Wind Power and Offshore Wind Farms

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I. INTRODUCTION

As concern over the use of fossil-based fuels and their effect on the environment has grown over the past decades, there has been increased interest in the development of renewable resources and renewable energy sources. Among many of the other candidate technologies, wind-based power had been receiving growing interest due in no small part to its "squeaky clean" appeal: wind turbines create no carbon emissions of any kind and tap an obvious energy source that is seemingly readily available in many parts of the world. Though the development of an economically viable wind farms is far more complex than it may first appear, as technology has improved and political motivation has increased, wind-based power generation is is getting more and more attention.

For Europe in particular, the development of wind-based power has increasingly been focussed on offshore locations; by the year 2030 it is projected that 50% of the wind-based power will come from offshore wind farms [2] due in some part to the higher population density and lack of suitable sites on-shore [1] (as compared to the United States). The presence of highly suitable wind resources in addition to a long continental shelf allowing for "shallow" water installations [1] have made the development of offshore wind farms viable. Efficient transmission of the power to the shore, inaccessibility of the wind farm for easy maintenance, and complexity of installation itself are just a few challenges that must be overcome, though.

This paper hopes to provide an overview of wind-based power generation in general as well as addressing some of the unique design considerations of offshore wind farms. The first section will cover the basics of wind-power generation while the second will explore offshore wind farm installations in more detail.

II. WIND POWER BASICS

There are four basic sub-systems to a single typical wind-based power generation site: the tower and its supporting foundation, the turbine itself including the turbine blades, the generator which is directly (or indirectly through a gearbox) turned by the turbine shaft to produce electrical power, and the interface and control electronics that connect the generator to the larger electrical grid and regulate the production of the electrical power. As in nearly every power-generation system, there is a large degree of multi-disciplinary skills needed to produce an economically viable product and wind-based power generation is no exception. Though there is much to discuss with regards to the support structure, aerodynamics and materials of turbine blades, reliability of gearboxes, etc.. this paper will largely focus on the electrical aspects. Before leaving such things, there are a few key essential matters that should be covered first.

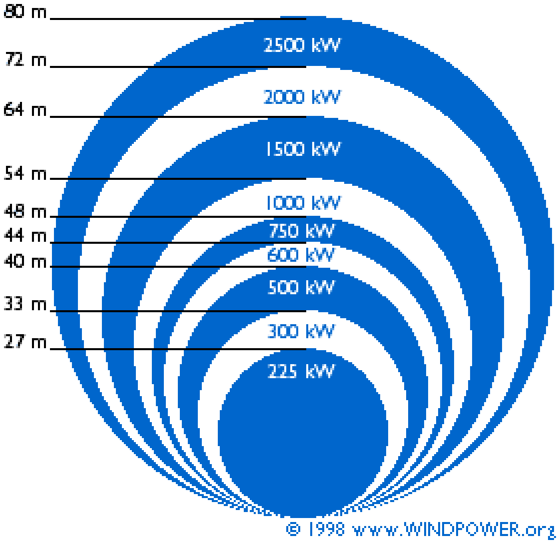


Fig. 1. Power output vs rotor diameter size [4]

Of Things Mechanical

In wind-based power generation, as in many power-gernation systems, size matters. The amount of energy a given turbine can produce from the wind follows the square of the rotor diameter; doubling the rotor size quadruples the energy output [4] (see Figure 1). There are, of course, physical limitations to how large a turbine blade can be. Not only are there limitations imposed by the choice of materials and manufacturability, there are the very real difficulties in transporting the blades to the installation site and installing them once there. [22]. The non-linear benefit from a larger blade diameter, though, will always motivate engineers to develop ever large blades for wind turbines.

