS) at component output, complex number	(V)
$I_{phase,out}$	current phasor (RMS) at component output, complex number	(A)
P_{out}	power at component output	(W)
Q_{out}	reactive power at component output	(VA)
$P_{in} - P_{out}$	component losses	(W)
$Q_{in} - Q_{out}$	reactive power produced by component	(VA)
$\sum(P_{in} - P_{out})$	sum of component losses	(W)
f	frequency	(Hz)
$\sum Invcost$	sum of component investment costs	(kEuro)
P_{fail}	power not produced due to component failure	(W)
$\sum P_{fail}$	sum of power not produced due to component failure	(W)

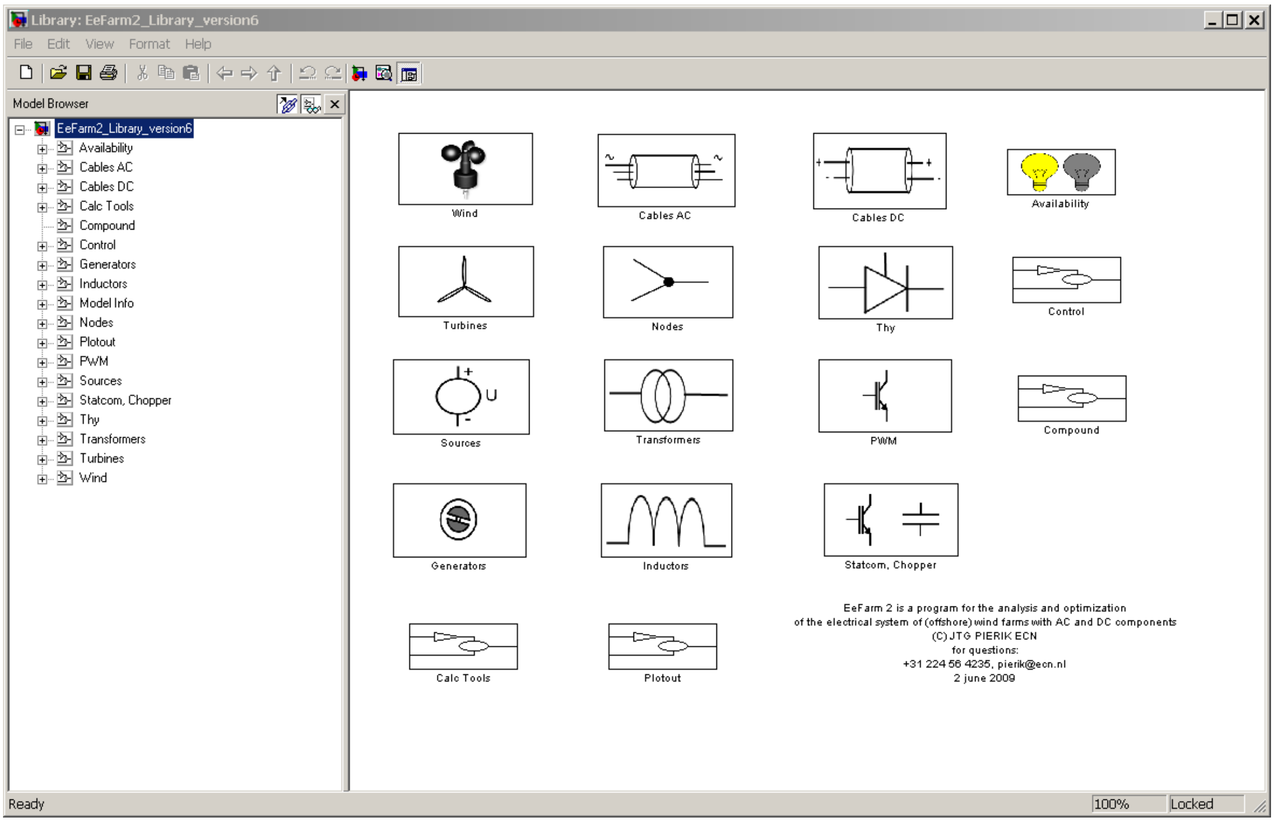

Figure A.1: EeFarm model library

Table A.2: Overview of EeFarm II components

Model	Simulink block	Remarks
Wind	Wind	wind input block
	GCL wake model	Simulink implementation of GCL wind farm wake model
Turbine	Turbine internal curve	single P(V) curve or FyndFarm or FluxFarm input
	Turbine WF eff.	VSP, CSP or CSS turbine, lookup table GCL preprocessor
	VSP turb	single P(V) curve or FyndFarm or FluxFarm input
Generator	Generator Generic	type independent simple generator model
	IM stat	directly connected induction machine
	DFIG	doubly fed induction machine
	FCIM	induction machine with full converter
	FCSM	synchronous machine with full converter
Transformer	TrafoQ	AC transformer with reactive power calculation
	Trafo Noloss Nofail	AC transformer, only the transformer ratio
Cable	CableAC	constant temperature π cable model
	CableDC	constant temperature, earth return DC cable
	CableDCbipolar	constant temperature, bipolar DC cable
Node	NodeAC	connects two AC bus signals
	NodeDC	connects two DC bus signals
	SplitterAC	splits an AC bus signal
	SplitterDC	splits a DC bus signal
Inductor	InductorQ	fixed size inductor for reactive power compensation
Thy	Thy rect	thyristor rectifier
	Thy inv	thyristor inverter
PWM	PWM rect Kaz, TUD, Inf	IGBT rectifier Kazmierkovski, TUD, Infineon model
	PWM inv Kaz, TUD, Inf	IGBT inverter Kazmierkovski, TUD, Infineon model
Chopper	Step-up chopper	DC-DC transformer
Statcom	Statcom TUD	IGBT inverter TU Delft model modified as Statcom
Availability	Availability	power reduction due to component failure
Control	Qfeedback	sets the reactive power of individual turbines

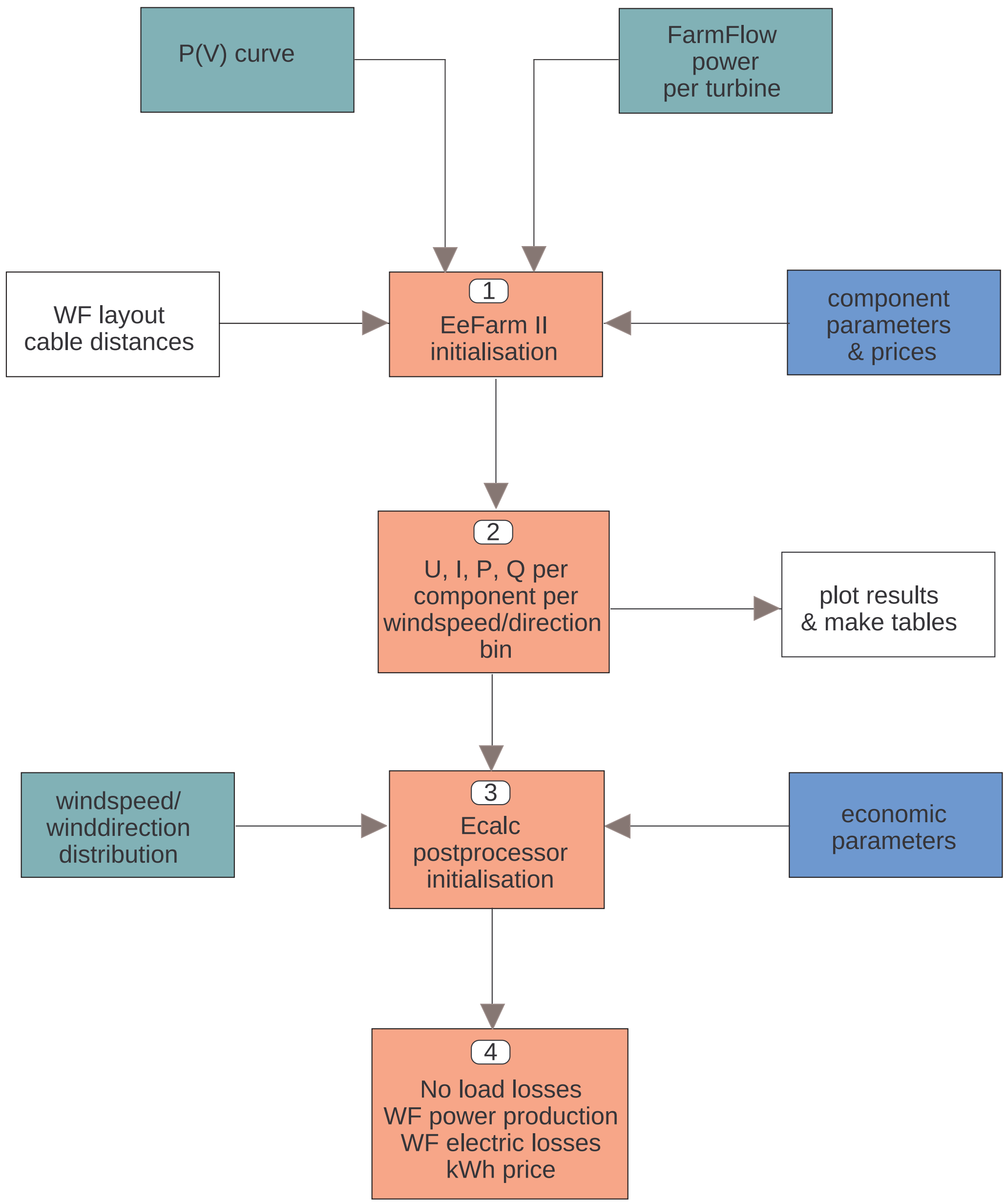

Figure A.2: EeFarm II model overview

EeFarm-II includes a database with electrical parameters (capacitance, inductance, resistance etc.) and costs of the components in wind farms. In the initialisation ($\boxed{1}$ in figure A.2) a wind farm specific m-file reads the component parameters from the database and fills the component parameter structures. The component parameters are passed to the simulation $\boxed{2}$ using a mask. This enables the use of different sets of parameters for different occurences of the same library block. The simulation calculates the voltage, current, power, reactive power, losses, not produced power due to unavailability and maintenance per component and per wind speed bin. This is input for the postprocessor $\boxed{3}$, which determines the LPC based on the wind speed distribution and the economic parameters.

