Technical and economical evaluation of distributed AC power collection for Off-shore Wind Power Plants

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***Abstract*—The paper outlines a technical and economical comparison of two power collection concepts for off-shore wind farms: an innovative distributed concept versus the commonly used centralized power collection. In contrast to centralized power collection on a single and large platform, integrated and compact switchgear and transformer modules enable the distribution of power collection across multiple strings of interconnected wind turbine generators. The increasing size of the new generation of wind turbines above 4 MW and the corresponding large tower structures allows distribution of such modules throughout the array grid. Distributed power collection reduces capital expenditure by eliminating the need for a single large off-shore platform and allows a step-wise development of the wind farm over time. The wind farm studied in the paper is assumed to have a final capacity of 624 MW with power collection at 72kV AC and export cables at 220kV AC. The paper also presents the electrical aspects of wind power plant grid connection as a result of load flow studies, including an assessment for reactive power compensation.**

Keywords-Offshore; 72 kV collection grid; offshore platform; compact switchgear; GIS

I. INTRODUCTION

The construction of off-shore wind energy is rapidly growing throughout the world with Europe having an installed capacity to date of 3.6GW and an estimated expansion up to 8GW until 2016 [1]. Along with this expansion, there is an increased focus to reduce capital expenditure by optimization of the off-shore operations as well as in the supply chain and the cost of equipment. One clear trend is seen in the ever increasing capacity of wind turbines with the latest development reaching 6MW and above per turbine [2], [3]. To reach these power ratings per turbine, rotor diameters have increased to about 150-160m with nacelle weights of more than 300 tons. To accommodate such a large rotor the corresponding tower, support structures and foundations have also increased in size which in turn opens up for the inclusion of larger electrical equipment in each wind turbine tower such as gas-insulated switchgear and transformers. Since a few years, the industry is for example focusing on raising the voltage of the power collecting array grid from 36kV to 72kV to minimize cable losses and allow more wind turbines per cable string [4]. A higher power rating per cable means also that for a given wind power plant size, fewer cable strings will enter to the off-shore transformer platform. An array voltage of 72kV may in some wind power plant locations be sufficient to connect the arrays directly to an on-shore grid hence eliminating the need for a free-standing transformer platform. For more distant wind power plants, e.g. 30-60km from shore, export AC cables at 220kV may be used. In this paper, we look at two different power collection concepts in collecting powers from large wind power plants and connecting them to an onshore grid by means of AC cables. The traditional way of collecting all the power from the array on a central platform is compared with a distributed power collection scheme where the wind turbine towers are utilized to house the switchgear, transformers and auxiliary equipment. Such a platform-less concept can yield substantial savings and enables a wind power plant to be built in steps where generated electricity can be brought to shore as soon as the first turbine has been installed. Due to the reactive power generation of the AC export cables it is considered that inductive shunt compensation will be at least needed on-shore. As previously studied in [5], the power electronics in the wind turbine converters can also be utilized for reactive power compensation needs.

II. WIND POWER PLANT DEFINITION. ASSUMPTIONS

The studied wind power plant is assumed to have eight strings of thirteen wind turbines each. The selected wind turbine is a commonly used turbine of 6 MW; therefore the total capacity of the offshore wind power plant is 624 MW. The wind turbine of 6 MW is expected to be a full-converter machine.

High voltage levels have been considered in the transmission and distribution system to increase the power evacuation and reduce the losses of the wind power farm. The power collection is done at 72 kV AC and the export cables at 220 kV AC.

The selection of AC or HVDC transmission cables mainly depends on the distance to shore and the transmission capability [6]. An AC transmission line cable has been selected since the considered length to the onshore connecting point is around 50 km, which can be regarded as a typical or average length for AC cable connections.