In addition to the benefits of larger blades, the energy present in wind is not linear but rather varies as the cube of wind speed [3]; for a doubling in wind speed there is a potential to glean eight times the energy from that wind (see Figure 2). This, in combination with a large turbine blade diameter presents a very alluring means of producing a great deal of power from the wind: install very large turbines in a very windy location and reap the benefits of bountiful electrical power. Herein, though, is where reality confounds a

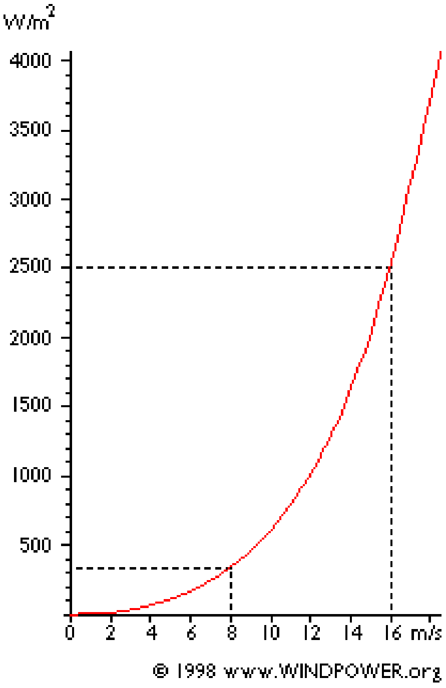


Fig. 2. Wind energy vs wind velocity [4]

simple plan and the difficulty boils down to one fact: we don't control the wind.

Though it is true that a very large turbine blade will collect a disproportionally large amount of energy from the wind, it cannot be so large that it takes only the strongest wind to turn it at any reasonable speed. Similarly, designing a wind farm so that it functions at its best when facing a very high (but infrequent) wind speed forces the farm to operate in non-optimal conditions most of the time. Given this reality, most wind farms are built with a statistical model of the region's winds in mind. Though it is always unfortunate to pass up on ”free” energy from a period of high-speed wind, it is more beneficial to be able to harvest energy from the more typical but less powerful winds. [22]

Similarly, for a wind farm to be economically feasible, it is easier to manage lower speed but more consistent winds than highly variable winds with larger deviations from the average. This has an impact not only on choice of turbine size but also which geographic areas make good candidates for development (among many other things). In fact, one of the areas of significant research related to wind-based power is developing good mathematical models for wind prediction. Knowing what the characteristics of the wind will be in the next three, six, twelve, twenty-four, and more hours serves as a great benefit for the operator of the wind farm. Such knowledge allows the operator to schedule the power production of the farm in an economically feasible way. [22]

Along those lines, atmospheric modeling is complicated in many ways by the terrain and landscape around the wind farm. Not only do mountains and hills complicate the equations, but also buildings, towers, and other man-made objects. For this reason, the best air for wind-based power generation tends to be away from the ground and the disturbances it causes. [23]. This again leads to a motivation to build larger towers and place as much of the turbine blade as possible as far away as possible from the ground (see Figure 3). In this case, there are no trade-offs involving the nature of wind itself, just the more traditional mechanical engineering limitations of materials, manufacturing and installation.

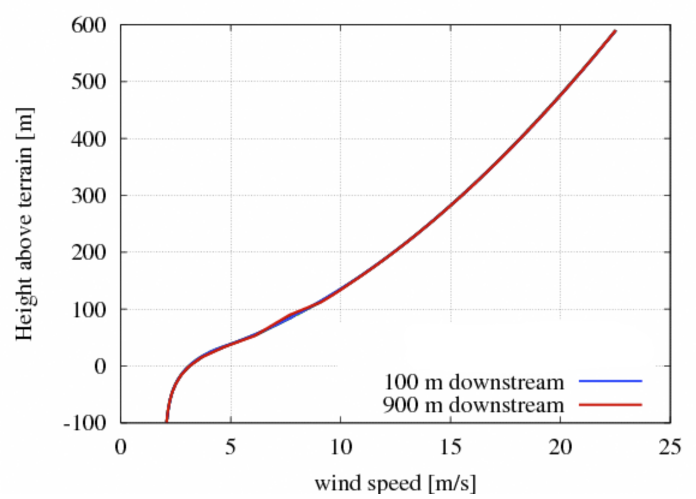


Fig. 3. Wind speed vs height measured 100 and 900m downstream from the turbine [23]