B

Levelised transport cost LTC

To calculate the transport costs of wind farm connection to shore, the method described by the Expert Group on Recommended Practices for Wind Turbine Testing and Evaluation [12] is applied. The levelised transport cost LTC is defined as the transport cost of one unit of energy delivered at a given node in the HV grid. The transport cost is determined by averaging the costs and revenues over the life time of the wind farm.

All costs are expressed in Euro of year 1 ($t = 0$). The costs of subsequent years are discounted or depreciated to $t = 0$. The levelised transport cost is defined by the ratio of the total discounted costs and the total discounted energy output. Discounting of the transported energy is required to account for the moment a revenue is received (an early revenue increases in value with the real interest rate compared to a later revenue).

The Levelised Production Cost LTC equals:

$$LTC = \frac{TC}{\sum_{t=1}^{n} AUE_t (1+r)^{-t}}$$

with:

$$TC = I + \sum_{t=1}^{n} OMR_t (1+r)^{-t} - SV(1+r)^{-n} \tag{B.1}$$

TC	=	present value of all costs, i.e. total cost discounted to year $t = 0$
AUE_t	=	annual utilized energy output in kWh in year t, all losses included
I	=	investment, including possible interest during construction
OMR_t	=	operation and maintenance costs during year t including eventual retrofit costs
SV	=	salvage value at the end for the economic life $t = n$
n	=	economic life time in years
r	=	discount or depreciation rate, i.e. the real interest rate:

$$1 + r = \frac{1+i}{1+v}$$

with: i = nominal interest rate
v = inflation rate

In many cases it is appropriate to assume the annual utilized energy to be constant from year to year, i.e. $AUE_t = AUE$ for $t = 1$ to n. In such cases, the LTC equals:

$$LTC = \frac{I}{a \cdot AUE} + \frac{TOM}{AUE}$$

The factor a is the annuity factor:

$$a = \sum_{t=1}^{n} (1+r)^{-t} = \frac{1-(1+r)^{-n}}{r}$$

and TOM is the total levelised annual downline costs:

$$TOM = \frac{\sum_{t=1}^{n} OMR_t(1+r)^{-t} - SV(1+r)^{-n}}{a}$$

C

Initial business case (Cobra cable)

As first exercise a relatively simple business case will be investigated, e.g. two Offshore Wind Farm projects in neighbouring countries with interconnection. This business case may indicate which options are potentially feasible and this can be used in the stepwise development of the NSTG. A suitable initial case is the DC connection between Denmark and the Netherlands, similar to the ”COBRA cable” investigated by TenneT, but now extended with wind power, see figure C.1.

The main parameters of the COBRA cable are [4]:

Rated power	600 MW
Cable length	275 (offshore) + 70 (onshore) km
Converter location	Eemshaven (NL) and Revsing (DK)

Detailed COBRA component data are not available. However, reference [4] does list the converter and cable losses, see figure C.2. This will be used to check the losses calculated by EeFarm, see appendix E.

The main building blocks of the EeFarm model of the Cobra system will be:

- the 570MW wind farm;
- AC-DC converters $\pm$150kV-570MW VSC;
- DC cables of corresponding ratings;

The power rating of the initial business case is adapted to the available component data in the EeFarm database. The two wind farms will have a power rating of 550 MW each, based on the available VSC converter size. The distance of the wind farms to the shore substation is 40 plus 60 km (Horns Rev - Revsing, 400kV) and 10 plus 90 km (Eemshaven I - Eemshaven, 380kV). In the initial business case the rating of the connections of the wind farms to shore and of the transnational connection are 550MW.

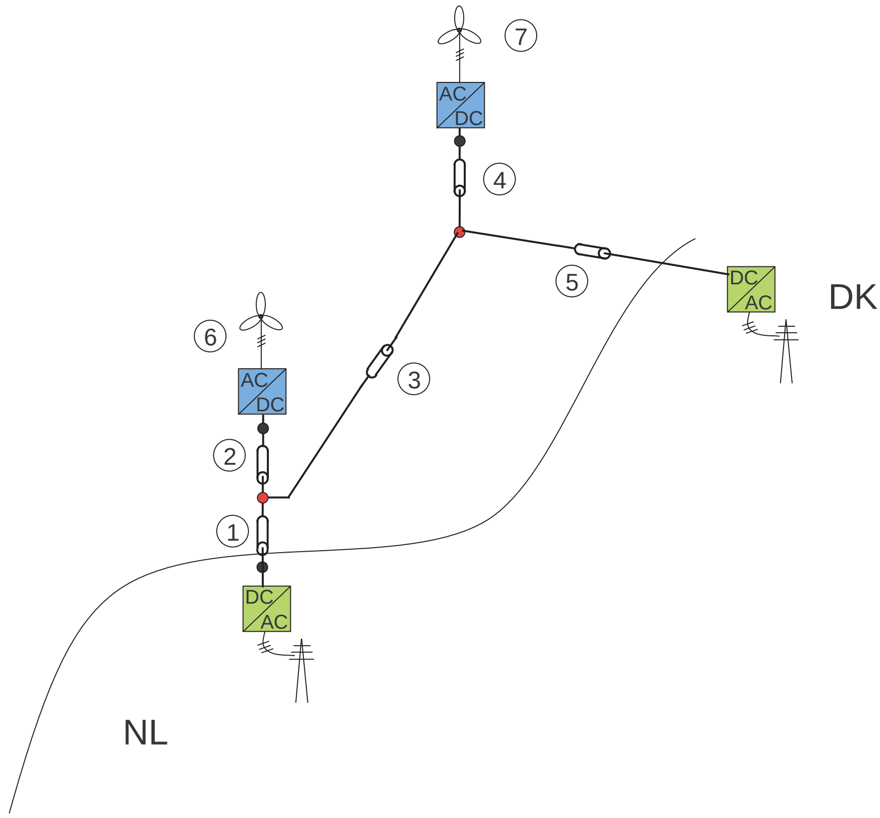

Figure C.1: Initial business case Denmark - the Netherlands with two wind farms (Option A)

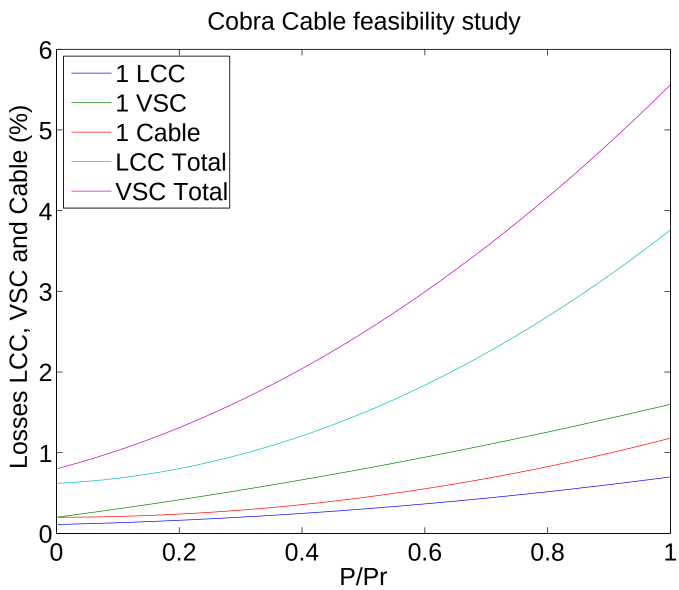

Figure C.2: Losses according to Cobra cable feasibility study [4] (wind farms not included)

Redundancy in Option A (figure C.1):

- since the wind farm power can be transported partly over two routes, the redundancy level S_{redun} of sections 1 and 5 is 0.5P_{rated};
- failure of the interconnection section 3 does not have a negative effect on the wind power production, since if this section fails, sections 1 and 5 are still able to transport all wind power (multiple failures at the same time are excluded), but it does reduce the maximum amount of energy that can be traded;
- since all DC connections are bipolar with two separate cables, it could be argued that these connections have inherent redundance as well if monopolar operation is posible, reducing the maximum power to half the original value. In case of the NSTG this would imply that the system, or a part of the system that can be separated from the rest, should change to monopolar operation during the fault.

Table C.1: Initial business case Denmark - the Netherlands with two wind farms

Cable section in figure C.1	Rated Voltage (kV)	Rated Power (MW/MVA)	Length (km)	S_{redun} no monopolar oper. (MVA)	S_{redun} monopolar oper. (MVA)
1	±150kV	550MW	10	0.5P_{rated}	0.5P_{rated}
2	±150kV	550MW	90	0	0.5P_{rated}
3	±150kV	550MW	275	0	0.5P_{rated}
4	±150kV	550MW	40	0	0.5P_{rated}
5	±150kV	550MW	60	0.5P_{rated}	0.5P_{rated}
6	197kV	570MVA	-	0	0
7	197kV	570MVA	-	0	0

Each wind farm consists of 110 wind turbines of 5 MW each. It is assumed that both wind farms are built in the same way. Based on the comparison of a 500 MW wind farm with 33kV and 69kV cables [8], a 69kV cable of 58.4 MVA will be used in the NSTG wind farm. Figure C.3 shows the wind farm layout, the position of the platform and the cable layout: 10 cables with 11 wind turbines each.

Figure C.4 shows the EeFarm model for the initial business case. Depending on the amount of wind power, the remaining transport capacity in sections 1 and 5 is used for trade. To set the amount of traded power in Option A a DC controller is used. Since wind power penetration in DK is much higher than in NL (in West Denmark wind power penetration is 200%, defined as maximum wind power compared to minimum load), it is more likely that DK wind power will flow to NL than vice versa. The direction of the traded power will not have a significant effect on the economic feasibility of the system. The amount of traded power, limited by sections 1 and 5, and the investment costs will have a significant effect. The first two options for the initial business case that will be compared are the system in figure C.1 with an integrated system of two wind farms and a transnational cable (Option A) and the system in figure C.5 with the two wind farms individually connected to shore by an AC cable and a separate DC transnational connection (Option B).

