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The X-Rotor Offshore Wind Turbine Concept

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Abstract. The following paper provides an overview of a novel wind turbine concept known as the X-Rotor Offshore Wind Turbine. The X-Rotor is a new wind turbine concept that aims to reduce the cost of energy from offshore wind. Cost reductions are achieved through reduced capital costs and reduced maintenance costs. The following paper includes results from an early feasibility study completed on the concept. In the feasibility study exemplary designs were created and structural analyses were carried out. Turbine capital costs and maintenance cost of the X-Rotor concept were then roughly estimated. X-Rotor turbine costs and O&M costs were compared to four existing wind turbine types to investigate potential cost savings from the X-Rotor concept. Results show that the X-Rotor has potential to reduce O&M costs by up to 55% and capital costs by up to 32%. The combination of the capital cost and O&M cost savings show potential to reduce the CoE by up to 26%.

1. Introduction

Vertical axis wind turbine (VAWT) designs have as yet been unsuccessful as far as large scale commercial generation of electricity is concerned. The only commercial manufacturer of consequence, Flowind Inc., supplied more than 100 MW (over 500 wind turbines) of the Darrieus “egg-beater” type VAWT to Californian wind farms in the 1980’s before becoming bankrupt in 1997. VAWT Ltd. in the UK (a subsidiary of Sir Robert McAlpine and Sons) built a number of prototypes up to 500kW rating of the H-rotor type. The 500kW VAWT 850 prototype ran for a period on a test site at Carmarthen Bay. High torque levels on the main transmission shaft caused a number of failures and the designs were never commercialised.

Compared to state of the art horizontal axis wind turbine (HAWT) designs, there are two fundamental challenges for VAWT design. First, the aerodynamic efficiency is intrinsically lower and a VAWT must be 15% to 20% larger than a HAWT in order to produce the same power. Second, the optimum rotor speed is less than half that of comparable HAWTs and the drive train has more than double the rated torque for any given power rating, therefore, tends to be at least twice as heavy and expensive. In respect of these key issues, the Flowind design avoided high torque by running at higher than optimum speed but these designs produced about half the energy output of a similarly rated HAWT.

In a VAWT with a V-rotor, the drive train components can be situated at ground level with associated maintenance and assembly benefits. The V-VAWT requires the least rotor material of all VAWT configurations for the required swept area and the low centre of thrust has advantages for offshore siting. Unfortunately, it suffers from extreme overturning moments on the main bearing. In a novel concept proposed by Sharpe [1], large transverse aerodynamic surfaces towards the ends of the blades are added to the rotor to cause some cancellation of the overturning loads. However, the large rotor and resulting intrinsically low rotational speeds drive up the weight and cost of the dive-train.

The X-rotor concept is a radical rethink of the VAWT that directly addresses its disadvantages, see Figure 1. (These images are provided to give a rough idea of how the concept will look. They are not design drawings.) It is essentially a heavily modified V-VAWT, thereby, retaining some of the advantages of that concept. Similarly, to the Sharpe concept, transverse blade elements are added to the main rotor, the upper half of the X, to reduced overturning moments on the main bearing but in a simplified manner as the lower half of the X, keeping down the size and weight of the rotor. The rotor has relatively conventional blades angled both up and down from the ends of a relatively short, stiff cross-arm. Attached to ends of the lower half of the X-rotor are two secondary horizontal axis rotors, see Figure 1. The role of the lower half of the X-rotor is, thus, to reduce the overturning moment and support the secondary rotors but it more than pays for itself by, also, increasing the energy capture of the turbine.

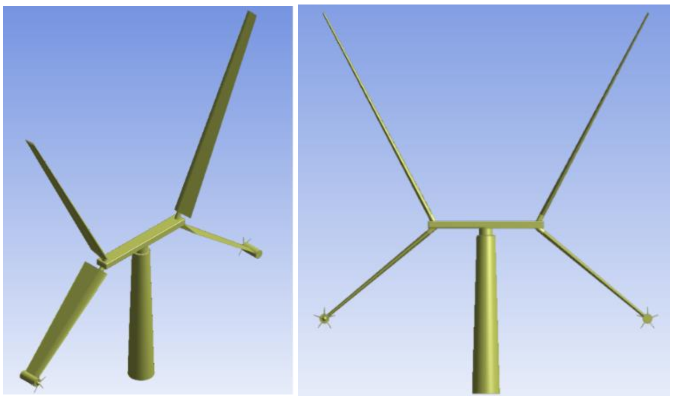

Figure 1. Design representation of the X-Rotor Concept

The secondary rotors primary role is to provide power take-off. Because the rotor speed is very low and the rated torque is very high, a fundamental issue for large scale VAWTs is in providing power take off. Irrespective of the technology used, whether direct or indirect drive, conventional systems for power take-off from the main rotor shaft have a weight and cost which is directly proportional to torque rating. Being able to dispense with the drive-train and replace it by direct power take-off from the secondary rotors potentially has a substantial cost benefit.

