OFFSHORE WIND FARM BOCKSTIGEN - INSTALLATION AND OPERATION EXPERIENCE

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ABSTRACT: The first Swedish offshore wind farm Bockstigen is operating since March 1998 near the coast of Gotland. It was built as a demonstration project by the Swedish wind farm developer Vindkompaniet, the Danish wind turbine manufacturer Wind World and the British offshore construction company Seacore and partly funded under the EU-THERMIE program. Bockstigen is the fourth offshore wind farm world-wide. While at previous wind farms the main emphasis laid on the demonstration of the technical feasibility of offshore wind energy utilisation, Bockstigen was aimed at demonstrating its economic viability. A number of innovative concepts have been employed: Drilled monopile foundations were used to save costs. A new construction method has been applied making use of a jack-up barge. A new control system for the turbines and the whole wind farm was developed, which controls the maximum power output, the flicker and the reactive power consumption depending on online measurements of the actual grid state. These new developments have been implemented successfully. A substantial cost reduction compared to previous offshore projects could be achieved.
Keywords: Demonstration Projects, Off-shore, Operating Experience, Bockstigen

1. INTRODUCTION

Offshore wind energy is one of the most important options for the future expansion of wind energy utilisation. In several European countries the available space with favourable wind conditions is getting scarce. Developing the offshore potential means to have ample space available with very favourable wind. The main disadvantages of offshore locations are the higher costs of foundations and sea cables and of the installation and maintenance work.
The aim of developing offshore wind energy is therefore to be able to build wind farms at a cost compatible to installations on land. Therefore the additional costs have to be low enough to be outweighed by the additional energy production due to the more favourable wind regime.

2. THE WIND FARM BOCKSTIGEN

2.1 Location

The wind farm is located south-west of the Swedish island Gotland in the Baltic Sea (see figures 1 and 2). Its distance to the coast is about 4 km and the water depth app. 6 m. The site has the main advantages of:

- low water depth in relative large distance to land
- suitable soil conditions for drilling and monopile foundation
- harbour for installation and maintenance within reasonable distance

Figure 1: Bockstigen wind farm

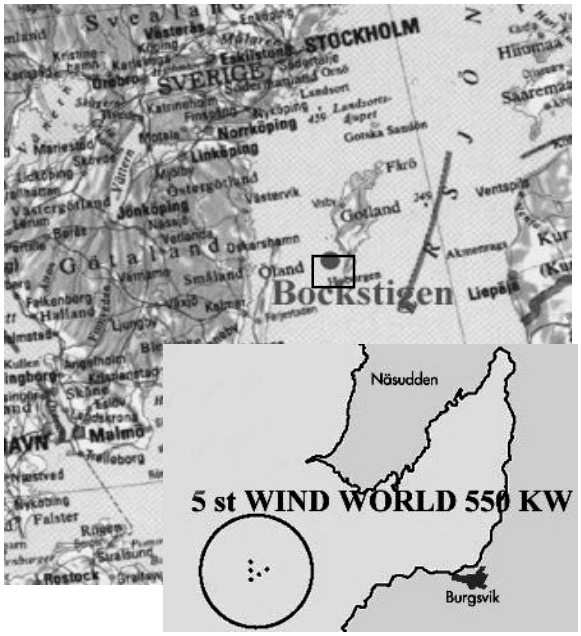

Figure 2: Site and layout of the wind farm Bockstigen

2.2 Turbines

The wind farm consists of 5 Wind World 550 kW turbines which were especially adapted to offshore conditions. This type was chosen because of its simple and reliable technology and high availability record. The design characteristic of all Wind World turbines is a ridged integrated gearbox with a flange mounted generator. This construction ensures long life time and low service costs. The 3 bladed rotor with a diameter of 37 m is mounted upwind of the tower. The turbine is stall regulated with tip air brakes. The tower is a modified 38 m standard tubular steel tower in two sections. It is flange mounted on a steel monopile of 21 m length. The hub height of the turbine is app. 40 m above normal sea level. For easy access a platform is mounted between tower and monopile. In the design of the whole construction special attention is paid on the resonance frequencies of the turbine with the monopile foundation and the additional loads from current, waves and ice.
Some offshore modifications have been applied to the turbines: Hoist equipment allows replacement even of major components. The compartments in the monopile and the tower are equipped with a closed ventilation system to ensure dry, cool and condense free environment for control system, switchgear and transformer.

