Optimal design of subsea grid for offshore wind farms and transnational power exchange

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Abstract:

Large-scale development of offshore wind power is needed to fulfil Europe’s future electricity needs and for reducing emissions from the electricity sector. Grid connection is a critical factor that should be regarded in accordance with the need for increased transnational power exchange to avoid sub-optimal offshore grid developments. This paper presents a methodology for identifying an optimum offshore grid structure, taking into account wind variations, price variations, power demand at oil rigs, and possible connection points to the onshore power system. The applicability of the method is demonstrated by a case study of offshore wind power development in Norway.

1 Introduction

Large-scale development of offshore wind power is needed to fulfil Europe’s electricity needs of the future and to reduce the environmental impact of electricity generation. Offshore wind farms are now gradually being planned and built farther from the shore, making the grid connection a more critical factor than earlier. At the same time, the increased integration of wind power, also onshore, and the demand for improved power system operation give rise to a growing need for transnational power exchange. These challenges should be approached in an integrated manner, and concepts for linking offshore wind farms and subsea interconnectors have been proposed in several studies and projects [1] - [5].

This paper presents an innovative methodology for identifying an optimum sub-sea grid topology for connecting offshore wind farms and transnational exchange of power. It explicitly considers the benefit of transmission capacity between differently priced areas and the value of connecting offshore wind power to the grid versus the investment cost of power cables. The methodology assumes that the locations and installed capacities of the wind farms are known, and finds a solution for the least-cost offshore grid structure and cable dimensioning, taking into account wind power variations, power demand at oil and gas rigs, and possible connection points to the onshore power system.

A case study has been carried out for the grid connection of 3 off-shore wind farms outside of the Norwegian coastline. It was found that transmission capacity should be built to form an extensive offshore grid which optimizes the utilization of wind power and at the same time facilitates trade between the power markets in Norway and Germany.

It is concluded that integrated planning of offshore wind farms and transnational power exchange is required to avoid sub-optimal offshore grid developments, resulting in e.g. radial wind farm connections side by side to a HVDC cable exclusively used for spot market trade. The methodology presented in this paper facilitates such an integrated approach, and is highly relevant for identifying cost-efficient solutions for connecting offshore wind farms to a common subsea transmission grid, enabling optimal market integration of offshore wind and improved power system operation.

This study has been carried out as part of a Norwegian R&D project “Deep sea offshore wind turbine technology", coordinated by SINTEF Energy Research and funded by the Research Council of Norway and industrial partners [6].

2 Problem description

For a small near shore wind farm, the obvious way to connect it to the power grid on shore is a radial connection with a submarine cable. As off-shore wind power plants grow in size and number, and are located farther from the shore it becomes natural to consider grid connection of wind power in relation to other plans for submarine power cables. Examples of other plans for submarine power cables can be interconnection between countries or power from shore to oil and gas rigs.

We will take the viewpoint of a hypothetical transmission system operator (TSO) charged with coordinating and building an off shore power grid with the objective of maximizing social economic benefit. Given are a number of planned off-shore wind power clusters (or other marine power), possible land connection points, and off-shore oil and gas rigs or other off-shore power consumption to be supplied with shore power. The TSO then has to connect these loads and generators in such a way as to minimize the total cost of building the needed marine cables and supplying the load while observing all physical constraints. This quickly becomes a difficult problem as the number of considered wind farms, land connection points, and off-shore oil rigs grow. For short, any location where a cable can be connected is called a node *n*. The number of possible cables to build is then:

$$\frac{n^2 - n}{2}$$

If the decision is only which cables to build, the possible number of configurations of cables is:

$$2^{\frac{n^2 - n}{2}}$$

Even for a small system, the number of configurations is so large that an evaluation of all possible configurations is impossible, as illustrated in Figure 1. In addition, the capacity of each cable has to be decided. However it is possible to solve the problem of the TSO with a quadratic programming (QP) routine by applying three restrictions:

1. Costs of cables/transmission lines and equipment must be expressed linearly (or quadratic) in terms of power rating with zero intercept
2. Physical constraints representing the power flow must be linearized
3. Marginal generation costs must be linear or constant