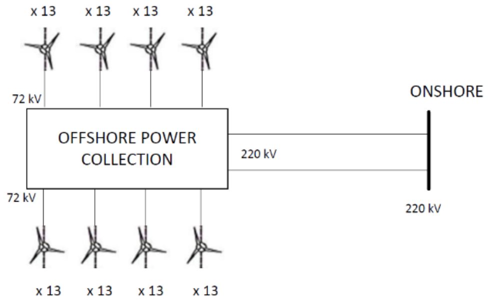

Figure 1. Schematic wind power plant

The length of the distribution cables is based on standard wind power plant turbine spacing principles [7] where typical values are: three or four rotor diameters perpendicular to the prevailing wind direction and around seven to nine rotor diameters in the prevailing wind direction. Taken into account a typical rotor diameter of 160 m [2], the considered distance at 72 kV is 1,5 km.

A typical water depth of 30 m is considered [8]. The most common wind turbine structure is a simple tower due to its simplicity; moreover the distance to seabed selected is suitable for this kind of pylon [9].

The aim of this paper is to compare two different power collection concepts for offshore wind power plants: an innovative distributed concept versus the commonly used centralized power collection with a dedicated offshore platform. The distributed concept implies the utilization of some of the wind turbine towers to collect the wind power getting rid of the main substation platform (see Fig.2b). The comparison is presented from a technical and an economical point of view.

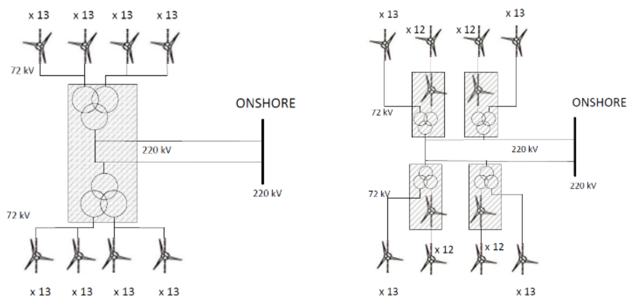

Figure 2. Traditional concept (2a). Distributed concept (2b)

In the traditional configuration example, two main three-winding transformers are installed in a dedicated offshore platform. Each transformer is in charge of collecting half of the power of the total wind power plant capacity; i.e. 350 MVA approximately. The 220 kV cables to shore are expected to have a length of 50 km each.

In the distributed concept the wind power farm is split in four sections with a three winding 175/87.5/87.5 MVA transformer each. The distribution of the collection equipment entails a reduction in size and weight. This reduction allows the equipment to be installed in several wind turbine platforms, with enough available space to allocate it. The wind turbine tower structure may have to be reinforced to withstand the additional weight. Following this approach the installation of a main platform would then not necessary and hence, it could be eliminated. In this case, the considered length to shore is almost 50 km and the 220 kV cables located in between win towers have a considered a minimum length of 0.5 km according to spacing principles [7].

III. TECHNICAL ANALYSIS

From a technical point of view, a detail model in PSS/E software is developed for the two wind power plant concepts. Steady-state analysis has been developed to verify the suitability and feasibility of the wind power plant selected. The studies have two main objectives: first a comparison of both systems in terms of the main system variables such as voltage levels, system equipment loading and power losses. Secondly an evaluation of the reactive power solutions to comply with the selected Danish grid code.

Several scenarios have been developed taken into account fluctuations in the power generation of the wind power plant (from 0% to 100%) and in the voltage at the interconnection point (from 0.95 to 1.05 pu). All the scenarios have been firstly converged and solved in steady state in the software PSSE.

A comparison of both configurations has been developed with the wind turbines working at full power and power factor one. Voltage levels, loadings and losses have been compared with the following results:

TABLE I. VOLTAGE COMPARISON

Voltage level at the offshore platform	**Voltage (pu)**	
	Traditional configuration	***Distributed configuration***
220 kV	1,015	1,015
72 kV	1,015	1,015

TABLE II. LOADING COMPARISON

Main transformer	**Loadings (%)**	
	Traditional configuration	***Distributed configuration***
	350/175/175 MVA	175/87.5/87.5 MVA
Winding 1	89%	89%
Winding 2	89%	88,5%
Winding 3	89%	88,5%

TABLE III. LOSSES COMPARISON

Power at the Interconnection point	***Traditional configuration***	***Distributed configuration***
Active power (MW)	611,3	611,4
Reactive power (MVAr)	92,4	93,2

Less than 0,3% of difference in voltage at 220 kV and 72 kV is detected, around 0,5% of loading deviation when 175/87.5/87.5 MVA transformer is selected and approximately 0,4% of reactive power losses more in case of distributed configuration. A sensitivity analysis has been done when the considered cable distance in the 220 kV level between turbines is higher, around 1,5 km. In this case, the reactive power losses will increase around 4 MVAr in the distributed option, basically caused by the difference configuration in the 220kV transmission system.