2.3 Grid connection

The connection point in Gotland-Valar is a 10 kV net with a short-circuit power of only 16.9 MVA, which means a ratio of almost 15% wind park power per short-circuit power. To operate such amount of stall-regulated turbines without conflict with the IEC standards required a complete new innovative solution: The 'Master Controller' system for a wind farm and the 'Optimal Speed' control system for a turbine have been employed to achieve this.
The 'Optimal Speed' control system uses a power converter to perform its two main functions:

1. At low wind speeds (up to app. 20% of rated power output) the converter operates as frequency converter. The turbines generators run with variable speed to increase the power output.
2. At medium and high wind speeds the turbines are directly grid coupled. Here the power converter operates as a precision blind current source. This gives a fast and full dynamic flicker compensation and also enables the cos-phi regulation.

The 'Master Controller' for the whole wind farm is located at the grid connection point on land. Its main function is to guarantee the IEC compatibility of the grid voltage between the connection point (CP) and the next bus-bar (10 kV to 30 kV station). These control tasks are:

- perform a complete 3 phase U/I/P measurement at the CP
- operate the whole wind park at cos-phi = 1 as long as the grid voltage is uncritical and to decrease cos-phi up to a specified value in order to hold down the voltage if it comes close to the limit
- use additionally a set of dumploads (0-500 kW in 20 steps) and to stop and restart one or more turbines to limit the wind park real power output
- control the flicker compensation parameter (psi-K) for all turbines to minimise the flicker along the line from the CP to the bus-bar

The wind farm 'Master Controller' additionally performs the functional control of the wind farm including turbine remote control. Data communication with the turbines is done via an optical fibre grid.

2.4 Foundation

To achieve a low foundation cost at Bockstigen the technology of drilled monopile foundations was used for the first time for wind energy applications. The foundation consist of a 21 m long tubular steel monopile. It is fixed with concrete in a 10 m deep hole drilled in the sea bed rock (see figure 3). The suitability of the rock and the required hole depth have been evaluated by probe drillings. The completed construction has the following advantages compared to previously used solutions:

- The weight is only 43 tons.
- Ice and wave loads are heavily reduced since the waterline is only 2.1m wide.
- The foundation can be towed to the site by a normal tug boat and can be lifted into place by a crane with 35 tons lifting capacity by using the lifting capacity of the water.

3. CONSTRUCTION METHOD

Turbines and monopiles were manufactured at Wind World's factory in Skagen. Monopile foundations are relatively simple and inexpensive to produce compared to concrete gravity foundations. Transport of the components was made by ship directly to the harbour Klintehamn from where the installation took place. Transport on site was performed by Vindkompaniet's own small ferry together with a barge and a small tug boat. For transport the monopiles were sealed watertight and could therefore be floated.
To drill the foundation hole the jack-up barge is used. A hole of 2.4 m diameter and 10 m depths is drilled in the rock. Drilling can be performed in any kind of rock which

is hard enough to be self supporting. When the drilling is finished the tug boat tows out the monopile which is then lifted into the hole. Finally the monopile is grouted into position by filling the gap between the 2.25 m diameter monopile and the rock with special concrete.
After finishing all foundations the jack-up barge was also used as a stable and efficient tool to erect the turbines. They are mounted onto the foundation by means of the platform's crane and the ability of the platform to lift itself up on the supporting legs.
The electrical sea cable and the glass fibre communication cable were laid with help of the ferry and anchored to the seabed. Thereafter they were connected to the turbines and to the land grid.