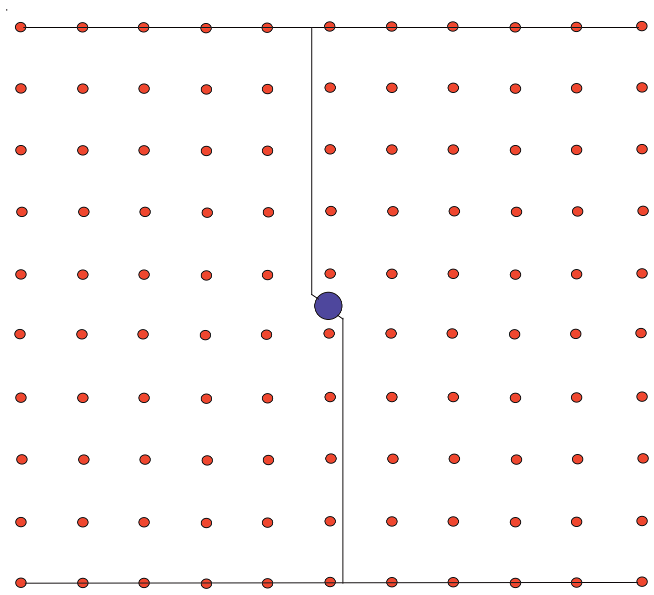

Figure C.3: NSTG wind farm layout

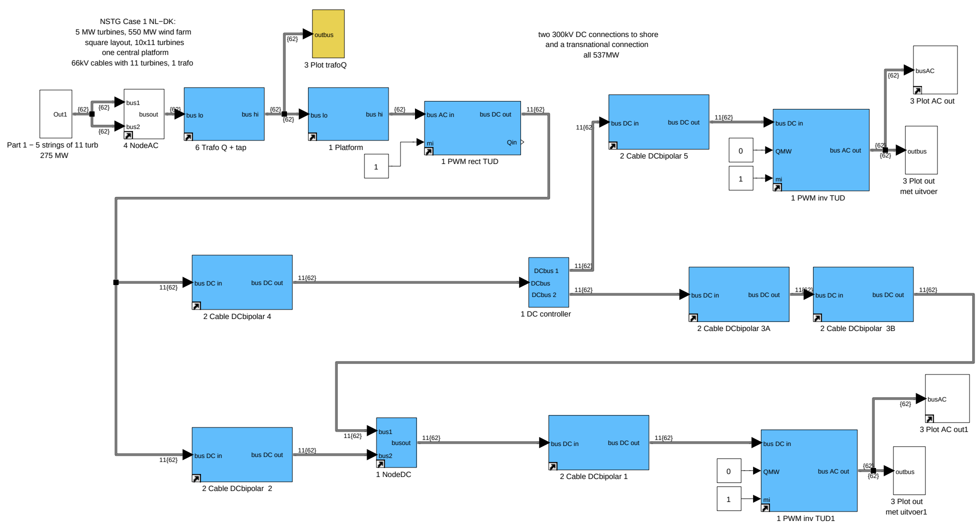

Figure C.4: EeFarm model of the initial business case Denmark - the Netherlands with two wind farms (Option A)

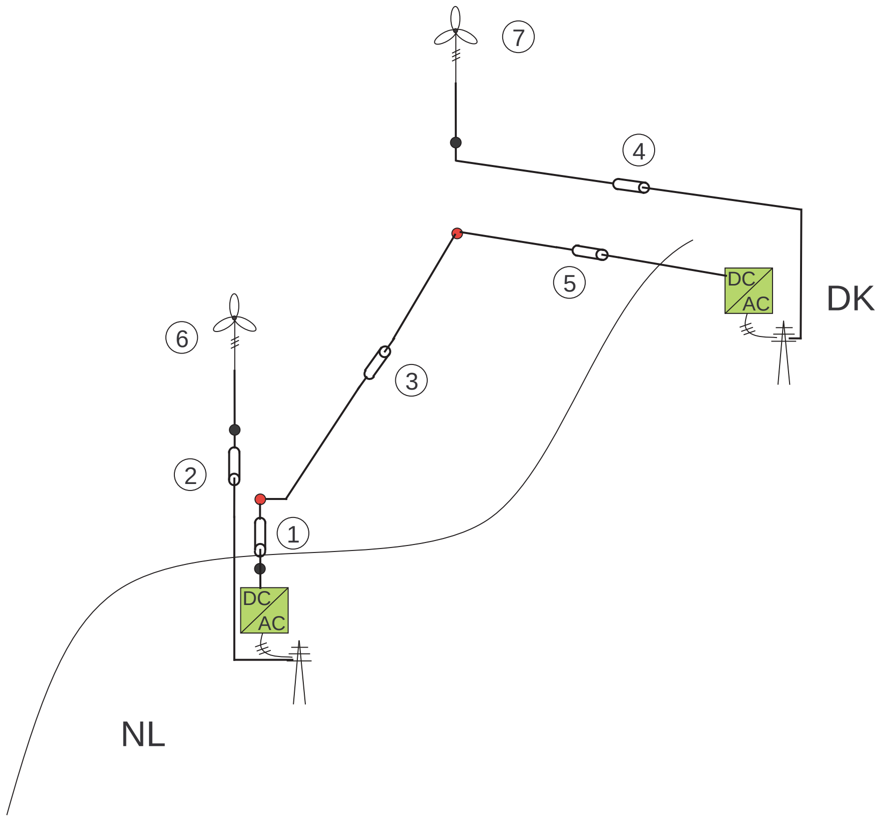

Figure C.5: Option B: two wind farms, individual AC connection

Table C.2: Cases Denmark - Netherlands (two wind farms at 100 km)

Option A: Two wind farms connected to transnational connection

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
totalwind	428.3	1012	86.4	54.6	8.5	5.4	957
trade	154.0	525	23.5	41.4	4.5	7.9	483

Option B: Two wind farms and separate transnational connection

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
totalwind	492.5	1054	45.2	22.4	4.3	2.1	1032
trade	273.0	491	54.6	56.3	11.1	11.5	434

Option A: Two wind farms connected to transnational connection

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
totalwind	4800860	421335	241477	8.8	5.0	551	0.5448	0.0075
trade	1980729	73417	112937	3.7	5.7	227	0.4337	0.0066

Option B: Two wind farms and separate transnational connection

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
totalwind	5150228	233486	85346	4.5	1.7	592	0.5609	0.0077
trade	3780907	475163	490157	12.6	13.0	434	0.8852	0.0066

Table C.2 summarizes the results for Option A and B:

- the investment costs of option B (separate connections) are significantly higher than for option A (integrated connection);
- the traded energy of option B is also significantly higher. This is caused by the limited transport capacity of section 1 in option A (see figure C.1);
- the nett produced wind energy for option A is less than for option B. This is caused by the higher ohmic losses and the higher not produced power due to failure for option A. The converters result in higher losses and the redundancy level of the connection of the wind farm to shore in option B is less than in option A (a single connection versus three parallel connections);
- not produced power due to failure is high in the transnational connection, even with a redundancy level based on monopolar operation. This is caused by the assumed high failure rate of offshore cables (0.011/km failures per km per year). Since the trade connection is 345 km long and the time to repair a cable failure is relatively long (20 days was chosen), this results in a total not availability of 0.00060274 per cable per km and 0.208 in total. If monopolar operation is possible, the effect of this high failure rate is reduced, especially if the connection is not always fully loaded (only option A, option B assumes full load). The failure rate was based on values for land cables in [2].;
- a recent study by GE [11] gives a high voltage offshore cable failure rate of 0.10 failure/yr for a cable of 60 km and 1440 hr repair time. This gives a total not availability of 0.00027397 per cable per km;
- for the given distance of the wind farm to shore (100 km) the wind power LTC of option A (DC connection) is slighly lower than for B (AC connection);
- this advantage for option A is not counteracted by the possibility to trade power through the integrated connection: the LTC values for power trade are equal.

Based on the results for option A and B there seems to be no clear advantage for the integration of offshore wind power and a transnational connection for energy trade. This conclusion is valid however only for the specific case of the Cobra cable with two wind farms. If the system changes significantly, this will change the conclusion, as will be demonstrated by the next options.

In the NSTG the transnational connections will have a significantly lower power rating than the wind farm connections. This will result in a better utilisation of the transnational connections. Table C.3 demonstrates this effect for the Option C with two windfarms of 550 MW connected to the Dutch side of the trade connection and one 550 MW wind farm at the Danish side. The direction of the traded power is still from Denmark to the Netherlands. The increased utilisation of the trade connection reduces the LTC for trade to 0.0052 Euro/kWh. The wind power LTC is unchanged.