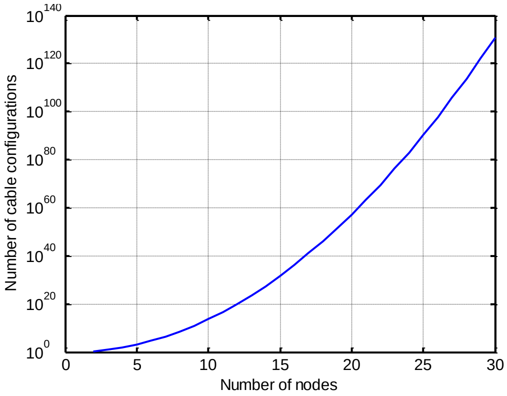

Figure 1: Possible configurations of cables as a function of the number of nodes

The problem described in this paper is a transmission expansion planning problem, Computer programs for the optimal design of networks in transmission expansion planning has been developed for many years [7]. Reference [8] gives a broad overview of optimization methods for solving of the general transmission expansion problem. The methodology in this paper is aimed specifically on grid expansion for offshore wind farms, particularly taking into account wind power variations in the optimization procedure.

The following outlines a QP optimization routine for dimensioning and structure of a subsea grid.

2.1 Description of algorithm

We are given a number of planned off-shore wind power clusters, their location and power rating. Also known are a number of off-shore and on-shore loads and other generators and their respective demand and supply schedules in terms of a linear price –

power relationship. Each cable has a power rating that defines how much power it can safely conduct, these power ratings are the unknowns that we want to determine. The cost of a cable is a function of its length and power rating. Since the location of each node is fixed, the cost of each cable can be expressed as a function of its power rating only; for our purpose the function must be a linear or quadratic relationship.

Generators are defined by their maximal generation capacity and their marginal cost which must be constant or a linear function of the power output. A single generator with a constant marginal cost can also be interpreted as the power price for the area in which the generator resides. **Example**: To model a node as having a constant price of 40 EUR/MWh and the ability to supply or use 2400 MW we create a fictitious generator at the node in question with a generation capacity of 4800 MW and marginal cost of 40 EUR/MWh. Additionally a 2400 MW load is created at the same bus.

Wind generators in particular are assumed to have a constant marginal cost of 0 and their generation capacity is determined by the wind speed at their location. The routine optimizes the power rating of the cables and the power produced by the generators. Since the marginal cost of wind power is 0 it will always generate according to the maximum available capacity as long as it has sufficient transmission capacity.

Furthermore, we assume that demand is completely inelastic; i.e. all load must be served at whatever the price. This assumption is not necessary, but reduces the number of unknowns and is often very close to the real situation.

The objective function we want to minimize can now be expressed as the sum of generation costs and cable costs. However, since the cable cost is a (one shot) capital expenditure at year 0 and the generation cost is calculated on an hourly basis and applies through the whole lifetime of the grid they cannot be compared directly. This is solved by assuming a discount rate and lifetime of the equipment and calculating the present value of the generation costs.

Having established the objective function and the decision variables, the constraints must be specified. We have used a model for the power flow that loosely represents a network of controllable HVDC links. It can be thought of as a transport model where power is “moved” through the grid wherever there is free capacity. This simplification allows us to use the following description for the power flow:

- Generation within limits [0, max]
- Flow on a cable no larger than the power rating of the cable in MW [-rating,+rating]
- Sum of generation and imports must equal sum of load and exports at each node

This approximation loosely represents a network of controllable HVDC links and is also descriptive for a radial AC grid. If the grid is built as a normal meshed AC grid, an optimal DC power flow would be a better approximation of the power flow equations. See [9] and [10] and for an overview of HVDC technologies.

To take into account the stochastic nature of wind power generation and power prices, the optimization is conducted with regard to several discrete cases that represent various wind conditions and prices levels. The resulting cost of each case is weighted with the probability that the case will occur. To create the discrete cases, wind power and power prices/generator costs are sampled from time series of hourly data. The objective function of the optimization algorithm can now be defined as:

$$F(X,L)=\sum_{m}\sum_{g}\left(X_{m,g}*P_{m,g}\right)*f*w_{m}+\sum_{i}L_{i}*C_{i}$$

$$f=\frac{1}{r}\left(1-\frac{1}{(1+r)^{T}}\right)*8760$$

Where X is generation in MW, P is the power price in EUR/MWh, w are the case weights that sum to one, L is the capacity of a cable in MW, C_i is the investment cost in EUR per MW of cable i, r is the discount rate, and T is the lifetime. Indices g, m, and i represent the generators, the discrete cases for wind and prices, and the transmission lines respectively. *X* and *L* are the decision variables that must be determined to minimize *F(X,L)*, i.e. the present value of the total cost of the system.

