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Impact of system power losses on the value of an offshore grid for North Sea offshore wind

Hossein Farahmand†, Daniel Huertas-Hernando*, Leif Warland*, Magnus Korpås* and Harald G. Svendsen*

***Abstract*—Grid connection is a critical factor for the integration of large scale wind power. This factor is even more important in the framework of transnational power exchange which is a way to improve power system operation. In this paper a comparison study has been carried out between two different grid building strategies for offshore wind farms in the North Sea using the 2030 medium wind scenario from the *TradeWind* project [1]. These strategies are i) radial and ii) meshed grid configuration. The paper has considered active power losses for both strategies and capture the effect of losses on different power system aspects, such as the total soci-economic benefit associated with each strategy, offshore wind power utilization, power exchange between the grid points, grid bottlenecks and utilization of HVDC connections. Using a meshed grid compared to radial there will be a total benefit of 2.7 billion Euro over the economic life time of the grid. However this benefit will be increased by 0.3 billion Euro by taking into account the grid losses for both cases. The results shows the benefit of using meshed offshore grid for future European power system with a large penetration of off- and onshore wind power.**

***Index Terms –Offshore wind energy, North Sea super-grid, Grid active power losses, Renewable energy*.**

I. Introduction

OFFSHORE wind farms are gradually being planned and built further from the shore. Grid connection is a critical factor for successful large scale integration of offshore wind power. The increased integration of wind power, both onshore and offshore, and the demand for improved power system operation give rise to a growing need for transnational power exchanges.

The flow-based market model *Power System Simulation Tool* (PSST), developed by SINTEF Energy Research and used in projects such as TradeWind [1] and OffshoreGrid [2], is a tool for studying the effect of large scale penetration of wind power in the European power system, that accounts for wind variations and network bottlenecks on production, demand and prices. PSST is a market model that includes linear DC power flow [3] as constraints to the optimization problem. PSST finds the optimal generation dispatch for each hour of the year, taking into account a detailed grid description. One of the assumptions of a DC power flow is that the resistances in transmission lines are negligible, thus ignoring all active power losses. However, the total power loss in the transmission system can be as much as 4 to 7 % of the total power consumption, and it is therefore important to include it when studying large systems. The inclusion of losses effectively puts a cost on power transmission that changes both the total generation cost and the optimal generation dispatch as compared to the lossless situation. It is the influence on generation dispatch and thereby on the power flow which is the main motivation for including losses in this study. Several approaches for including losses in the PSST model have been implemented and assessed for the study in this paper.

In paper [4] a comparison study between radial and offshore meshed grid was done for the 2030 medium wind scenario of *TradeWind* (302 GW of installed wind in continental Europe [1]). The optimal grid design for each strategy is found by the “Net-Op” grid optimization tool [5]. The offshore grid gave an annual total benefit for the European interconnected power system of 2.6 billion Euro as compared with the radial grid. These results were however obtained neglecting losses in the power system. This paper aims to study how inclusion of power losses affects the results from the previous study [4].

II. Power System Simulation Tool (PSST)

In the European project *TradeWind* [1], a model of the European power system was established and hour–by–hour simulations were run for different scenarios up to year 2030. The main focus of the *TradeWind* project was to investigate how large amounts of wind power may affect the power system operation, and emphasis was put on market design and need for new transmission capacity. For this purpose a flow–based market model, referred to as the PSST, was developed. The PSST tool and how transmission power losses can be included in the marked model, is briefly described in the next two subsections.

A. PSST description

PSST is a simulation tool based on a market model with simplified grid representation, assuming aggregated capacities and marginal costs of each generator type within specified grid zones. PSST assumes a perfect market (nodal pricing) and runs an optimal DC power flow that minimizes the total generation costs in the system for each hour of the year. The optimization takes into account the high voltage (HV) network topology, capacity limitations on generators and interconnectors, wind power variations, hydro power characteristics and fuel price scenarios.