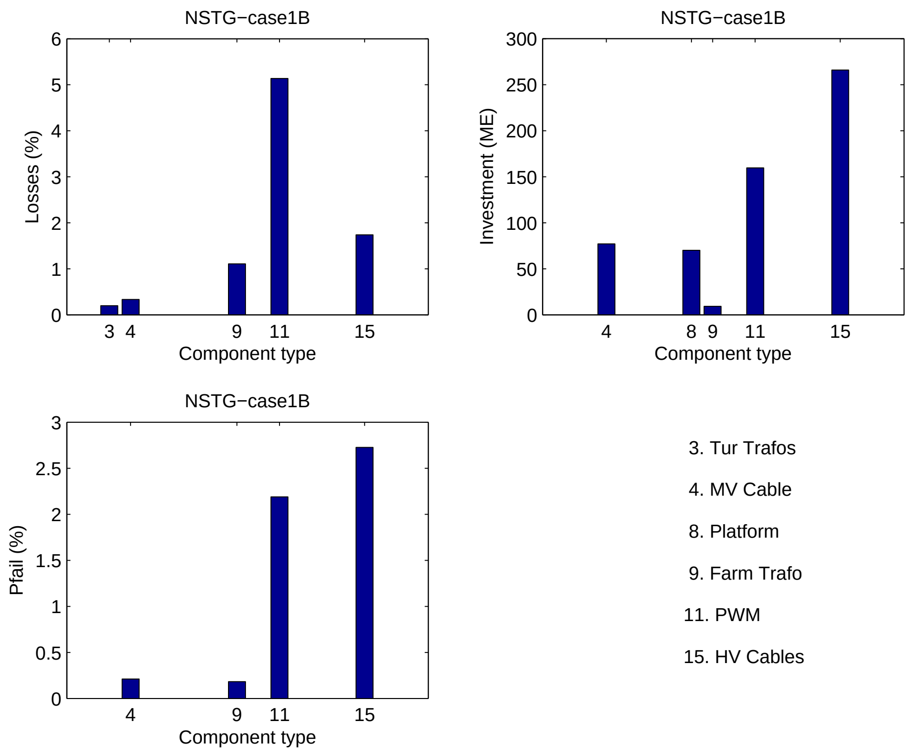

Figure C.6: Option A: two wind farms connected to transnational connection

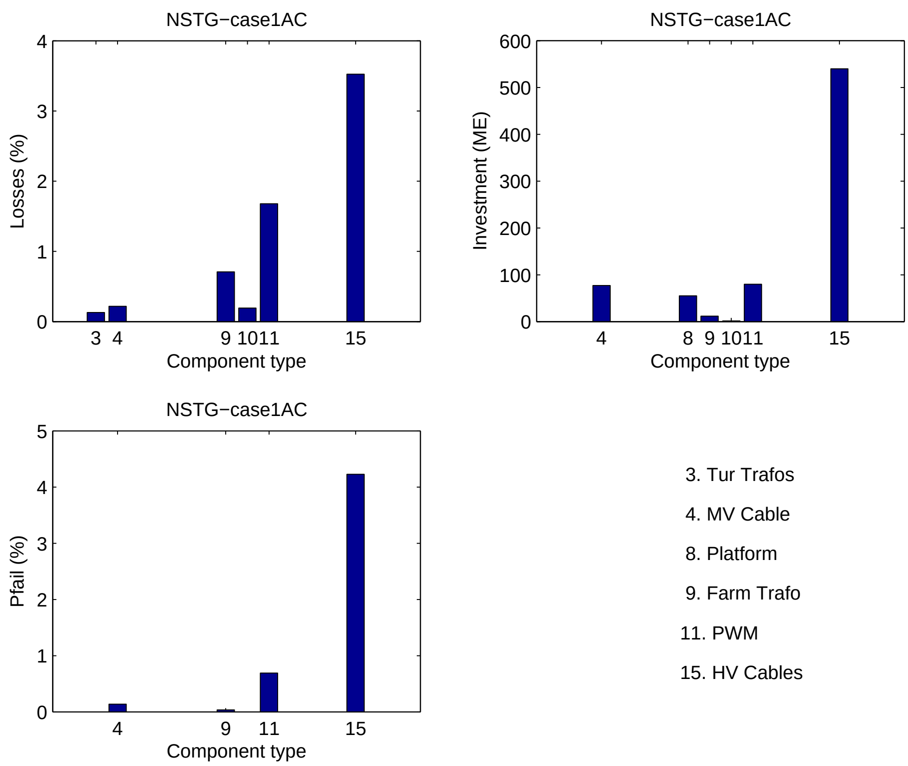

Figure C.7: Option B: two wind farms and separate transnational connection

Table C.3: Cases Denmark - Netherlands (three wind farms at 100 km)

Option C: Three wind farms connected to transnational connection

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
totalwind	642.4	1518	129.6	81.8	8.5	5.4	1436
trade	154.0	522	23.4	41.0	4.5	7.8	481

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
totalwind	7201277	632003	362229	8.8	5.0	827	0.5448	0.0075
trade	2524039	107853	181166	4.3	7.2	290	0.5552	0.0052

Secondly, the distances to shore of some of the wind farms will be more than 100 km, which will reduce the advantage of the AC connection in option B. At 100 km the threefold connection has reached its maximum current of 730 A. If the distance of the wind farm is increased to 150 km, the number of AC connections per wind farm increases to four, while for the DC connection only the length of the cable is increased.

Table C.4: Cases Denmark - Netherlands (two wind farms at 150 km)

Option D: Two wind farms at 150 km connected to transnational connection

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
totalwind	484.3	1003	94.3	67.7	9.4	6.7	935
trade	154.0	525	23.5	41.4	4.5	7.9	483

Option E: Two wind farms at 150 km with separate transnational connection

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
totalwind	843.8	1046	53.3	14.9	5.1	1.4	1031
trade	273.0	491	54.6	56.3	11.1	11.5	434

Option D: Two wind farms at 150 km connected to transnational connection

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
totalwind	4710610	455329	292464	9.7	6.2	541	0.5395	0.0087
trade	2000180	73834	113050	3.7	5.7	230	0.4380	0.0065

Option E: Two wind farms at 150 km with separate transnational connection

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
totalwind	5082268	310208	75882	6.1	1.5	584	0.5579	0.0134
trade	3780907	475163	490157	12.6	13.0	434	0.8852	0.0066

Table C.4 summarizes the results for Options D and E (two wind farms at 150 km):

- compared to the previous options the investment costs to connect the wind farms have increased but for the AC connection (E) much more than for the DC connection (D);

- the wind power LTC increases to 0.0087 Euro/kWh for the integrated connection and to 0.0134 Euro/kWh for the separate connection;
- the LTC of the traded power has not changed by increasing distance of the wind farms to shore.

Suggestions for the step by step development of the NSTG:

- the overall economic feasibility of the NSTG is stimulated by combining transnational connections of moderate size (i.e. 1000 MW) with wind farm connections of larger size (i.e. 2000 MW or more). This is consistent with the NSTG development plan [7];
- a wind farm distance above 100 km favours DC connection of the wind farm, which on its turn enables integration into the DC based NSTG. The inventory of planned North Sea wind farm locations shows that most locations are above the 100 km mark [7]. The Belgian and Danish locations are the exception;
- small wind farms at distances below 100 km profit from AC connections and will probably not benefit from integration into a NSTG. Connection to an existing NSTG may still facilitate this option, due to smaller incremental costs.

D

Adapting EeFarm to the NSTG grid structure

Bidirectional power flow in EeFarm

EeFarm was built with a unidirectional power flow in mind, from the wind farm in the direction of the grid. Based on that assumption, modelling of the connection of an offshore wind farm to the onshore grid is relatively simple and an iterative solution was prevented. For unidirectional power flow, the power in each block is positive, corresponding to a power flow from the signal input side of the block (the wind farm side) to the signal output side of that block (the grid side). In a transnational (country to country) connection, the power flow can be in both directions however. This requires **bidirectional** EeFarm models, at least for the components used in the transnational connections. These are the DC cable, AC-DC converter, DC spitter and DC node, AC transformer, AC cable, AC spitter and AC node. In this section, the EeFarm models are checked for negative power flow and modified if required.

In the AC models the angle between voltage and current (the power angle) determines the direction of the power flow. The AC models operate correctly for a power angle between 0 and 360 degrees, with the modification of the availability calculation (see below). This has been verified by an AC testsystem calculation.

For the DC models two options for power reversal exist: either the voltage (at both ends) or the current changes sign. The DC cable model will operate correctly for a negative power. For the AC-DC block, i.e. the converter model, this is less clear because a previous calculation demonstrated that a large power angle can be a problem for two of the three converter models [10]. The TUDelft and Kazmierkowski models could not handle a small or zero power factor. For the TUDelft model this has been be corrected: the current used to calculate the losses was calculated from the apparent power instead of the active power. Operation at negative power values has now been verified as well. Appendix D shows that the Infineon and TUD rectifier and inverter models and the DC cable model behave correctly (again with the modification of the availability calculation, see below). In the thyristor rectifier and inverter model the current changes direction. In practice, this is only possible if each side of the DC link is equiped with a rectifier and an inverter, gener-

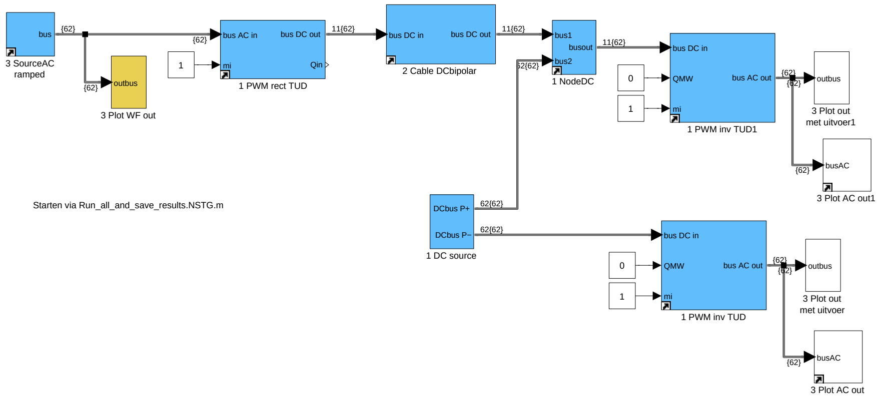

Figure D.1: EeFarm test model for power flow control using the DC source block

ating a four quadrant system. If the current or the voltage changes sign EeFarm calculates losses, availability, power production and costs correctly. In NSTG a two quadrant system will be used from a cost perspective. The Kazmierkowski inverter model does not handle the negative power flow correctly, as could be expected regarding the previously found problem with small power factor, and will not be used. The TUDelft model will be used in the NSTG calculations because the required parameters are available. For the rectfier, the AC values are input and the DC values are calculated (output). For the inverter model it is the other way around. The loss model of the rectifier and the inverter is the same.

Availability and redundancy calculation correction

For a negative power, the availability calculation gave a zero value for the not produced power due to failure. The availabilty calculation is corrected by taking the absolute value of the power before calculating the not produced power due to failure. Proper operation has been verified by an availability test calculation.

Power flow control in EeFarm

A DC source block at the input of the AC-DC converter can be used to control the power in the AC-DC converter and the corresponding country node. This block has two outputs of equal size but opposite sign. To realise a negative power in an inverter, the negative output is connected to the DC side of the inverter and the positive output is connected to the DC cable side connected to the inverter. In a multi-node system, a controllable DC source can be used at each inverter except one. The DC sources in combination with the DC splitters and the power produced by the wind farms determine the power flow in the NSTG grid sections. The AC connections to the land grid will always absorb the power from the wind farms and the DC controllers (sources). Correct operation has been verified in a test system consisting of a wind farm, a controlled DC source and two country nodes, see figure D.1.

A second option to control the flow of DC power is the DC power controller block. This block is inserted between the wind farm and the connections to shore (country 1) and to country 2 (the trade connection). The block controls the power in the connection to country 2, based on a criterion. The input wind power is divided over two output connections, possibly increased by extra power from country 1 to country 2 (making the power to country 1 negative). Two criteria have been implemented:

1. all wind power to country 2 until the trade connection is fully loaded;
2. all wind power plus extra trade power to country 1, until the trade connection is fully loaded. This implies extra power to country 2 at low wind speeds and negative power in the end section to country 1 of the trade connection.