As a result of this analysis only minor deviations have been observed, hence both systems have similar electrical behaviour.

In order to simplify the analysis and due to the similarity of both configurations, the reactive compensation analysis could be extrapolate to be similar for both configurations.

Apart from the voltage and loadings defined by the different components of the system, the grid operator defines some requirements to be fulfilled by the wind power plant. Further scenarios have been done considering different reactive power capacities. Typically, it is required to comply with a P-Q curve depending on the generation profile. The Danish grid code [10] has been selected to analyse its requirements in terms of steady-state P-Q. The high penetration of installed offshore wind power plants in Denmark and the requirement itself make this grid code a good option for the evaluation.

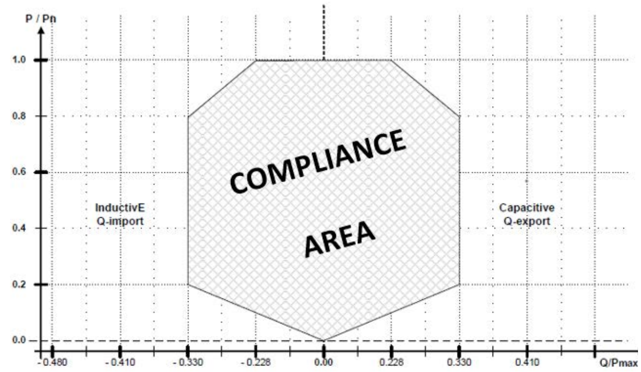

Figure 3. Reactive power requirements – Danish grid code

The grid code establishes an area in which the wind farm shall be capable of absorbing or generating the reactive power as shown in previous figure; i.e. an inductive area (Q-import) and capacitive area (Q-export) represented in the pattern area shall be fulfilled.

Even if a minimum reactive solution could seem like an optimal solution, other important factors such system losses should be kept in mind. Therefore, several approaches have been evaluated considering the combination of both factors.

The wind power plant has capacitive behaviour for the whole generation range when the machines are working at power factor 1, i.e. not considering the reactive power capability of the wind turbines. This case represents the case of minimum losses; however, it would be necessary to add a solution of around 520 MVAr inductive and approximately 245 MVAr capacitive to fulfil the reactive power requirements.

It is highly recommended to use the reactive power capacity of the wind power plant to reduce the size of the solution. As much as this capacity is used, the less investment is needed. Two different solutions have been analysed depending on the investment cost and the power losses in the system:

- Solution A. The maximum reactive capacity of the wind turbines is considered; therefore the minimum investment is needed.
- Solution B. The system losses could be minimised by selecting a special control of the wind turbines. The turbines will follow this control by using their reactive capacity and an additional solution will be in charge of fulfilling the grid code requirements.

A. Solution A: Minimum investment cost

In this solution, the wind turbines provide the reactive power needed at the interconnection point. This reactive power is transmitted through the transmission cable and may result in large voltage drops at the offshore 220 kV level.

The following figure represents the reactive power at the interconnection point for different external grid conditions and wind turbine operation. It indicates the maximum capacity (capacitive or inductive) at three different voltage levels.

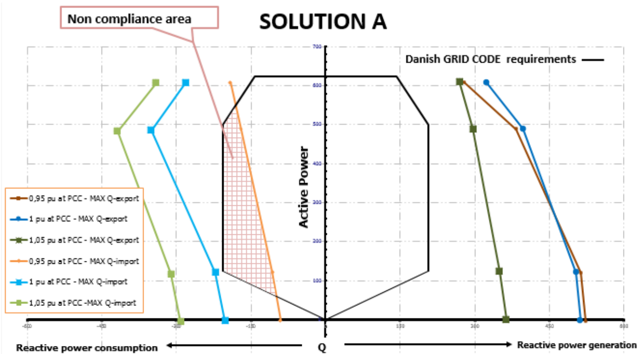

Figure 4. Maximum reactive absorption and generation of the wind power plant while using the maximum capability of the turbines

It is clear from the graph above that at 0.95 p.u. voltage level the maximum reactive power consumption requirement cannot be met.