Ideally, the number of discrete cases should encompass the entire dataset to capture the full variability of prices and wind power production. However, this is not feasible for large datasets; instead we draw *M* cases randomly and optimize with regard to these as if they represented the whole range of wind power fluctuations and price variations. Each case is assigned equal probability such that all the case weights $w_m = 1/M$.

The methodology is implemented in Matlab using the CLP solver from the COIN library [12].

3 North Sea example

A small example with three wind farms is studied in the following chapter. Six areas around the North Sea are part of the model. There are 3 land connection points for the subsea grid: Bergen and Stavanger in Norway and Wilhelmshafen in Germany. Two wind farms located close to the oil fields “Ekofisk“ and “Troll” and one wind farm further north are the possible sea connection points. A summary of the nodes is given in Table 1, and a map of the area is shown in Figure 2.

Node	**Comment**
Møre	Wind farm 1000MW
Troll	Wind farm 1000MW and load 200MW
Ekofisk	Wind farm 1000MW and load 200MW
Bergen	Generation capacity 3000MW and load 2000MW
Stavanger	Generation capacity 3000MW and load 2000MW
Wilhelmshafen	Generation capacity 4800MW and load 2400MW

Table 1: Nodes in the model

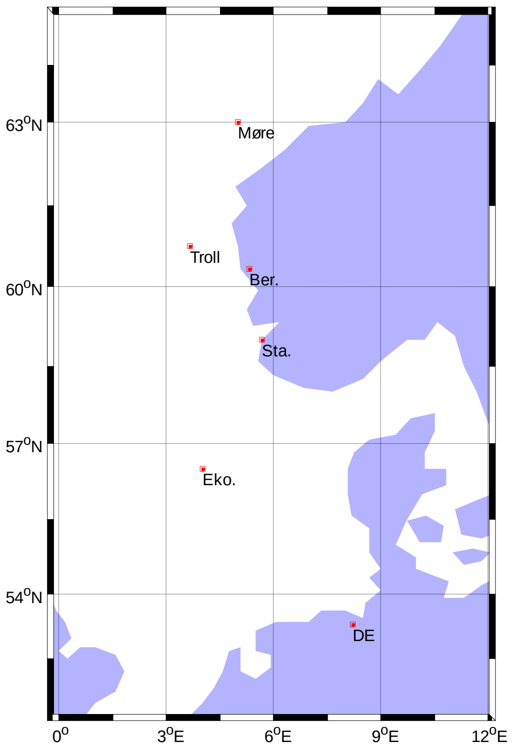

Figure 2: Map of the area.

3.1 Assumptions

Hourly power prices from 2006 and 2007, downloaded from energinet.dk [11], are used when sampling. The prices at the two Norwegian connection points are equal to the South-Norwegian price at Nordpool, and the price in Germany is equal to the price at EEX.

The expected absolute hourly price difference between Norway and Germany was 18.8 EUR/MWh for the years in question. The expected average price in Norway was 37.5 EUR and 44.4 EUR in Germany. The power price at the land connection points was assumed to decrease by 0.005 EUR per MW import and conversely increase by 0.005 EUR per MW export. Thus 1000 MW of power fed into any on-shore node would reduce the price there by 5 EUR/MWh. This number was chosen arbitrarily and is intended only to suggest a slight feedback between demand and supply and the price.

Hourly wind velocity data from coastal meteorological stations close to the modeled offshore wind farms have been used to create time series of wind power generation. Wind velocity was converted to power generation by applying the power curve in Figure 3. The utilization time of the wind power series is about 4000h for all three sites.