Circular DC grid in EeFarm

Since the proposed NSTG grid contains circular connections, the next hurdle to take is to verify proper operation of a circular DC grid in EeFarm. Especially relevant is to check if the fixed sequence of calculation of the blocks in EeFarm leads to a problem. It was already demonstrated that it does not matter if blocks are evaluated with positive or negative power value. However, the direction of the power flow in a component is determined at the entrance of the component block and thus can only be set at the entrance. The test system in figure D.2, consising of a circular connection at the DC side between 3 AC-DC converters, was used to verify proper operation of a circular DC grid. The system is controlled by two DC source controllers and the third converter absorbs the balance power. The model works correctly.

The next step is to include wind power in the circular DC grid. Figure D.3 show a circular DC grid with four converters, one of which is connected to an AC source representing a wind farm. The model works correctly.

Costs and benefits for the transported wind power and the transported trade between countries]

In the North Sea Transnational Grid two types of components can be found: components which are primarily used to transport wind power and are dimensioned for that purpose and components which are primarily used for trade between countries. A trade component rated power is not influenced by the installed amount of wind power. Therefore it makes sense to discriminate between the costs and benefits of both component types. In this way, two Levelised Production Costs are calculated, one for the wind power and one for the transnational power.

EeFarm has been modified to accomodate this aspect in the calculation. In EeFarm a component.type index vector is used, which ensures the summary of the component losses, not produced power due to component failure and investment cost per component type (index 1-17) and in total (index 18). With the introduction of wind and trade components, this number increases from 18 to 2x18+1=37.

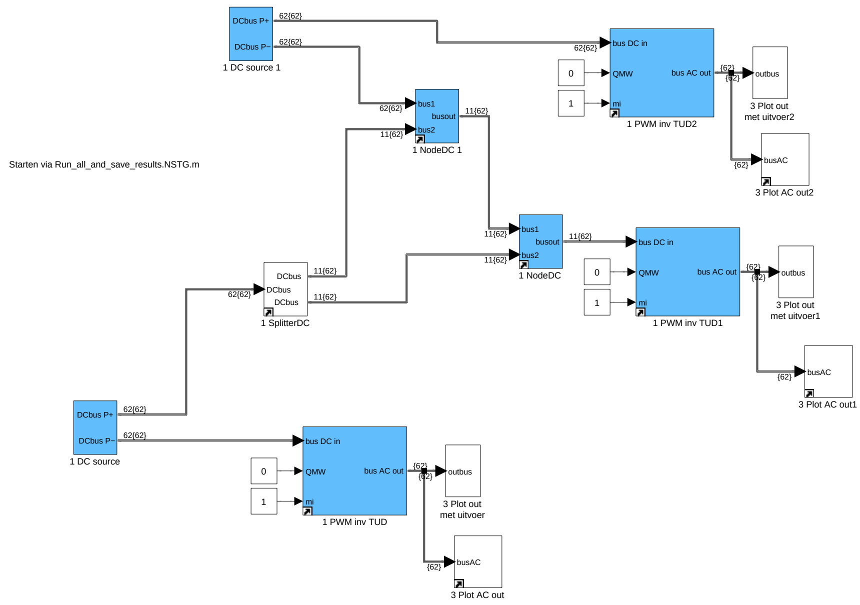

Figure D.2: EeFarm test model of a circular DC grid with three connections

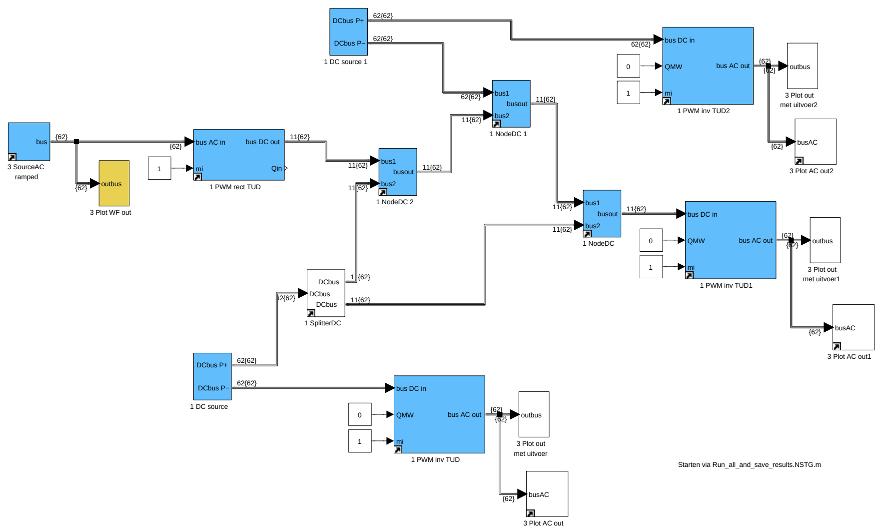

Figure D.3: EeFarm test model of a circular DC grid with wind farm and four connections