As described above, the X-Rotor concept is a hybrid of vertical and horizontal axis wind turbines. Unlike conventional vertical axis wind turbines, the purpose of the vertical axis rotor is not for power take-off. Rather, it is to considerably increase the wind speed impacting on the secondary horizontal axis rotors. The size of the secondary rotors is consequently much reduced and their rotor speed much increased, sufficiently to enable the power take-off to be by direct drive using a conventional generator, i.e. no gearbox or bespoke generators are needed. Ignoring generator losses, the efficiency of the secondary rotor power take-off is $P/(T*\Omega)$, where P is the aerodynamic power, T is thrust on the rotor and Ω is the rotational speed of the X-rotor. To keep this efficiency high, the secondary rotor is designed to have lower optimal tip speed ratio, approximately 4, and a lower aerodynamic efficiency than normal. However, since the wind speed relative to the secondary rotor varies sinusoidally as the X-rotor rotates, the average efficiency over a rotation is about 5% higher than that with a constant wind speed. Consequently, the overall efficiency of the secondary rotor power take-off system approaches 90%. Since the optimal tip speed ratio for the X-rotor is, also, approximately 4, the overall tip speed ratio for the combined X-rotor and secondary rotors is approximately 16. Hence, the maximum tip speed for the secondary rotors is 160m/s to 180m/s. (Since the X-rotor concept is for offshore deployment, noise is not considered to be an issue.) Consequently, the characteristics of the horizontal axis secondary rotors are substantially different than existing horizontal axis wind turbines, being designed for low tip speed ratios and low aerodynamic efficiency. A further feature of the secondary rotor power take-off system is that, due to the relative wind speed on the rotors being induced by the near constant rotation of the X-rotor, the torque acting on it varies much less than the torque acting on a conventional power take-off on a VAWT.

The secondary rotors have the additional role to control the rotor speed about the vertical axis in below rated wind speed. This is achieved by varying the rotor speed of the secondary rotors to adjust their thrust. A fairly conventional below rated control strategy is proposed whereby in below rated wind speeds the rotor speed about the vertical axis is varied to maximise the aerodynamic efficiency of the X-rotor and in above rated wind speeds the rotor speed about the vertical axis is kept constant. The secondary rotors are designed to ensure that they are at optimal tip speed ratio when the X-rotor is at optimal tip-speed ratio. The variable speed operation of the secondary rotors is achieved by independently varying the frequency of the AC power generated at each rotor. The power electronics to provide this frequency variation are housed at the hub of the X-rotor. It is proposed to use a rotory transformer to transfer power from the rotating hub to the stationary support structure, i.e. an electrical machine for which the frequencies of the stator and rotors differ by the rotational speed of the hub so that their magnetic field rotate with the same speed. The frequency of power delivered to the rotary transformer is varied in line with the rotational speed of the hub by the power electronics. [2]

To assist with shut-down and to provide over-speed protection in the event of faults, it is proposed to pitch the blades on the upper half of the X-rotor. In below rated operation, the capability to pitch the blades could be exploited to increase the aerodynamic efficiency of the X-rotor by cyclical pitching. Doing so has the potential to increase the efficiency by 10%. In above rated operation, the pitching capability is exploited to the control the rotational speed of the X-rotor about the vertical axis.

Because of the simplicity of the power take-off systems in the X-rotor concept, its light weight and closeness to the surface of the sea, 20-25m, the O&M costs are expected to be much reduced compared to alternative wind turbine concepts. For example, almost all repair and maintenance could be undertaken without recourse to heavy lift vessels. Given that the total weight of the power take-off system is under 10 tonnes, they could be made replaceable so that maintenance and repair can be done onshore.

Some of the potential advantages of the X-Rotor concept are summerised below. Not all are investigated in this paper, but are listed below for overview/introductory purposes:

1. Cost of energy reduction in comparison to similar wind energy technologies due to:
   - Lower capital costs (No gearbox, no requirement for bespoke multi-pole generator, no twist in blades)
   - Lower operation & maintenance costs (Greater reliability and the need for heavy lift vessels almost eliminated)
2. Floating platform potential due to:
   - Lower centre of gravity than current technologies
   - Lower centre of thrust and reduced overturning moments allowing for a smaller/cheaper floating platform
3. Up-scaling potential due to:
   - The ability to add additional secondary rotors
   - Up-scaling issues for horizontal axis wind turbines (HAWTs), such as size and mass of the drive-train at hub height, are avoided and some such as, gravitational blade loads, are reduced.

The remainder of this paper consists of 5 sections. Those sections include an overview of an exemplary X-Rotor concept design, a detailed structural analysis on the X-Rotor main structure, an O&M cost analysis, a short section on the CoE of the X-Rotor with some simple comparisons to existing offshore wind turbines and lastly a conclusion and further work section.