†with Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU), Trondheim NO-7491, Norway
Email: Hossein.Farahmand@elkraft.ntnu.no

*with SINTEF Energy Research, Trondheim NO-7465, Norway
Email: daniel.h.hernando@sintef.no, Leif.Warland@sintef.no, Magnus.Korpas@sintef.no, Harald.Svendsen@sintef.no

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The free (controllable) variables in the optimal power flow problem are the power output of all generators and the flow on HVDC interconnections. The power outputs of the generators depend on the maximum and minimum capacity, marginal cost relative to other generators and limitations of power flow on the physical lines. Aggregated wind farms are modelled as generators with maximum power equal to the available wind power for the specific hour. The marginal cost of wind production is set to zero, so that wind power plants will always produce if not limited by grid constraints. Marginal costs of hydro power are determined by the so-called “water values” [6], deduced from the EMPS model [7], and the current reservoire level for the hour simulated.

The European grid model used in the simulations consists of separate DC power flow data files covering the Continental [8], Nordic, UK and Ireland regions as defined by the European Network of Transmission System Operators for Electricity (ENTSO-E). The entire model consist of 1410 nodes, 2222 branches, 56 HVDC connections, 540 generators and 152 wind farm clusters [1].

In order to study the main power flows in the system, each country has been divided into one or more zones. Due to limited data available, all branches within a country have been modelled with unlimited capacity except the Nordic countries and parts of Germany. Net transfer capacities (NTC) between countries, as given by ENTSO-E, are used as constraints in the power flow optimization.

B. Power losses in DC Power Flow

The PSST marked model uses a DC optimal power flow. One of the assumptions of the DC power flow description [3] is that all active power losses can be ignored. The resulting dispatch of power production given by the optimization will then be significantly less than the actual value, and the problem of transporting power over great distances is not reflected by the model as long as the losses are not included in the optimization.

Active power losses can be included in a DC optimal power flow analysis in several ways. Two different approaches have been considered in this study, where both involve iterations: 1) Simply account for losses, where computed losses $P_{loss} = RI^2$ (constant values) are “injected” on transmission lines before the next iteration; and 2) Include losses in the optimization through a linearization of the quadratic power losses around values computed from the previous iteration $P_{loss} \cong A_0 + B_0 I$. Here A_0 is the "constant" value of the losses at the working point computed in the previous iteration and B_0 is the value of the slope for the first order linear expansion term around this point. Both approaches require an iterative method, where the parameters of the loss description is updated between each LP solution within one optimal power flow.

In the linearization approach, both the constant value A_0 and the slope of the losses B_0 are calculated for each iteration. In principle both values must be updated between each iteration, but keeping the slope B_0 fixed has the distinct advantage of allowing “warm start” of the LP problem (i.e. using the previous solution as a start point for the next iteration) giving a significant improvement in calculation time, especially for cases where the DC optimal power flow has to be solved many times, as is the case in PSST studies that typically run for each hour of a whole year. In this paper the transmission power losses are included in the optimization problem using the method of iteratively upgrading the constant part of the linearization only. HVDC power losses are assumed to be linear with the flow, and are handled by using two state variables for every HVDC connection, one for each direction where both have to be greater than zero. The HVDC active power losses is consider as the constant percent of the exchange power at HVDC cable. Two different cable technologies are considered for HVDC connections, LCC or VSC. LCC HVDC technology is used for point-to-point connection between mainland converter substation (CVST) and offshore wind farm while VSC HVDC technology is mainly used for connecting two offshore wind farms. Table I shows the percentage of losses for different cable technologies [9].