AC system test

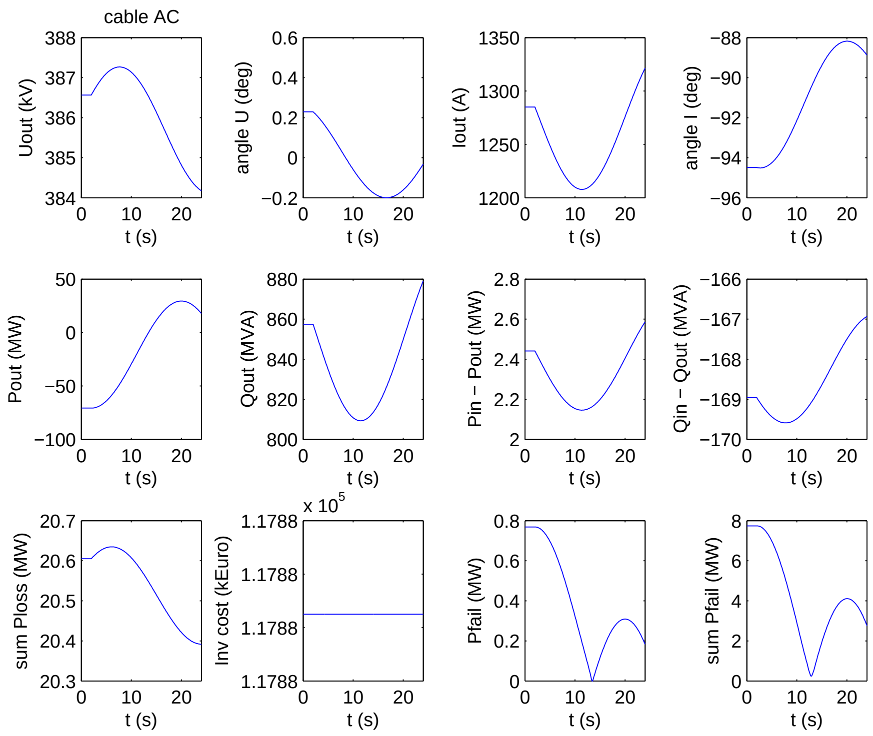

Figure D.4: AC cable model with negative power

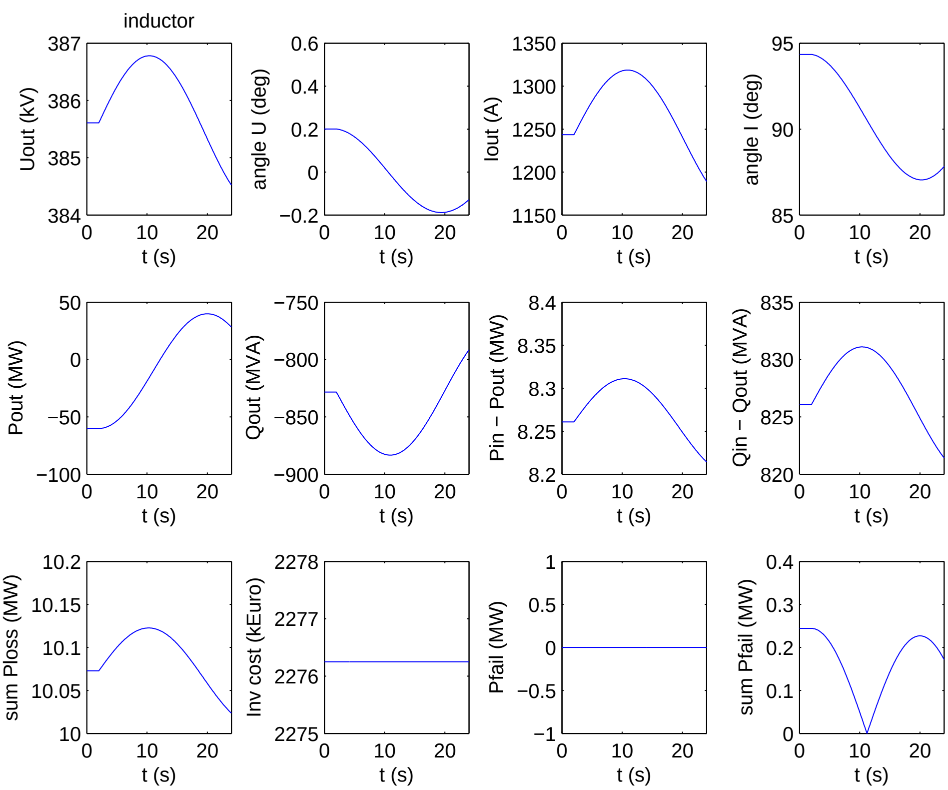

Figure D.5: AC inductor model with negative power

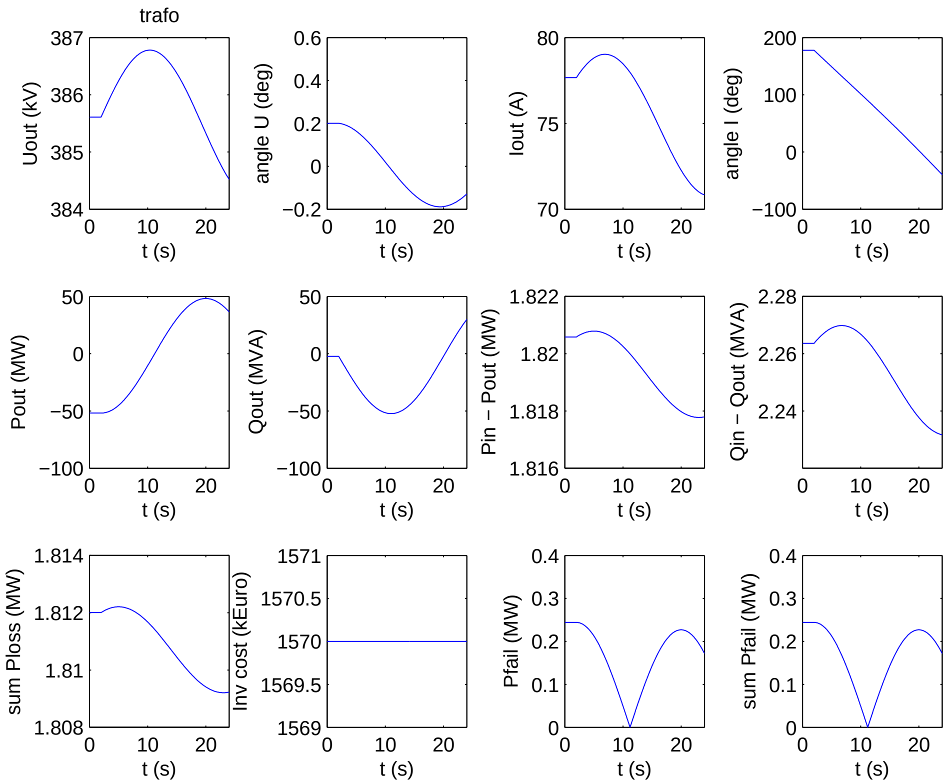

Figure D.6: AC transformer model with negative power

DC system test

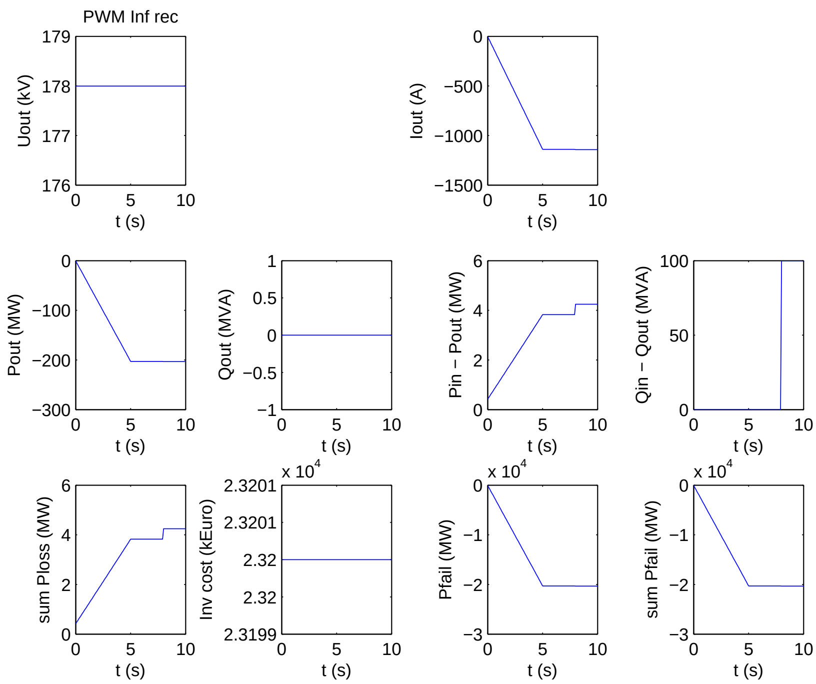

Figure D.7: Rectifier model Infineon

The small step in the losses at t=8s is caused by the increasing retifier current due to reactive power production.