4. PROJECT ECONOMICS

The total cost of the Bockstigen wind farm was 4 mio. Euro. The projected power output is 8 GWh per year. The cost per estimated yearly power output is 0.50 Euro/kWh/y. This figure can be compared with the cost of previous offshore installations and with that of land based wind farms:

- Vindeby offshore wind farm: app. 0.91 Euro/kWh/y [1],[2].
- Tunø Knob offshore wind farm: The cost per estimated yearly power output is app. 0.76 Euro/kWh/y [2].
- The last land based wind farm (10 MW) built by Vindkompaniet cost 0.41 Euro/kWh/y.

It turns out that a substantial cost reduction compared to the wind farms Vindeby and Tunø Knob could be achieved which were about 80% and 50% more expensive than Bockstigen. A favourable location on land is now only about 15-20% cheaper than the offshore installation at Bockstigen.

Figure 4: SEACORE jack up barge used for drilling and erection

5. LESSONS LEARNED

A number of new technologies were developed and implemented to make the offshore wind farm Bockstigen technically and economically feasible. Through the whole construction process only one genuine technical problem was encountered, which was the anchoring of the sea cables. The water current was larger than assumed due to an acceleration of the flow over a ridge and the difficulty to anchor the sea-cable to the sea bed was underestimated. Where large areas of the seabed were free from loose layers it proved necessary to anchor parts of the sea-cable with the use of steel hoops. The first attempt was to use concrete sacks as weights. The second attempt was to anchor the cable with hooks made of 12 mm steel. Both failed and first the third attempt employing 25 mm U-shaped hooks anchored in two holes in the sea bed was successful
On the planning side, the time plan could not be met. This was due to the combination of a number of reasons:
The late arrival of the jack-up barge delayed the start of the construction work. The lifting of the monopiles into the holes turned out to be very sensitive for waves. Also wave heights at the site were higher than assumed due to the building up of waves when they reached lower water depth. This further delayed the work and finally the anchoring problems could not be solved before winter started. Therefore the wind farm was operational first in spring 1998.
Despite these delays the cost plan could almost be kept with only about 10% cost rise over the budgeted cost. The cost rise was mainly due to the problem with anchoring the sea cable.
The main lessons learned during the project are:

- Wind, wave and sea current conditions at the site should be carefully investigated.
- Installation of the sea-cable can be carried out at a lower cost if the right method is chosen from the beginning.
- The installation process of the monopile foundation can be made even less weather sensitive, reducing time and therefore cost.

Throughout the planning, construction and operation a lot of valuable knowledge was gained by all partners involved. Plans are going ahead to build further offshore wind farms in Sweden with the same technology which was successful at Bockstigen. It is believed that due to the experience and knowledge gained from this first demonstration wind farm future projects can be build at even lower costs.

6. POWER OUTPUT MEASUREMENTS

On Gotland several turbines of the same type as used for the offshore wind farm are operating very close to Bockstigen. Measurements are performed to investigate the difference in production between land based and offshore turbines. Meteorological measurements including 1-min. mean values of wind speed and direction at different heights are available from a 145 m high mast at Näsudden. The power output of the Bockstigen turbines is available as 10-min mean values from the wind farm 'Master Controller'. For a number of land based turbines hourly power output measurements are available for comparison. The locations of the different measurements are shown in figure 4. In a first preliminary measurement campaign these values have been collected for a period of two weeks.

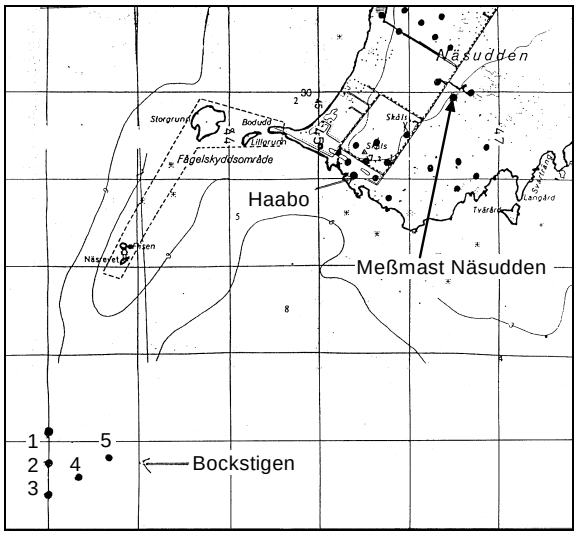

Figure 4: Map of the locations of the measurements

As it can be seen in figure 4 there is a great number of wind turbines located on the peninsula Näsudden. This limits the wind directions for which the measured turbines are not disturbed by wakes of other turbines. The turbine Håbo on land and the Bockstigen turbine 3 have a common sector of undisturbed wind flow for wind directions between 150° and 290°. For these directions both turbines have sea fetch.