Not all physical aspects of wind-based power generation are fixed at the time of construction. There is one dynamic element that has significant impact on the power-generation element of a wind turbine: the pitch of the rotor blades themselves is often adjustable during turbine operation. This variable pitch is very useful for regulating power output and rotational speed. In fact, having dynamically adjustable blade pitch is probably the single best tool in handling the unpredictable nature of the wind as it allows for some degree of flexibility in meeting production requirements even when wind conditions make this difficult. [3]

Of Things Electrical (Mostly)

As mentioned earlier the two main electrical components in a wind-based power generator are the generator itself and the controlling/interconnecting electronics. Historically, the generator was a purely synchronous machine using a gearbox (with a fixed gear ratio) to allow for the mechanical rotational frequency to differ from the electrical frequency of the AC energy being generated. Though gearboxes are still very common, industry has moved away from the purely synchronous generator to reduce the mechanical stress on the system and provide more efficient power capture by allowing the generator shaft speed to deviate further from synchronous speed. [5] [6] [7]

There is a cost, though, in decoupling the generator mechanical frequency from the grid electrical frequency: grid stability. More traditional power plants that derive their power from

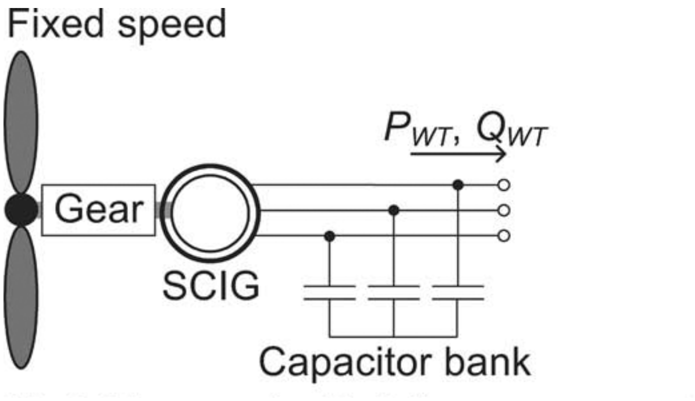


Fig. 4. Fixed speed generator with gearbox [29]

controllable energy sources are able to provide consistent and regular energy output from the grid. These larger sources of electrical power are the foundation of grid voltage, frequency regulation and grid stability [24]. These are the base generators that run at virtually 100% capacity nearly all the time and form the backbone of the electrical grid. Uncertainty is always an enemy of stability and usually the main source of uncertainty is the load on the grid.

When wind turbines were largely synchronous machines, they served to help reinforce grid stability as best they could (see Figure 4). If the wind speed was too low or too high to allow for synchronous operation the generators would take themselves offline until conditions changed to allow them to operate at synchronous speeds. Additionally, the mechanical inertia of the system would act as a stabilizing effect, particularly on the electrical frequency on the grid [8]. With the more common use of asynchronous machines as generators, that stabilizing effect has been removed.

Without the mechanical inertia, wind-based power generation cannot aid in stabilizing and maintaining the system frequency. [6] This is particularly true for wind farm installations that are not geographically near large load centers or base generation sites where the grid is more stable. In many cases, these locations are where wind resources are most suited to wind farm development as they are some distance from the unsettling effect that human population centers have on wind flow.

That being said, the most popular generator for wind turbines today is the doubly-fed induction generator (DFIG) [25] (see Figure 5). The DFIG attains asynchronous operation (up to 30% deviation from synchronous speed) by directly attaching the stator coils to the grid while indirectly attaching the rotor coils through power electronics [8]. The power electronics are what make the DFIG so popular: they are designed to provide full 4-quadrant control (both real and imaginary power, positive and negative) for the rotor power. Additionally, since not all the power from the generator is flowing through the power electronics they don't need to be rated at full generator power and are usually rated at 30% [8] [9].