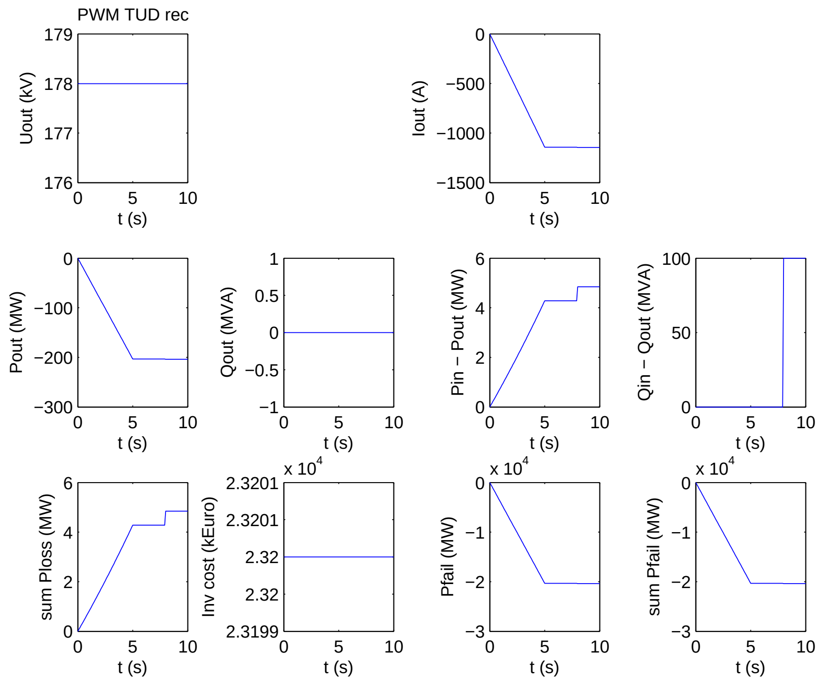

Figure D.8: Rectifier model TUD

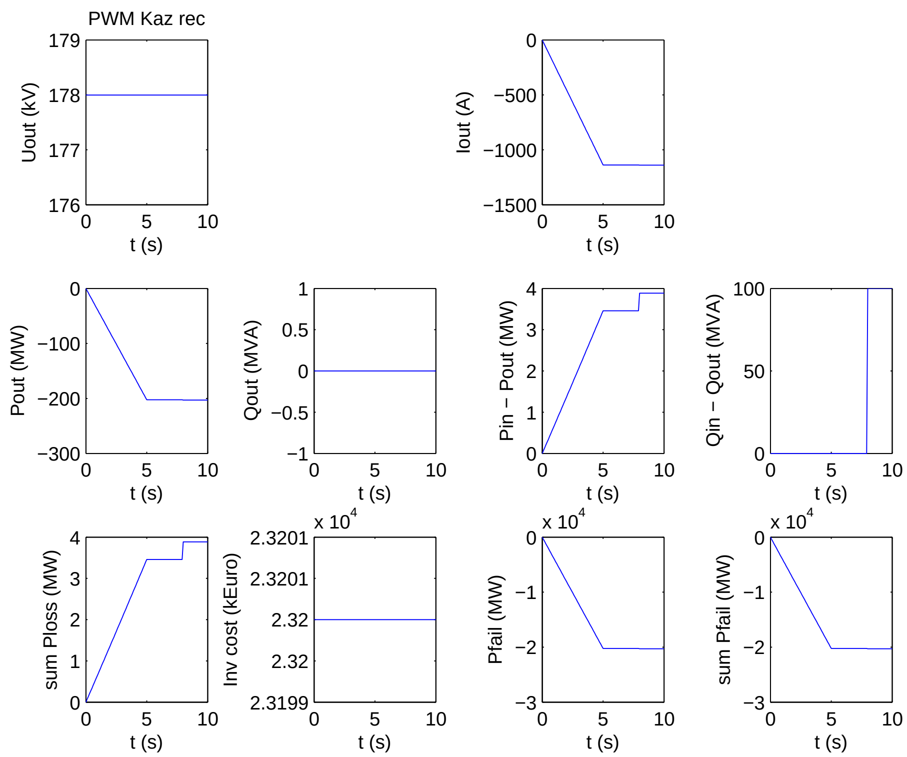

Figure D.9: Rectifier model Kaz

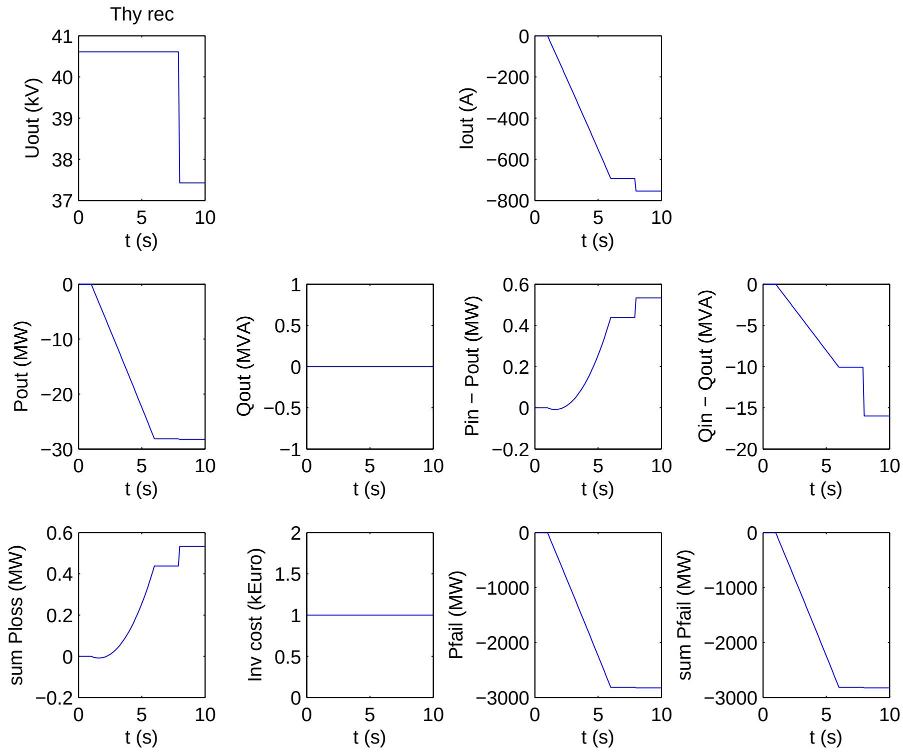

Figure D.10: Rectifier model Thyristor

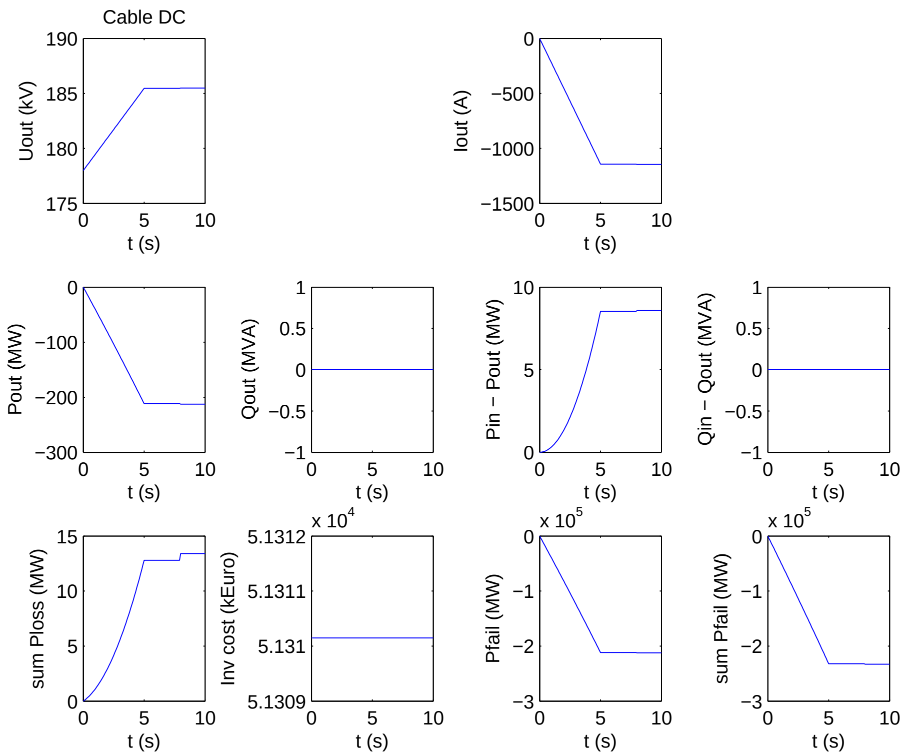

Figure D.11: DC cable model

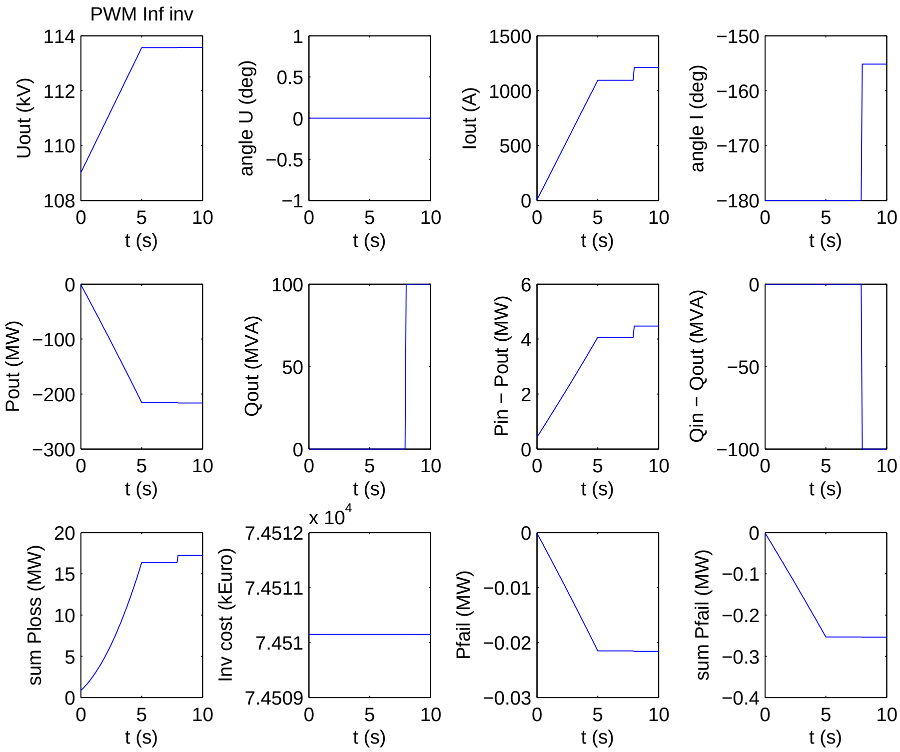

Figure D.12: Inverter model Infineon

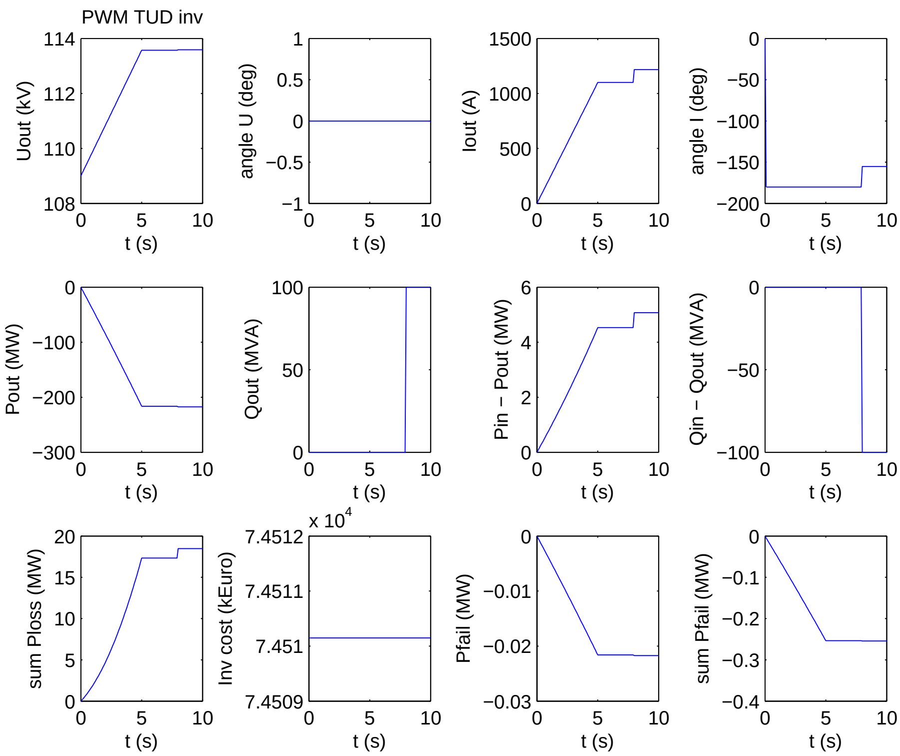

Figure D.13: Inverter model TUD

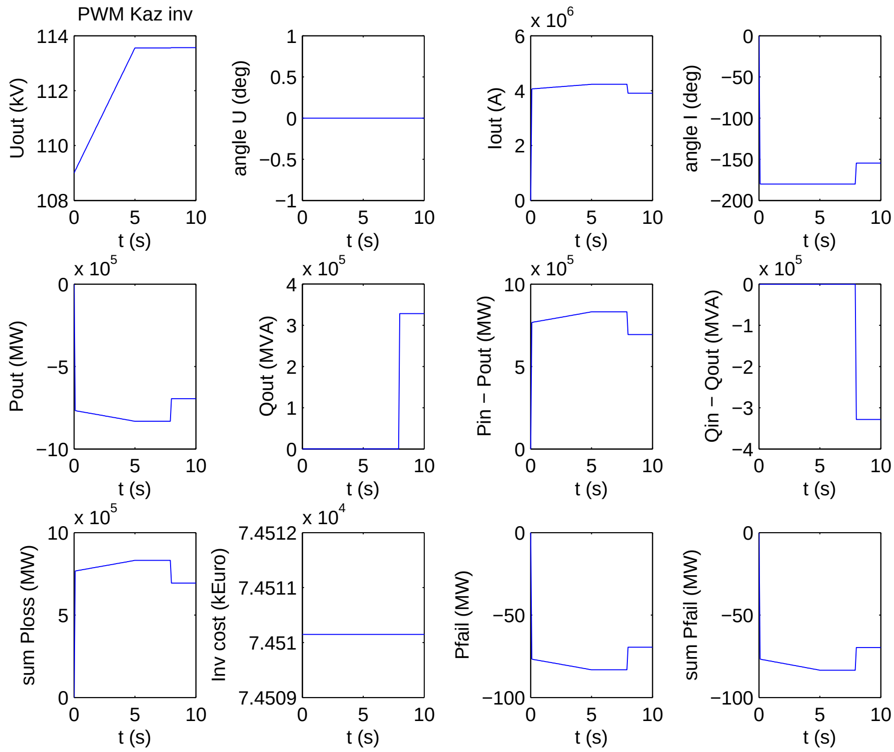

Figure D.14: Inverter model Kaz

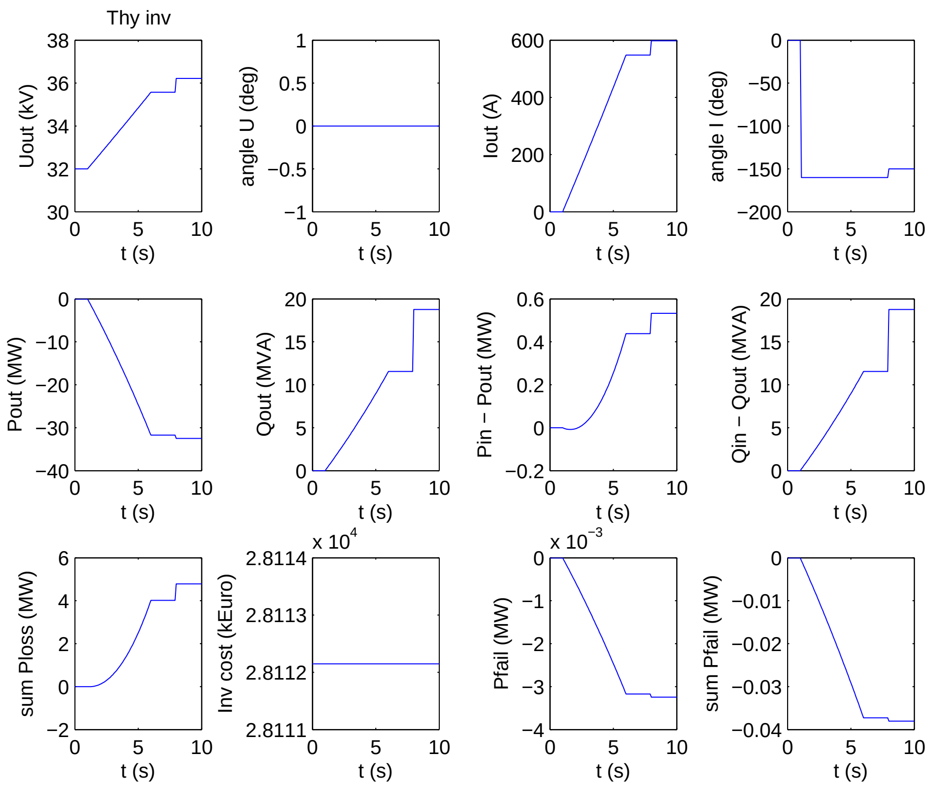

Figure D.15: Inverter model Thyristor

E

VSC converter parameters and budget price

The EeFarm database includes component parameters and budget prices received from manufacturers in 2009 [9]. The maximum size of the VSC converter in the database was 570 MW. The ABB program currently includes a 1216 MW VSC converter [1]. This converter size will probably be the best option for the NSTG since increasing the size most likely reduces the relative investment costs. A larger converter and corresponding cable also reduces the number of components and connections in the NSTG system which will reduce the installation and maintenance costs.