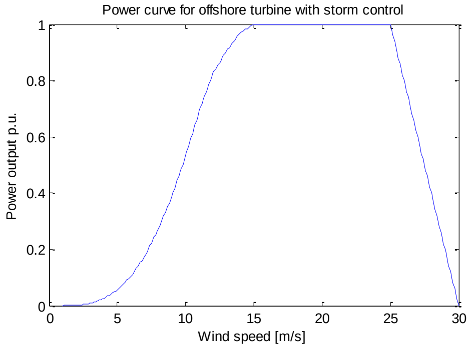

Figure 3: Wind power curve with assumed storm control.

The cost of cables was modeled as a simple function of distance, *D,* and rating, *R*:

$$C = 712.5 * D * R + 250000 * R \quad [EUR]$$

The actual cost is somewhat lower than that of the NordNed cable between Norway and the Netherlands (€ 550 mill for 576 km, 700 MW, LCC HVDC) [13], and is therefore also on the low side for a meshed HVDC grid using VSC HVDC technology. It is emphasized that the cost function is intended only as an example. Since only submarine cables were to be considered the connection between Bergen and Stavanger was left out of the optimization.

Furthermore a discount rate of 4.5% and a lifetime of 30 years were used to calculate the present value of generation costs.

3.2 Results

The first step in the optimization procedure is to determine the necessary sample size *M*. It can be expected that a grid that was optimized with regards to many samples, i.e. large *M*, on average performs better than a grid optimized with regards to a few samples, i.e. small *M*. However, the exact number of samples necessary will differ from grid to grid and cannot be known beforehand.

The procedure is as follows: We draw *M* random samples from the data set. These *M* samples then represent the distribution of wind power generation and prices at the three sites and are used to optimize the capacity of the cables. After the optimization procedure has completed, the grid configuration that was found to be optimal is tested on the whole set of data and the cost of satisfying the load is noted. In other words, after the optimal grid has been found with regards to *M* samples, the grid is tested in a separate procedure. This procedure calculates the operation cost for the system – given the optimal grid as exogenous input – for the whole dataset. The aim of this test procedure is to test how well the grid that was optimized with regards to a small subset *M* of data performs on the whole dataset.

The procedure was conducted on the example grid, with 8 repetitions for each sample size *M*=[5,10,20,50,150,400]. In Figure 7, one can see the total costs for a year divided into operation costs and annualized cable costs. The variation between the solutions is fairly large for a sample size of five and decreases until it is virtually unnoticeably for a sample size of 150. The improvement in cost from 150 to 400 samples is almost neglectable.

The example grid optimized with a sample size of 400 is shown in figure 4. For comparison a grid locked to only radial connections and a grid without wind has also been optimized. The results are shown in figure 5 and 6 respectively and the costs are summarized in Table 2.

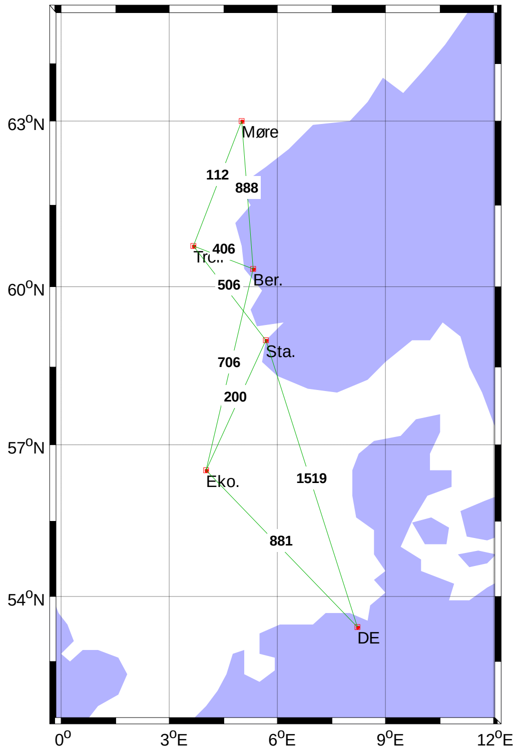

Figure 4: Optimized grid.