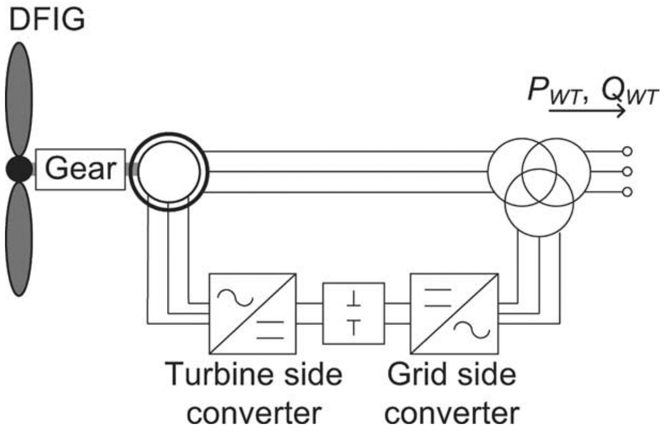


Fig. 5. Doubly-Fed Induction Generator [29]

The other generator type that is growing in popularity is the variable speed permanent-magnet (PM) generator. As in the DFIG, the generator frequency is decoupled from the grid electrical frequency to allow the turbine to run at whatever speed is most optimal for energy production. Unlike the DFIG, though, the PM generator can run at virtually any speed (mechanical limitations aside) because the power electronics are fully inline with the generator output and the grid (see Figure 6). That is, 100% of the power produced by the generator flows through the power electronics before touching the grid. [26]. Aside from the greater flexibility of generator speed, the PM generator can also run without a gearbox saving the design complexity and removing the most troublesome component in most wind-basd power generators. On the downside the PM generators are much heavier due to the strong magnets required [10] and the power electronics must be more substantial since all the generated power is flowing through them.

Concerning the power electronics, becoming more and more popular is a voltage source converter (VSC). These converters have become feasible in high power applications with the advent of a high-voltage insulated-gate bipolar transistor (IGBT). These converters are essentially back-to-back converters where the AC produced by the generator is turned into a PWM bipolar DC signal which is then converted back into AC (see Figure 5 for an example of the converter arrangement). Though

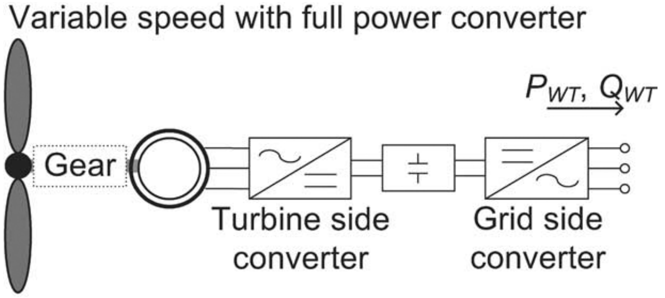


Fig. 6. Permanent magnet generator with full power converter [29]

it seems wasteful to go through two conversion processes and end up with something very much like what is being generated, the advantage is the previously mentioned four-quadrant control over the final power output. Since the power coming into the final converter is DC and the new AC signal is going to be entirely synthesized, it is possible to control all aspects of it, namely phase and frequency. This is what enables the four-quadrant control. This flexibility is a great asset to wind farm operators as it allows them be able to cleanly interface with the grid regardless of poor conditions on the generation side or the grid side. The big cost in using back to back converters, though, is obvious: increased power losses in going through an extra conversion process. [27]

III. Offshore Wind Power

Given the above discussion of fundamentals of wind-based power generation, developing wind power offshore adds a few extra layers of complexity to the design and operation of wind-farms. These complexities are accepted for good a reason; as discussed in the introduction, for some countries, there is no choice but develop offshore wind resources as there are no viable onshore options. With Europe's much higher population density, free land for turbine installation tends to be at a premium. Though the turbines themselves do not take up much space (as compared to a coal-fired power plant) and produce no air pollution, not all members of the public appreciate having a wind turbine in their backyard's. There is also an issue with noise generated by the tips of the turbine blades and some find the big windmills unsightly. Both of these issues can be eliminated by moving the turbines offshore and out of sight. [12]

The relatively smooth terrain of the ocean creates a much more accessible and friendly wind-resource to develop. The lack of elevation changes and man-made structures made wind modeling easier and allows for a simpler and more predictable operation once the farm is built [13]. This also allows for lower tower heights as there is less variation in wind speed with elevation; lower towers are cheaper towers. Due to lower temperature differentials between the ocean and the air above it, there is less turbulence as well which leads to longer turbine lifetimes and more reliable operation [14].