In case this condition is required, an additional solution of 110 MVAr inductive in the onshore substation is needed to fulfil the grid code in terms of reactive power. The solution cannot be defined as fixed since it would not comply the reactive requirements in case of the power generation is around the 80% of the total power and the voltage at the interconnection point is 1.05 pu, when the wind power plant must be working in the capacitive region. Fig. 5**Error! Reference source not found.** reflects the expected shifting in the reactive power curves.

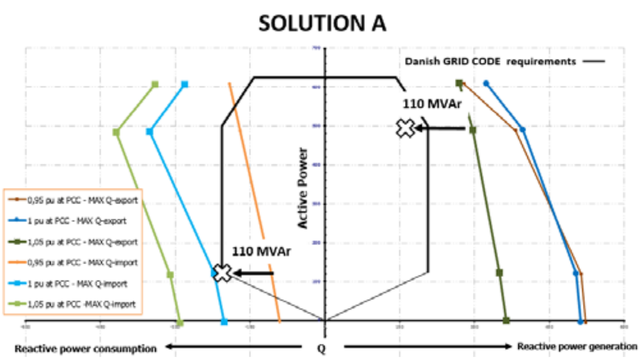

Figure 5. Influence when installing a fixed solution of 100 MVAr

Therefore, two steps could be needed: a fixed solution of 80 MVAr and an additional compensation of 30 MVAr, both inductive.

B. Solution B: Low losses operation strategy

A special strategy to minimise the losses in the system is considered in this solution. This strategy is based on the following principles:

- The wind turbines will be controlled to obtain 0 MVAr at the interconnection point. Fig.6 represents this control.
- Additional reactive power arrangements will be needed in order to fulfil the reactive power required by the system operator (grid code). The size of the solution needed is ± 230 MVAr, i.e. 230 MVAr inductive and 230 MVAr capacitive.

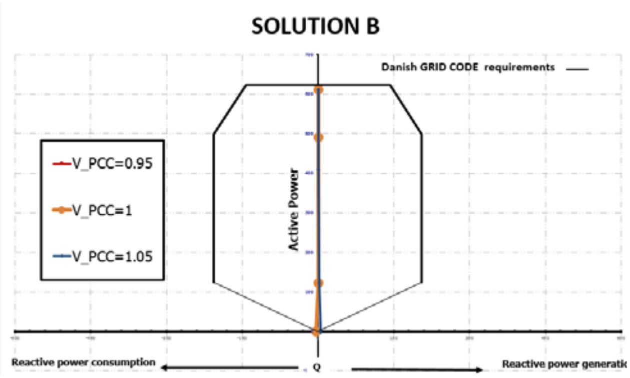

Figure 6. Control strategy to minimize system losses

C. Comparison of the reactive solutions

HV, MV and LV levels have been checked with values within the normal operation range in both cases. The selected on-load tap changers (±12) of the main transformers in the offshore platform are able to control the voltage at the 72 kV distribution system. A reasonable profile (around [0.98-1.02] for both solutions) is detected in the 72 kV level and therefore, the LV side (0.69 kV) are within acceptable limits in all the cases. A more flat profile at 220 kV level is observed for case B (around [0.92-1.04]) compared to case A (around [0.9-1.09]) as the cable is less loaded.

The main difference in terms of electrical variables is seen in the losses. It is remarkable that the losses will be reduced in case B. Around 5% less of loading at full power is seen in the export cable when this option is chosen.

Although case B presents a reduction in the losses, the investment of the reactive power solution is significantly higher. A detailed cost-benefit analysis will define the suitability of the solution in a separate case study.