TABLE I
PERCENTAGE OF LOSSES FOR DIFFERENT HVDC CABLE TECHNOLOGIES

HVDC cable Technology	Losses typical system [%]
LCC HVDC	3.5
VSC HVDC	5

III. Offshore grid strategies

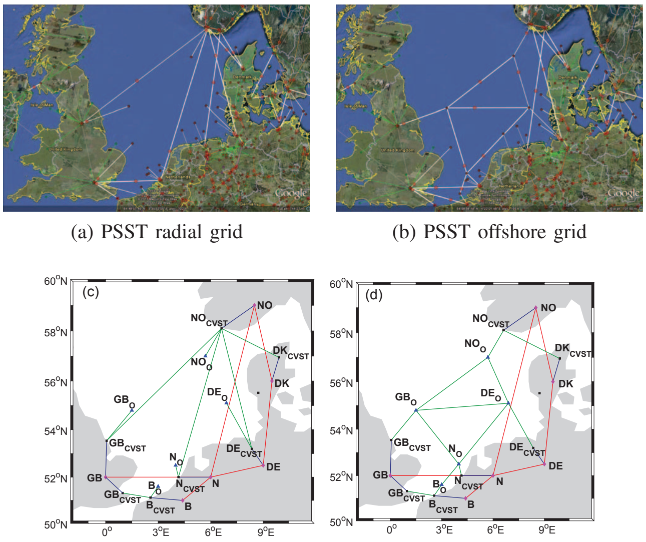
In this paper, the PSST tool is used to investigate two different strategies for the development of the grid connection of offshore wind farms in the North Sea, namely:

- *Radial Grid:* Radial connection between each offshore wind farm and the main grid onshore and point–to–point HVDC connections between countries across the North Sea (see Figure 1a, 1c).
- *Offshore Grid:* A strategy based on the use of offshore nodes to build a meshed HVDC offshore grid (see Figure 1b, 1d).

The scenarios used are the medium wind 2030 from TradeWind [1], except for the load forecast data for which the “Combined high renewables and efficiency” load demand scenario from EWEA [10] has been used instead. The grid design used in PSST for each strategy is shown in Figure 1a, 1b). These offshore grid designs have been determined by the *Net-Op* grid optimization tool [5]. Net-Op is a transmission expansion planning tool for power systems with large shares of renewable energy sources like *e.g.* wind.

Figures 1c, 1d), show the labels used for each country, the offshore wind farm clusters (O) considered in the Net-Op optimization and the corresponding CVST connecting the offshore HVDC cable to the main AC grid. Table II lists all the labels further used in the text.

Several important differences between Net-Op and PSST should be mentioned: i) PSST includes detailed onshore grid topology (see Red lines and nodes in Figures 1a, 1b) whereas in Net-Op, countries are modeled as single nodes (see Figures 1c, 1d). Net-Op only includes net transfer capacity limits



(a) PSST radial grid (b) PSST offshore grid

(c) Net-Op radial grid (d) Net-Op offshore grid

Fig. 1. Grid configurations:Red lines: AC grid; Blue lines (in c and d): Connection between AC node and CVST; White lines (in a, b) and green lines (in c, d): HVDC connections; Google Earth maps in (a,b) under "© 2009 Google, © 2009 Europa Technologies, Image © 2010 GeoContent, © 2009 Tele Atlas"

TABLE II
COUNTRY, LABEL, CONVERTER SUBSTATION (CVST) AND OFFSHORE WIND FARM (O)

Germany	Denmark	Norway	Netherlands	Belgium	UK
DE	DK	NO	NL	BE	GB
DE_{CVST}	DK_{CVST}	NO_{CVST}	NL_{CVST}	BE_{CVST}	GB_{CVST}
DE_O	–	NO_O	NL_O	BE_O	GB_O

between countries but no internal grid constraints for each country; ii) Only the farthest offshore wind farms to shore have been considered in the Net-Op optimization for the radial and offshore grids. Additional wind farms closer to shore have only been considered in PSST as radially connected to land (see Figures 1a, 1b). iii) In PSST the future connects between Norway and Germany (NorGer) as well as second NorNed cable between Norway and the Netherlands have been considered.

In the TradeWind medium wind scenario used [1] there is 302 GW of installed wind power, of which ∼90 GW is offshore wind. These numbers are in agreement with EWEA's [10] targets for the 2030 medium scenario: 300 GW (180 GW onshore and 120 GW offshore). Note that EWEA's offshore wind target of 120 GW is higher than the 90 GW offshore wind used in this study. The case study thus presents a relevant wind scenario study case in line with EU targets, with a more conservative offshore wind installed capacity.