In addition to more reliable winds, the offshore winds tend blow at a higher speed; a 20% increase in wind speed offshore is not uncommon. Since the energy in the wind follows the cube of the speed, this increase is actually a 73% increase in production potential. Though an actual operating wind farm would not expect to realize all of that gain, the potential is non-trivial and once installed, could be capitalized on for years [14].

These advantages of off-shore development come at a price. Much of the complexity of current off-shore installations has been minimized as the wind farms have not been placed far from shore. The geographic near-ness allows for a relatively short cable run back to the main onshore grid, the use of turbine foundations that rest on the sea bed floor and relatively easy access to the wind farm for inspection and maintenance. As offshore wind farms continue to be developed, these farms will be built in deeper and deeper water require more and more complex installations. For now, though, the current shallow-water installations present challenges enough.

Despite the fact that these installations allow the turbine foundation to rest on the sea floor, waves and currents can cause erosion of the sea floor around the plyon foundation. This erosion forms what are called scour holes and due to the shallow depth of the water, these holes can grow to be quite large, sometimes as large as the turbine tower itself. [15]. Obviously, having sea bed erosion of this magnitude at the foundation of a wind turbine tower is undesirable. To mitigate the effects of scour, gravel and stones are usually piled around the foundation of the tour. This is an effective preventative measure but one that requires maintenance (adding more gravel and stones over time).

In addition to eroding the sea bed around the base of the turbine, the wind and waves of the ocean create significant loads on the tower itself. Theses loads are highly complex and difficult to analyze requiring significant engineering effort to build a foundation and tower structure to handle the loads. Once the design is complete, as mentioned above, the installation process itself is difficult leading to significant costs to install the complete foundation/tower/turbine assembly. All of this extra per-installation costs motivates offshore wind farm developers to create as much energy as possible from each tower which results in relatively large turbines and generators. [1]

Lastly, all offshore wind farms suffer the difficulty of easy access for maintenance. There must be docking structures included on the tower for whatever means of transportation will be used (sea- and/or air-bourne) for the maintenance. The transportation to the tower can be costly and depending on the weather conditions, access to the towers may be limited by high wind and waves. This lack of easy maintenance access places a higher premium on high reliability system components; this will grow to be even more the case as installations move further offshore and into more inhospitable areas. [18]

Transmission of power back to the onshore grid also presents some difficulties. The first and most obvious of which comes from to need to use undersea cabling to transport the energy. As mentioned above, almost all current installations are in shallow water areas and for these situations, laying the power cable on or slightly underneath the sea bed floor has seemed a feasible option. At this time, it is not economically feasible to bury the power transmission cabling deep enough to ensure protection from anchors and fishing equipment. Similarly, redundant cabling is also not an economical option. Due to these economic limitations, nearly all offshore wind farms use a single power transmission. Depending on the location of undersea cable repair ships, this places the operator at risk for significant down-time if damage to the cable occurs. [1]

Integrity of the cable aside, there are electrical difficulties caused by the long transmission distance from wind farm to the onshore grid. These long cable runs tend to require a lot of reactive power due to the capacitance in the cable. This reactive power must be generated by the offshore wind farm and as the cable length increases, so does the reactive power requirement. To compensate, the wind farm must raise the transmission voltage. This cannot be done without limit and effectively creates a maximum length of cable that can be used for AC power transmission for a given transmission voltage. [16]

In addition to the reactive power requirements of the cable, an AC power transmission system directly links the onshore grid with the offshore wind farm. Depending on the generator type and structure of the wind farm, this can lead to stability problems between the two and difficulties in efficiently integration the generation capacity. [17] This problem can be compounded by the fact that the grid tie-in point for the wind farm will tend to be relatively far from the base generation capacity and the grid itself tends to be weak at this point. Lastly, a direct AC link presents all the traditional difficulties of grid fault tolerance while compounding these difficulties by preventing easy access for repairs and maintenance. [30]