IV. ECONOMICAL ANALYSIS

An economical evaluation has been done taken into account both configurations. Common offshore elements such cables, transformers, GIS substation, wind turbines and the foundations have been analysed. The reactive compensation considered for this economical evaluation has been a fixed solution of 80 MVAr inductive and a switched reactance of 30 MVAr for both configurations. Grid connection cost, civil works, service, and commissioning works are not considered.

For the distributed option reinforcement of the WTG structure may potentially be needed since additional equipment will have to be accommodated. The equipment to be added inside the WTG structure includes:

- An integrated GIS 72 kV 3-bay module
- An integrated GIS 220 kV transformer bay module
- An integrated GIS 220 kV cable module A
- An integrated GIS 220 kV cable module B
- The three-winding transformer rated 175 / 87.5 /87.5 MVA

A simple representation of this equipment is shown in the following figure:

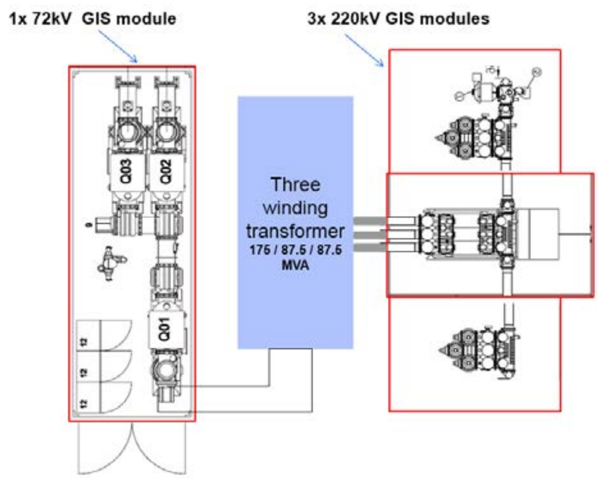

Figure 7. Compact equipment to be installed at the WTG platforms

Based on [11], [12], [13] and ABB experience, the cost of the equipment has been calculated. The overall cost of the traditional configuration has been considered as a reference point. The representation in percentage of the different configurations is seen in the next table and figures taken into account the 100% of the cost is referred to the traditional option.

TABLE IV. OVERALL COST COMPARISON

Element	**Overall cost comparison (%)**	
	Traditional configuration	***Distributed configuration***
Onshore shunt reactors	0,1	0,1
Offshore cables	13	13
Offshore transformers	0,5	0,6
Offshore GIS 220 kV	0,2	0,4
Offshore GIS 72 kV	0,1	0,2
Wind turbines	34	34
WTG ([1]) structures	45,2	45,2
Dedicated platform	6,7	-
Wind tower reinforcement	-	1,5
TOTAL	**100**	**95,1**
Savings	-	4,9