The next section presents results addressing aspects such as the total socio-economic benefit associated with each offshore grid strategy, the export/import power exchanges, offshore wind power generation, grid congestions and utilization of HVDC cable capacity.

TABLE III
OPERATIONAL SAVINGS

Cases	Mill €
Without grid Loss	114.6
With grid Loss	129.0

TABLE IV
INVESTMENT COST [4]

Grid topologies	Mill €
Radial grid	8283.2
Meshed grid	7279.4
Difference	1003.8

TABLE V
TOTAL BENEFITS

Cases	Mill €
Without grid loss	2765.5
With grid losses	2986.8

IV. RESULTS

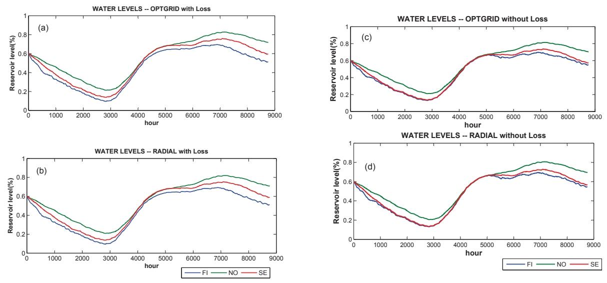
In this paper the impact of losses on the results presented in [4] have been addressed. Losses influence the operating costs and thereby also the difference in costs between radial and meshed offshore grid. Different cases will be present, addressing the impact that power losses have on different power system aspects, e.g. power exchanges between countries, offshore wind power utilization, grid congestions and utilization of HVDC cable capacity.

A. Total benefit

The operational savings calculated using PSST with and without losses are presented in Table III. The operational saving is defined as the annual operation cost difference between radial and meshed offshore grid. For both cases, with and without active transmission power losses, the savings are found to be positive. The largest difference is seen when including active power losses. It is 14.4 €/year greater than the case without losses.

The total benefit is define as in [4]: *Total Benefit= the operational saving* × *Lifetime Factor* + *Investment Cost Difference*. *Difference* is defined as "Radial – Meshed grid". The *Life Time Factor* for a lifetime of 30 years and 5% discount rate is $\sum_{n=1}^{30} 1/\left(1+0.05\right)^n = 15.3725$ and it allows a comparison of the operational savings accumulated throughout the lifetime of grid project.

The results are presented in Tables IV and V, and reflect the fact that the meshed grid configuration provides a flexible infrastructure to exchange potential wind energy across the North Sea area. However grid losses introduce more constraints for energy exchange and is translated into larger benefit associated with the meshed grid compared to the radial grid configuration. More detailed power flow results are presented in the next sections.



(a) PSST with grid losses (b) PSST without grid losses

Fig. 2. Hydro reservoir levels: Blue curve is Finland (Fi), Red curve is Sweden (SE) and Green curve is Norway (NO). All the curve are based on the present of reservoir capacities in each country

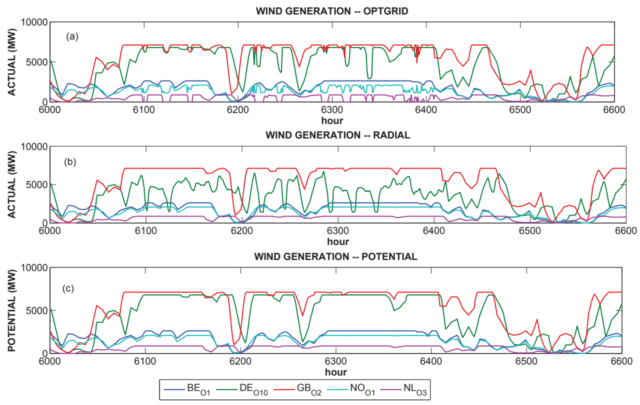


Fig. 3. Offshore wind production wit grid losses a) Wind production for the offshore grid case b) Wind production for the Redial grid c) Potential wind production based on installed capacity scenarios

B. Nordic hydro production, offshore wind production and energy exchange

Figure 2 shows the simulated hydro reservoire filling levels throughout the year for the Nordic area. Figures 2a and 2b show that more hydro power has been used in Norway and Sweden in order to compensate for the transmission losses. However, in general Norwegian hydro level has been slightly increased at the end of the year around hour 6000 which is due to the fact that high wind generation continued in the surrounding countries and the grid congestion in the central Europe, resulting in export of surplus wind power from the North Sea further north.