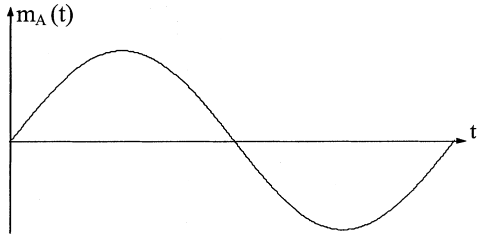
Alternatively, rather than using AC voltage transmission from the wind farm to the onshore grid tie-in, it has been proposed that high-voltage DC (HVDC) be used instead. HVDC experiences none of the reactive power loading which would allow for less energy loss in the cable itself. Especially considering the inherent point-to-piont nature of the power transmission from farm to shore, HVDC seems like a good choice. The big cost associated with HVDC, though, is the additional cost for the power electronics and the energy loss from the electronics themselves.

The most promising technology for a HVDC link is actually the same one mentioned previously in reference to generator control: pulse-width modulated voltage-source converters (PWM VSC, or often, simply VSC). For all the same reasons that it is attractive to use for an individual generator, VSC can solve many of the problems presented by an AC connection to the grid(see Figure 7 for an example of a PWM VSC waveform). By abstracting the power generated by the wind farm from the grid itself, a lot of flexibility is gained.

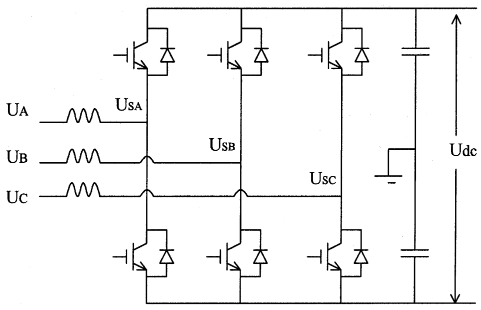
As in the case of the generators, full four-quadrant control of the power is available, allowing the HVDC converter station at onshore side to adept the voltage, phase, and frequency to meet the needs of the onshore grid. Faults and failures on the grid do not translate across the converter to adversely affect the generators allowing them to continue to operate normally through the failure event.

The cost of VSC for HVDC is, again, the power electronics. Not only are the electronics expensive but they also have power loss associated with them [1]. Despite these obvious downsides, HVDC can solve the problems of long transmission cable runs and provide flexibility that an entirely AC system cannot.

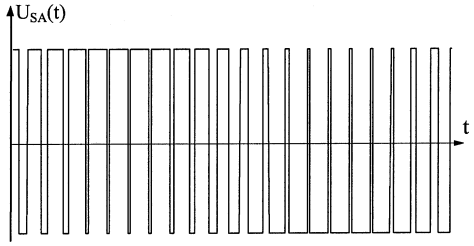
In addition to transferring the power from offshore to onshore, there is also the issue of collecting the power from the individual generators on the wind farm. The choice of method for doing this is highly dependent on the choice of generator and must be developed side-by-side with the individual generator itself as well as the offshore to onshore transmission system.



(a) AC waveform as input to the VSC circuit



(b) VSC circuit to convert AC to DC



(c) Bipolar pulse-width modulated DC output

Fig. 7. Pulse width modulation voltage source converter [30]

Traditional onshore wind farms typically use DFIG with an isolation transformer up near the generator in the nacelle or down at the base of the tower. The output from a DFIG is 60Hz AC and this power is collected at a substation where it is stepped up to a very high voltage for transmission. This architecture is a viable option for offshore wind farms as well and is used in many installations to date [19]. Unfortunately, the location for the isolation transformer on offshore wind farms must be in the nacelle which places further demands on the tower and foundation of the turbine. Also, in addition to building towers for all the turbines, a centralized sub-station platform must be built.

An alternative proposal in [18] calls for a DC based distribution system within the wind farm. The output from the generator could be coupled through a transformer and then rectified. This rectified current could be serial- or shunt-connected through all generators and then be simply transmitted to shore over a HVDC cable. The onshore substation would then convert the power to AC and interface it with the grid.