Up till 194° for the land turbine and 186° for the Bockstigen turbine the fetches are influenced by the southern part of Gotland. For all other directions both have the same long fetch across the Baltic Sea to Sweden.

Figure 5 shows a one day long time series of wind speed and direction at 145 m from the Näsudden mast and power output measurements from the turbines Håbo and Bockstigen 3. The wind direction is around 180°, i.e. the fetch is limited by the coast of Gotland. Here the Håbo turbine has a sea fetch of 5 km while the Bockstigen 3 turbine has about 10 km fetch. It can be seen that this fetch

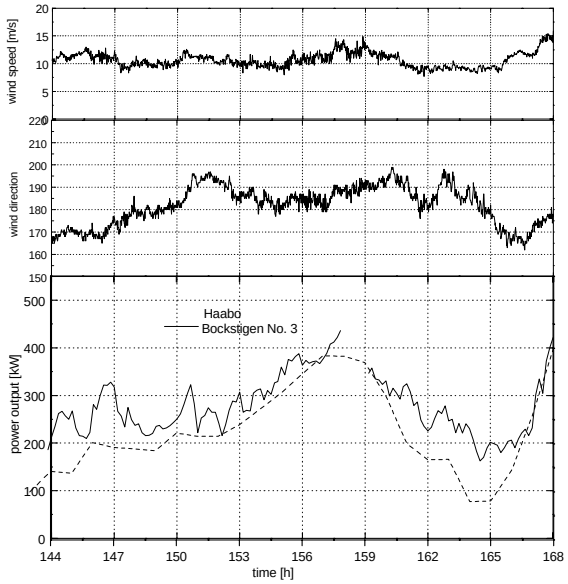

Figure 5: Time series of the 9.9.1998 of wind speed and direction at 145 m height measured at the Näsudden mast and power outputs of the turbines Håbo (hourly means) and Bockstigen 3 (10-min. means)

difference leads to a significant difference in power output. For the directions with wind speeds from the open sea such a difference can not be found.

However, to quantify this effect a statistical analysis of a much longer measurement period is required.

7. CONCLUSION

The first Swedish offshore wind farm Bockstigen near Gotland has been constructed successfully and is operating since March 1998. The farm consists of 5 Wind World turbines of the type W-3700/550 kW which were especially adapted to offshore conditions. A number of new innovative technological solutions have been developed and implemented successfully which make offshore wind energy technically and economically more attractive.

For the first time rock-socketed monopile foundations were used. Drilling of the holes and erection of the turbines was performed from a mobile jack-up barge. It has been shown that this technology considerably reduces the cost of offshore installations compared to the conventional gravity foundations. The previous Danish offshore wind farms Vindeby and Tunø Knob were about 80% and 50% more expensive than Bockstigen. A favourable location on land is only about 15-20% cheaper. With the experiences from this demonstration project future offshore wind farms will be build at an even lower cost.

The maximum power output of the wind farm is limited by the capacity of the grid at the connection point. This is done by means of the newly developed wind farm 'Master Controller'. It uses online measurements of the grid properties to control the reactive power production of the turbines as well as the maximum total delivered power of the wind farm. This is possible since the wind turbines are equipped with Wind World's Optimal Speed Control. This system delivers a high power quality with low inrush current, full compensation of reactive power and very low flicker.

Measurements are performed at the Bockstigen turbines as well as at turbines of identical type on land. These are used for a direct comparison of the power output between onshore and offshore turbines. Preliminary results indicate a significant difference of power outputs depending on the lengths of the sea fetches involved.

ACKNOWLEDGEMENTS

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