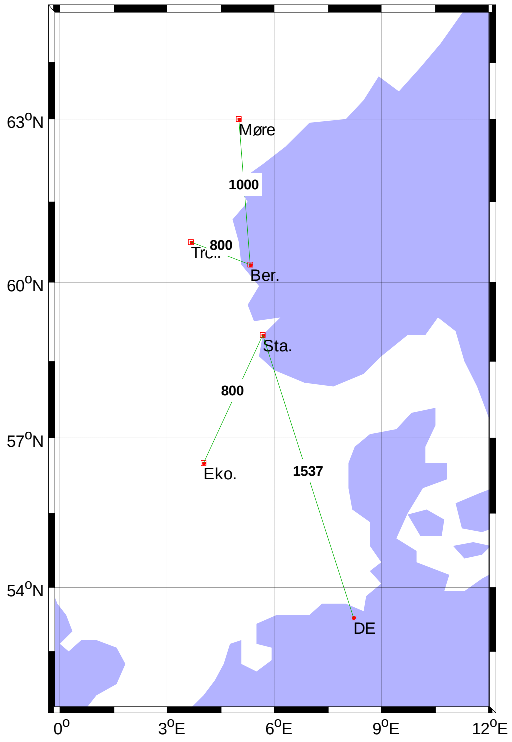

Figure 5. Optimized grid with radial connections only.

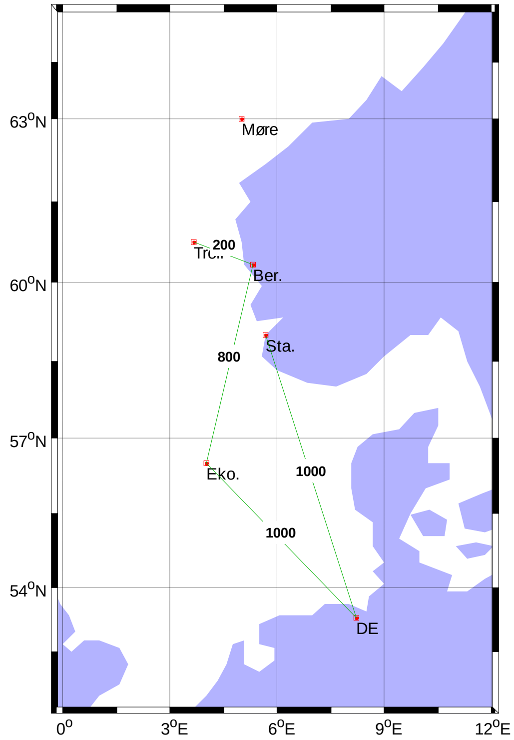

Figure 6: Optimized grid with no wind.

Configuration	**Cable cost** **Million EUR**	**Total social economic cost Million EUR**
Optimal	2862	23 156
Radial	2182	23 944
No wind power	1787	30 687

Table 2: Costs for three grid variants.

As one can see from table 2, the optimal grid requires a greater investment in subsea cables, but the total cost (including cable costs) over the entire lifetime is 788 million EUR lower than the radial configuration. The configuration “No wind power” refers to an optimization of the grid with zero offshore wind power (the subsea cables are then only used for supplying power to the oil and gas rigs and for power trade between the countries).

Comparison between the optimal grid configuration and the grid without wind power gives an upper bound on the acceptable investment cost of the wind farms themselves. For the example grid with 3000 MW wind power, the total cost difference is about 7.5 billion EUR; thus, the upper limit on the investment cost of wind power – for it to be viable in a socioeconomic perspective – is 2.51 million EUR per MW installed. Bear in mind that this is valid only for the specific example in question.

Even though the variation in total cost is neglectable when a sample size of 400 is used, there is still the possibility that the solutions in terms of optimized capacities can vary from one solution to the next. Repeated simulation shows that there is some variation in optimal grid capacities depending on the sample size, even though the costs are next to identical, see Figure 7.

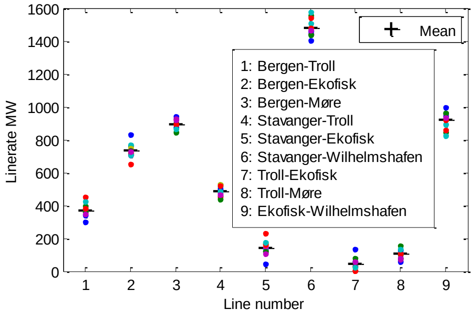

Figure 7. Variations in cable capacity (linerate) for 12 simulations with different samples.