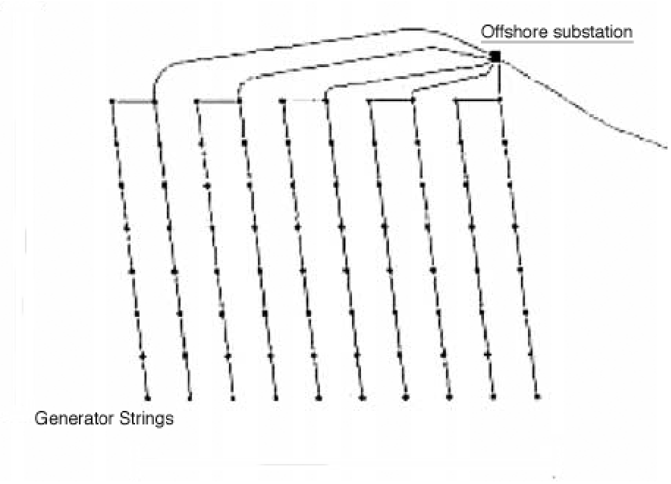


Fig. 8. Turbine arrangement of Horns Rev Offshore Wind Farm near Denmark [1]

This architecture would require no centralized sub-station but still requires transformers at each generator.

IV. OVERVIEW OF DENMARK'S HORNS REV

As a means of demonstrating the recent commercial offshore wind farms, this section will provide a short overview of Horns Rev A, one Denmark's offshore wind farms. There are other planned and in construction offshore wind farms throughout the world using newer technologies but Horns Rev was one of the first large-scale installations and as such has served as a model and test case for other such installations. There is a second planned phase to the Horns Rev installation (B) but it is not operational at this time.

Horn's Rev A is located roughly 15 km from the coast of Denmark and consists of 80, 2MW generators giving the entire farms a rated capacity of 160MW and can nominally produce 160 million kWh every year; this is enough energy to power 133,000 Danish households [14]. The installation was brought online in April 2002 at a cost of 270 million euros (305 million USD at the time of completion) [21]. The total land area taken by the wind farm is roughly 30 square km (see figure 8 [1].

Each tower is designed using a "mono-pile" construction where the tower is driven into the seabed floor for extra stability. [14] The towers are 70m tall. [21]. The turbines at the top of the tower are three-bladed with a sweep diameter of 80m [21] this is 25% longer than the wingspan of a Boeing 747 [14]. The ocean depth over the installation is 6 - 13 m at mean sea level with wave heights as high as 8 m and ocean currents moving at an average of 0.88 m/s [20]. The mean wind speed in the area is 8 - 10 m/s (18 - 22 mph) and is as high as 20 m/s (45 mph) on a regular basis.

Each tower consists of the turbine, gearbox, 2MW DFIG, and 50Hz transformer. The weight of the generator and transformer alone is estimated at 15000kg (15 tons) [18]. Each tower also includes a hoist platform that allows the tower to be accessed for service by helicopter if travel by sea is not feasible. Additionally the towers are equipped with food, sleeping bags, and toilets so that maintenance personnel can survive on the tower for a brief time if inclement weather prevents sea or air access. [14]

The output from the transformer on each turbine is nominally 36kV [17]. A string of 8 generators are connected in series at this voltage and then connected to the offshore substation creating a total of ten independent strings of generators. [1]. The substation has a 1000 ton transformer [18] which switches the 36kV generation system voltage up to 150kV to transmission to the shore [1]. The main transmission cable that runs to shore three-core AC cable and is compensated by a 75MVAR reactor which helps to regulate the voltage and keep it below 170kV (Western Denmark to which Horns Rev connects operates at 165kV to 1689kV) [16].

Though Horns Rev was built using an architecture very similar to something that you might find in an onshore wind farm, wind farms that are currently being built will likely employ some of the techniques discussed here, particularly HVDC as Horns Rev has demonstrated the difficulty of using AC transmission at even close distances from shore [16]. Also promising is the use of power electronics that allow individual generators and/or onshore substations to achieve full four-quadrant control. This could be key in providing an attainable way to allow offshore wind farms to add to and aid grid stability. As more efficient and higher rated electronics are developed we are sure to see the adoption of these power converters in great numbers.

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