Comparing Figure 3a, 3b and 3c, shows that the actual wind production is constrained. This is reflected by the dips in the wind generation shown in Figure 3a and 3b. Grid bottlenecks in the European continent prevents potential wind power to be utilized in certain periods. This is especially clear in the radial case where there is curtailment of wind production from the German wind farm clusters (Green line in Figure 3a and 3b). Comparing wind simulations ignoring losses (Figure 4) it is clear that transmission losses increase the level of wind power curtailment. This effect is quite pronounced in the German wind farm cluster $\mathrm{DE}_{\mathrm{O}10}$ between hours 6200-6400.

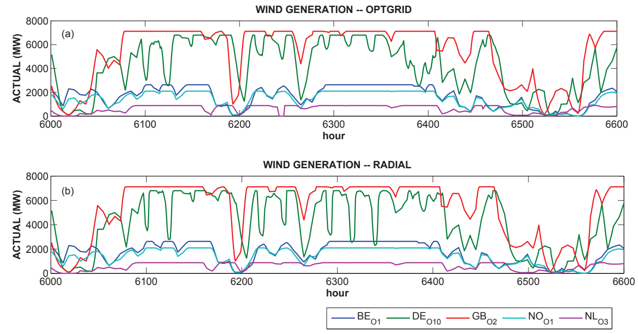


Fig. 4. Offshore wind production without grid losses a) Wind production for the offshore grid case b) Wind production for the Redial grid

Figure 5 illustrates the correlation between the hydro production in Norway (NO) and the total offshore wind production from the North Sea during hours 550-850. In general, Figure 5a shows that the Norwegian hydro power follows the wind power fluctuations and ensure the balance between production and consumption. For instance in situation with low wind production around hours 550 and 660 the hydro production in Norway follows the Norwegian load profile closely and take over the security of supply. However the surplus production during theses hours can be exported to Continental Europe through HVDC links. In the next period (hours 700-850), with high wind penetration from the North Sea the hydro production is substantially below the Norwegian demand. Figure 5b presents similar behaviour for the meshed offshore grid with and without grid losses while the hydro production for the case with grid losses is slightly higher than the case without grid losses. The additional power is used for compensating of grid losses.

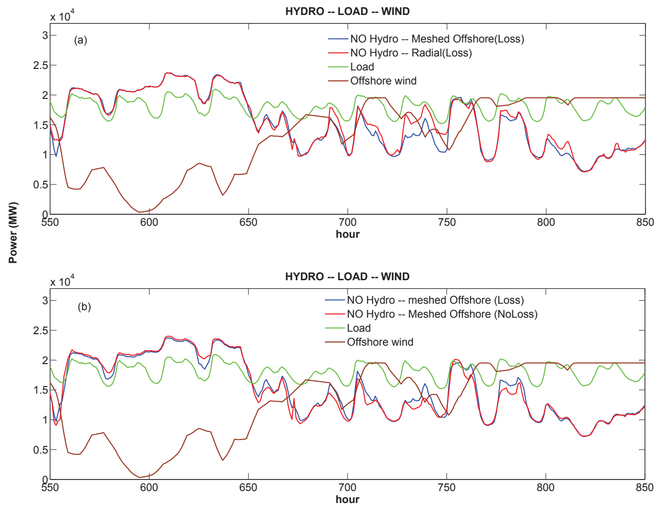


Fig. 5. Norwegian Hydro and load *vs* the North Sea offshore wind production

Figure 6 illustrates the flow dynamics for the meshed offshore grid connection between the countries across the North Sea. The flow has more or less the same behaviour as discussed in [4] where for the connections : $\mathrm{DE_O} - \mathrm{NL_O}$