For a 30% increase in investment costs of cables there is little difference from the optimal solution presented in Figure 4. Repeated simulation shows that the algorithm converges to the same cable configuration only with slightly different capacities. A doubling of the investment costs does on the other hand remove the connection between Møre and Troll and the total exchange capacity between Germany and Norway is reduced from the maximum of 2400 down to 1531.

4 Conclusions

A methodology for optimizing an offshore grid structure has been developed in this work. The methodology assumes that the locations and installed capacities of the wind farms are known, and finds a solution for the least-cost offshore grid structure and cable dimensioning, taking into account, wind power variations, power demand at oil and gas rigs, connection point alternatives to the on-shore power system, and the possibility for transnational power exchange. To take into account the variability of wind power output from the wind farm sites and power price variations on shore, the optimization is conducted with regard to several discrete cases that represent various wind and price conditions. The resulting cost of each case is weighted with the probability that the case will occur. An example on the use of the method was shown for a case with 3 wind farms, 2 offshore loads (oil platforms) and 3 possible connection points to the on-shore grid. It has also been shown how the algorithm can be used for grid optimization without offshore wind power, where the grid is optimized for power exchange and electricity supply to oil platforms.

The method proves to create a grid with lower lifetime costs than simply connecting the wind farms by radials to shore. However, the algorithm is bound to use only linear, convex cost functions which are not very well suited to model the costs of HVDC cables. In reality there are economics of scale when installing subsea cables, this may make it optimal to build fewer and higher rated cables than suggested by the linear algorithm. Such modelling of the cost function is not possible with linear programming as the optimization problem then becomes non-convex. We are presently working on solving parts of the optimization problem with a genetic algorithm that will allow more realistic cost functions.

Furthermore, a large meshed power grid will seldom be built in one step. The usual course is to develop the grid in steps as demand for capacity materializes. However, using scenario analysis or a Monte-Carlo approach in combination with the described methodology can still aid a stepwise development of the grid.

Even with the discussed limitations the presented methodology can be a valuable decision support tool when planning new off-shore grid investments.

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Appendix

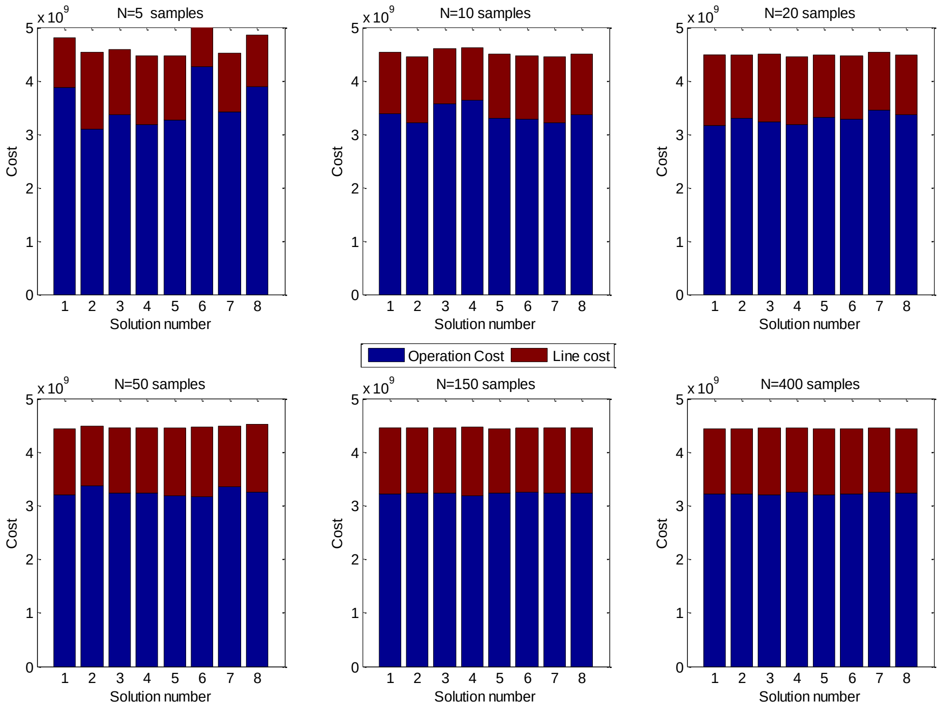

Figure 7: Variations in cost for different samples sizes.