[1] Wind turbine generator

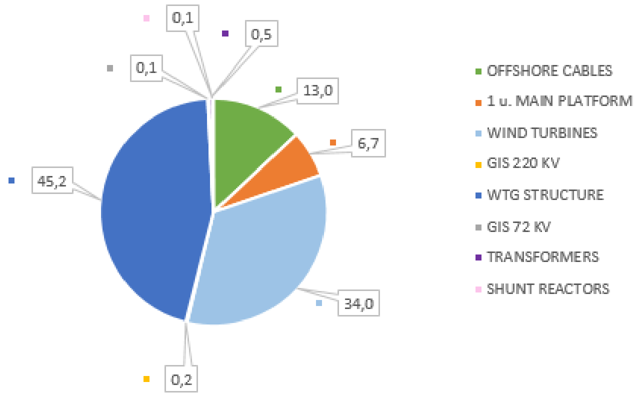

Figure 8. Overall cost for the traditional configuration

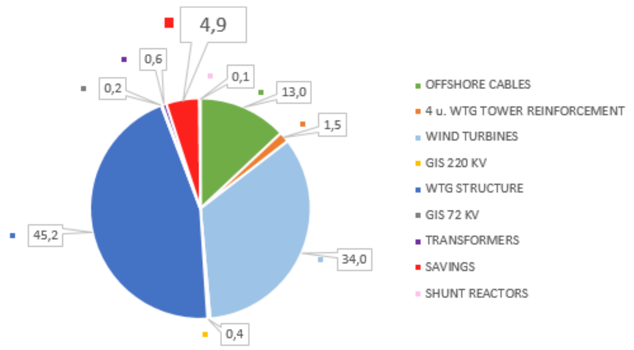

Figure 9. Overall cost for the distribution configuration

Some of the equipment are common for the both configurations. However, the reinforcement needed in case of distribution configuration, the dedicated platform in case of traditional option, transformers and GIS substations make the difference between both configurations. For a better understanding of the difference, next figures show the cost of the uncommon equipment, also referred to the 100% of the overall cost of the traditional configuration:

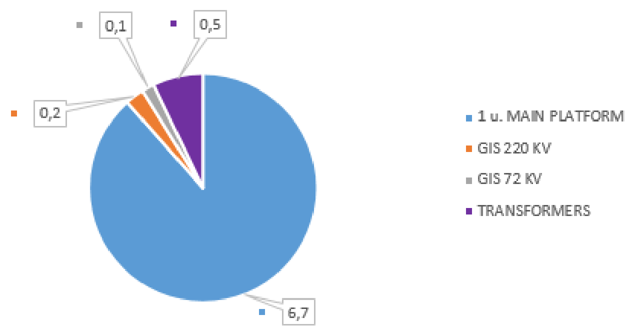

Figure 10. Uncommon equipment - Traditional configuration

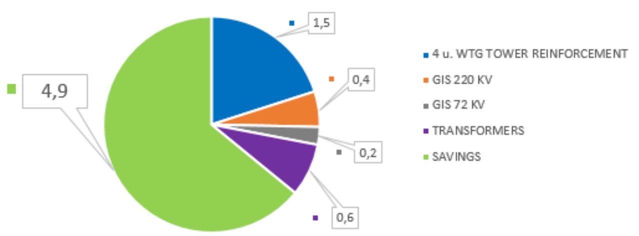

Figure 11. Uncommon equipment - Distribution configuration

As a result of the economical analysis, it can be concluded the following:

- The wind turbines and their structure represent almost the 80% of the total investment cost of the wind power plant.
- The distribution concept has a reduction of around 5% comparing to the traditional configuration with a dedicated platform.

V. CONCLUSIONS AND DISCUSSION.

The evaluation presents the comparison between two concepts for offshore wind collection platforms: a traditional configuration based on one main offshore platform versus a distributed concept solution in which the structure of the wind turbines are utilized.

From a technical point of view both system present the same results in terms of voltage, system losses and loading.

The reactive compensation needed is also evaluated considering two approches: minimum investment vs minimum transmission losses. Further cost-benefit and dynamics analysis will be needed to verify the suitability of each solution.

From the economical comparison of both configuration it is observed a big impact of the cost of the wind turbines in the overall initial investment with approximately 70-80% of the overallcost.

Moreover, the economical comparison reveals cost savings of approximately 5% are expected with the distributed concept, based on the assumptions considered. This is based mainly on the use of the wind tubine structure as offshore platforms to allocate the offshore 220/72 kV transformers and GIS substations.

As shown in the above comparison, the distributed power collection option does offer a considerable investment cost saving potential. To evaluate the full potential of this concept some further work is required in order to determine the costs of re-inforcing the off-shore wind turbine structures to include the additional structural loads of switchgear and transformer modules. It may also be required to compare the possibility of a step-wise deployment of the the windfarm and earlier collection of revenues compared to the conventional construction of a free-standing platform as a pre-requisite to transfer power to shore. The study of the electrical system has not included shunt reactor compensation off-shore which may be required if the distance to shore is increased to e.g. 100-120km. These shunt reactors may not necessarily need to placed together with the step-up transformers but could be placed on an adjacent wind turbine tower-platform to avoid excessive structural loading.

Further studies are recommended to fully investigate the improvements of the distributed concept such as RAMS[2] or grid code compliance. It is highly recommended to analyse the mechanical and economical impact of the especific structure of the wind turbine towers in detail for each study.

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