(Figure 6a), $\mathrm{GB_O - NL_O}$ (Figure 6e), $\mathrm{NO_O - DE_O}$ (Figure 6c) and $\mathrm{NO_O - GB_O}$ (Figure 6g) the large offshore wind production is re-directed towards the Netherlands and Norway. While in the radial offshore grid as it is shown in Figure 3b this amount of power has been reduced due to internal German system congestion and insufficient exchange capacity between Germany and Norway. The exchanged energy through $\mathrm{GB_O - DE_O}$ (Figure 6b) between Germany and UK, the two largest offshore wind farm production during this period, has reduced significantly and in most of the time there is not exchange between these countries showing that the injected power has been absorbed by internal grid losses in these countries. When losses are included, Figure 6d shows that there only a small difference in the usage of the $\mathrm{DE_O - DE_{CVST}}$ connection between the radial and meshed grid structure. This is a significant difference from the similar result without losses (Figure 5 in [4]), which showed markedly more constraints in the German power system for the radial case. On the other hand, the Dutch wind farm connector to the land ($\mathrm{NL_O - NL_{CVST}}$ (Figure 6h)) has the same as shown in [4] showing a redistribution of the wind power injection into the mainland grid in order to cover load and grid losses. The $\mathrm{NL_O - BE_O}$ connection has also the same behaviour as in [4] showing wind penetration "shifts" more towards Belgium in the meshed offshore grid case (see Figure 6f).

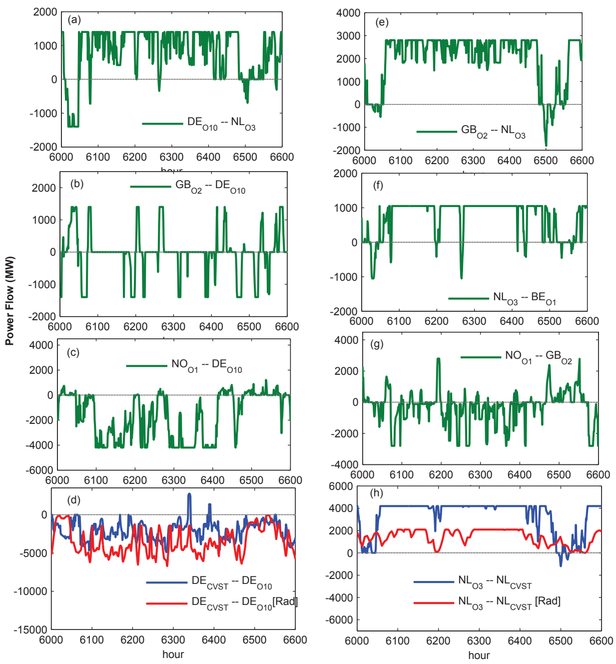


Fig. 6. Example of flow results at the most exploited corridors, Green line represents the case taking into account the active power losses and the Red line without losses: For each connection A-B, positive values mean flow from A to B: A $\rightarrow$ B and negative values mean flow from B to A: A $\leftarrow$ B

As it has been mentioned in sections IV-A and IV-B the effects of grid bottlenecks is more pronounced in the case with power losses than without losses. This paper investigate the flow between the most utilized offshore grid HVDC links

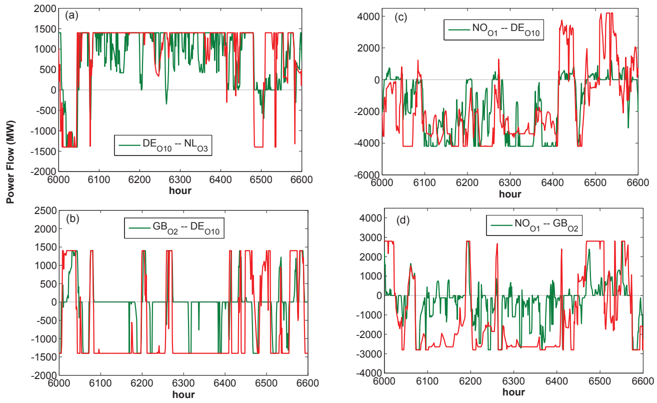


Fig. 7. Example of flow results at the most exploited corridors, Green line represents the case taking into account the active power losses and the Red line without losses: For each connection A-B, positive values mean flow from A to B: A $\rightarrow$ B and negative values mean flow from B to A: A $\leftarrow$ B