Therefore, the database has been extended with parameters of a 1216 MW VSC converter based on the information in the ABB brochure *It's time to connect* [1] and the feasability study on the Randstad project, performed for ABB by KU Leuven [3]. The feasibility study gives a budget price for a single 1100 MW VSC converter of approximately 50 MEuro. The ABB brochure does not give the parameters required for the TUD converter model in EeFarm. It only gives the full load losses: 3.291% for a set of converters back-to-back connected, so about 1.65% per converter. This value corresponds to the full load losses reported by TenneT for the Cobra cable converter [4]. Figure E.1 compares the losses calculated with the TUD converter model in EeFarm for a 570 MW converter to the losses reported in the Cobra cable feasibility study. Except for a constant offset of 0.2%, the no-load losses, the two curves are practically the same. The no-load losses occur in the interface transformers, filters, phase reactors and auxiliaries and are not included in the TUD converter model in EeFarm. Since the TenneT full load value is near the ABB value, the TUD converter model in EeFarm will be modified by adding a constant additional no-load loss of 0.2% of the rated power. Figure E.2 compares the losses calculated with the TUD converter model for a 1216 MW converter with parameters derived from the 570 MW converter to the losses reported in the Cobra cable feasibility study for the 570 MW converter.

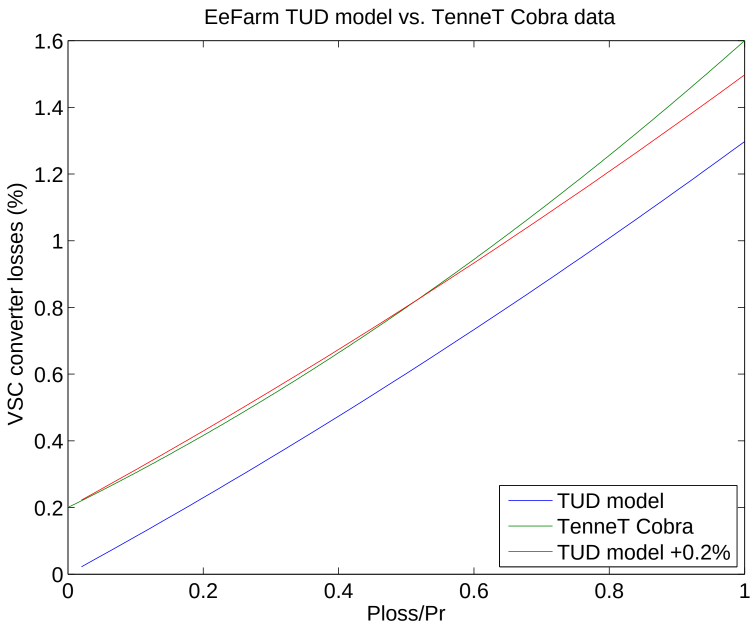

Figure E.1: Losses of a single VSC converter calculated with the EeFarm TUD model compared to the TenneT Cobra Cable feasibility study [4]

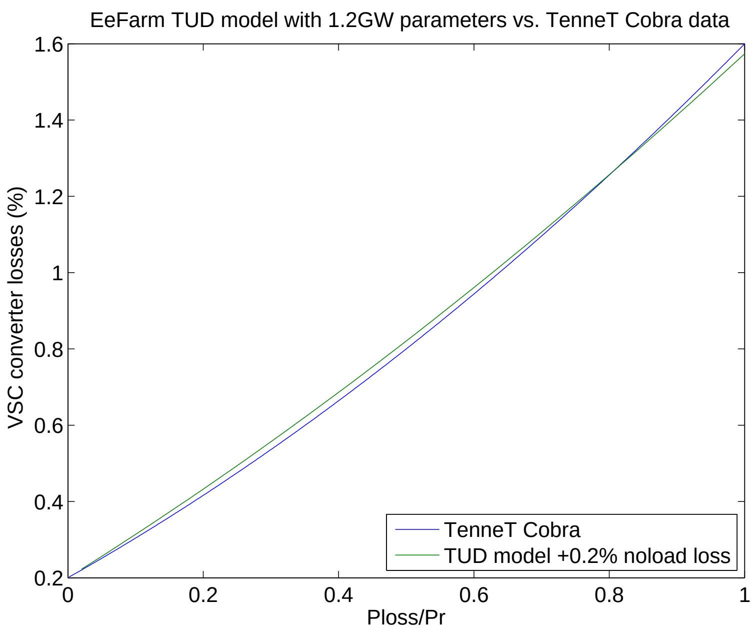

Figure E.2: Losses of a single VSC converter (EeFarm TUD model, 1.2GW parameters) compared to the TenneT Cobra Cable feasibility study [4]

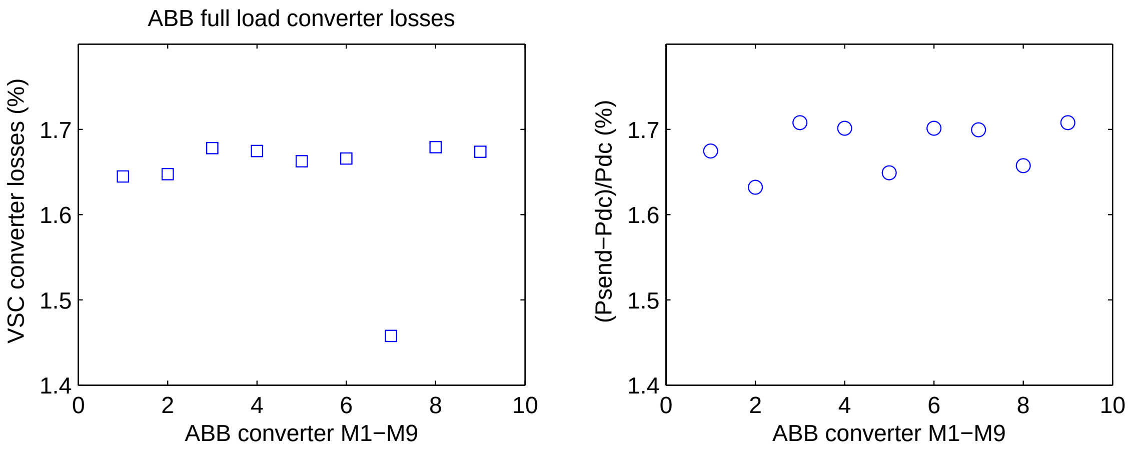

Figure E.3: Losses ABB VSC converter types M1-M9 [1]

F

Changes in the NSTG layout and node names

Well into the project TUD-EPS proposed a number of changes in the layout of the NSTG system, which also influenced the EeFarm model and its results. This section lists these changes to be able to trace them, since the EeFarm model still uses the old nomenclature. Apart from the renaming, the changes are:

- the NSTG connection to Germany (Bremerhaven) was changed to two connections to Diele and Brunsbuttel respectively;
- the distance of eight connections (see table below).

The new names are only used in this report, to make the results compatible with the TUD-EPS results in WP 6.

NSTG node	Description	EPS node	
1	GB offshore N	1	
2	GB offshore S	2	
3	BE offshore	3	
4	NL offshore IJmuiden	4	
4a	NL offshore Eemshaven	5	
5a	DE off Diele	6	original 5 inbetween 5a and 5b
5b	DE off Brunsbuttel	7	
6	DK offshore	8	
7	NO offshore	9	
C	GB N	10	
F	GB S	11	
G	BE	12	
I	NL IJmuiden	13	
J	NL Eemshaven	14	
K	DE Diele	15	
M	DE Brunsbuttel	16	
N	DK	17	
Q	NO	18	

Distance of wind farm connections to NSTG nodes and to the AC grid on shore:

	Distance WF to NSTG node (km) (WF connected to NSTG)	Distance WF to grid on land (km) (WF AC connected to shore)
UK3	100	140
UK4	50	90
UK5	50	75
B1	50	60
NL1	50	60 (H)
NL2	50	60
NL3	50	100
NL4	50	100
G1	50	100
G2	50	100
G3	50	150
G4	50	150
G5	100	180
D1	50	75
D2	100	75 (O)
N1,2,3	50	150

NSTG nodes to shore

Line name	From	To	Original name	Original distance [km]	Final distance [km]
L01	1	10	1-C	40	40
L04	2	11	2-F	25	25
L06	3	12	3-G	80	80
L09	4	13	4-I	60	60
L10	5	14	4a-J	40	40
-	6	15	5-L	110	-
L12	6	15	5a-K	-	125
L14	7	16	5b-M	-	150
L16	8	17	6-N	75	55
L18	9	18	7-Q	120	120

NSTG node to next NSTG node

Line name	From	To	Original name	Original distance [km]	Final distance [km]
L03	1	2	1-2	250	250
L05	2	3	2-3	100	100
L07	3	4	3-4	125	125
L08	4	5	4-4a	0.6*325 =195	260
-	-	-	4a-5	0.4*325 =130	-
-	-	-	5-6	160	-
L11	5	6	4a-5a	-	40
L13	6	7	5a-5b	-	75
L15	7	8	5b-6	-	50
L17	8	9	6-7	200	225
L19	1	8	1-6	500	500
L02	1	9	1-7	600	600

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