in the meshed grid configuration and the results are shown in Figure 7. As the figure shows the exchange capacity between Germany and the Netherlands, Great Britain as well as Norway has significantly decreased showing that this amount of power is used to cover internal grid active power losses within German grid. Therefore introducing losses has highly affected the penetration of wind in countries across the North Sea.

C. Energy exchange duration

Duration curves for annual exchange of energy through the meshed offshore HVDC links are shown in Figure 8. Generally HVDC usage has been reduced in the case with active power losses meaning that all countries could use the available wind power to cover inter area losses.

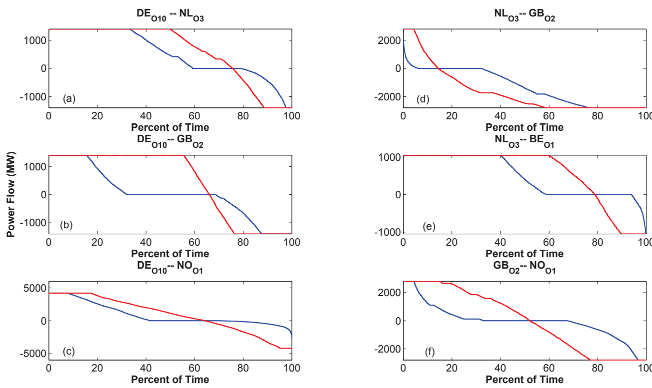


Fig. 8. Utilization of the meshed offshore HVDC connections: The offshore grid with- (blue curves) and without transmission active power losses (red curves)

In the case of radial offshore grid, the point-to-point connection between CVSTs in different countries are represented in Figure 9. As it is shown in this figure the exchange energy has been reduced taking into account the grid losses except the connection between Norway and Germany $\mathrm{NO_{CVST} - DE_{CVST}}$ (Figure 9). The exchanged power from Norway has been increased in order to cover the grid losses in

Germany. The internal grid congestion in Germany adds the this energy re-dispatch towards Norway.

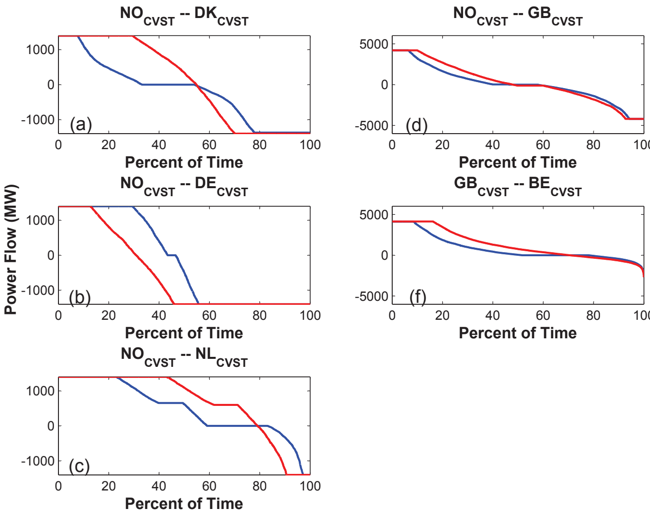


Fig. 9. Utilization of the radial offshore HVDC connections: The offshore grid with- (blue curves) and without transmission active power losses (red curves)

The annual power exchange between different European countries for both meshed and radial offshore grid strategies is shown in Figure 10. Due to highly changed flow pattern in the countries surrounding the North Sea all the exchange power to/from neighbouring countries has been substantially altered. This effect also influences exchange between countries further south. The most affected countries are Germany and Norway and the main corridors are NL-DE, FR-DE, No-DE, SE-NO and IT-FR.

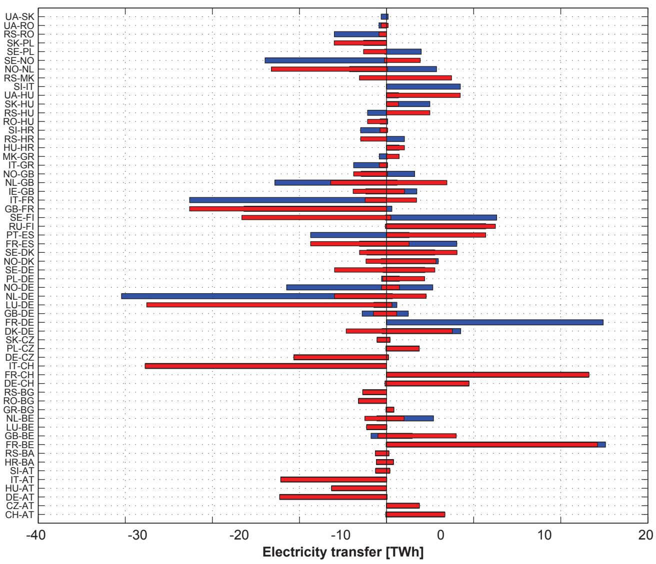


Fig. 10. Annual exchange flow between the countries taking into account the transmission losses: Red bars - Radial grid case; Blue bars - Meshed offshore grid case

There is higher benefit associated with the meshed offshore grid as shown in Table V. This is due to a better and more flexible utilization of exchange infrastructures. Therefore more power can be injected into mainland power grid and this is clearly observed in Figure 10 by generally larger bar for meshed offshore power grid. This effect is more significant here, taking into account power losses than observed in [4].

V. Conclusions

A comparison between two different offshore grid expansion strategies in the North Sea has been studied. In the absence of the active power losses the total benefit of meshed offshore grid with respect to the radial grid is estimated to be 2.7 Billion Euro. This shows the effectiveness of meshed grid to relieve the expected grid bottlenecks due to high penetration of wind power from the North Sea. Taking into account the losses makes the power flow more constrained and meshed grid strategies play an even more important role to relieve grid bottlenecks. This is reflected in the total benefit results which is then increased to 3 Billion Euro. Future work will include reserve procurement in each control area across the North Sea and identifying needs for onshore grid reinforcement in order to improved distribution of onshore and offshore wind.

VI. Acknowledgements

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BIOGRAPHIES

Hossein Farahmand was born in Iran, on September 16, 1979. He received both B.Sc. and M.Sc. in electrical engineering in 2002 and 2005 respectively. Currently he is pursuing the Ph.D. degree in the area of balance management in multinational power markets at Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Daniel Huertas-Hernando was born in Spain, on May 6, 1975. He received M.Sc. and Ph.D. in Theoretical Solid State Physics in 1998 and 2002 respectively. Currently he is Research Scientist at SINTEF Energy Research. Research activities focus on modeling of grid connection of large scale offshore wind power, wind forecast uncertainty and balancing of intermittent renewable generation.

Leif Warland received his siv.ing (graduate degree in electrical engingeering) and dr.ing (Doctorate in electrical engingeering) from Norwegian University of Science and Technology (NTNU), Trondheim, Norway in 1997 and 2002 respectively. He is currently working at SINTEF Energy Research in Trondheim.

Magnus Korpås received his siv.ing (graduate degree in electrical engingeering) and dr.ing (Doctorate in electrical engingeering) from Norwegian University of Science and Technology (NTNU), Trondheim, Norway in 1997 and 2002 respectively. He is currently working at SINTEF Energy Research in Trondheim.

Harald Svendsen was born in Norway in 1975. He received his cand.scient. from the University of Oslo in 1999, and his PhD from Durham University in 2004, both in the field of theoretical physics. His work experience includes two years at the Max Planck Institute for Gravitational Physics in Germany and two years at Senergy Econnect, a renewable energy consultancy and product development company in the UK, before joining SINTEF Energy Research in 2009.