2. Exemplary X-Rotor Configuration

In terms of primary and secondary rotor design, the optimised X-Rotor concept configuration is yet to be determined. However, the design of the turbine is subject to a number of constraints. Aerodynamic considerations impose a maximum value on the tip speed of the blades of the second rotors. In a system each secondary rotor directly driving a generator without the need for a gearbox, generator considerations impose a minimum value on the rotational speed of the second rotors. Taking the constraints into account, the mechanical power extracted by the first rotor is proportional to the fifth power of the tip speed of the blades of the second rotors, $\boldsymbol{v_{ts}}$, and inversely proportional to the cube of the tip speed ratio of the blades of the second rotors, $\boldsymbol{\lambda_s}$, and the square of the rotational speed of the

second rotors, $\boldsymbol{\Omega_s}$; that is, the mechanical power is proportional to $\boldsymbol{v_{ts}^5/(\lambda_s^3\Omega_s^2)}$. Nevertheless, designs that meet all the requirements do exist.
In an exemplary arrangement that meets all the requirements, the rotor comprises an upper part with two blades in the form of a V and a lower part with two blades in the form of an inverted V. A secondary rotor is attached to the tip of each lower blade. Each secondary rotor directly drives a generator, with 4 pole pairs and a nominal frequency of 25Hz. The primary rotor has maximum aerodynamic efficiency at a tip speed ratio of 4.65. The secondary rotors operate at a tip speed ratio of 3.13 with an aerodynamic power coefficient of 0.27 and an aerodynamic thrust coefficient of 0.3375. (The combined tip speed ratio, the product of the tip speed ratios for the first and second rotors, is 14.57.) The power extracted from the wind by the primary rotor, $\boldsymbol{P_F}$, is $\boldsymbol{P_F = 28,387V^5/\Omega_s^2}$, where $\boldsymbol{V}$ is the wind speed. When the rotational speed of the secondary rotors is 39.21rad/s and rated wind speed is 12.66m/s, the tip speed for the secondary rotors is 184.3m/s and the mechanical power extracted from the wind by the primary rotor is 5.99MW. The secondary rotors deliver 5.02MW of mechanical power to the generators in 12.66m/s wind speed, 84% of the power extracted from the wind by the primary rotor, increasing to 5.50MW in 20m/s wind speed, 92% of power delivered by the primary rotor. The secondary rotors have a combined area of 138.8m^2. The primary rotor has a maximum value of aerodynamic power coefficient of 0.39 and an area of 12,351m^2.

3. Structural analysis of primary rotor blades for two-blade design
The following sub-sections provide an overview of the structural analysis carried out on an exemplary two blade X-Rotor concept, as shown in Figure 1.

3.1 Primary rotor Blade design
The primary rotor blades consist of symmetric aerofoil profiles, which are strengthened by two spar caps that take most of the bending loads. The spar caps are connected by two parallel shear webs. The blade shell is also reinforced at the leading and trailing edges. In Figure 2 the layout of blade internals is presented. The dimensions of the primary rotor blades can be seen in Section 3.2.1.

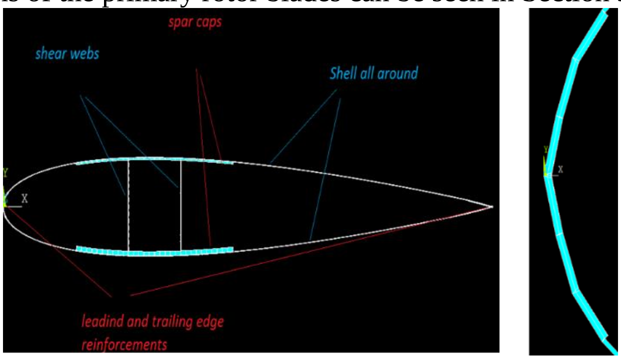

Figure 2: The layout of internals with detail for the leading edge reinforcement.

According to the wind turbine design guidelines [3], [4], the wind turbine blade structure should be able to pass the followings checks:
- Ultimate strength
- Buckling
- Fatigue
- Deflection

The deflection control refers to clearance between tip of the blade and tower for horizontal axes turbines. Due to the innovative configuration of X-Rotor, this check is irrelevant here, but the deflection values should not be too high, since unfavourable aerodynamic damping might occur.

3.2 Turbine loads

X-rotor's loads are obtained based on the design configurations for the turbine operational and extreme wind conditions. The operational and extreme loads are required for the sake of turbine's power production adjustment, fatigue analysis and the design of blade section internals.

3.2.1 Operational loads

The operational loads are obtained from simulation results using the QBlade software. The upper and lower blades are 100 m and 65 m long at the coning angles of 30˚ and 50˚, respectively. The chord lengths of the upper and lower blades are 10 m and 14 m respectively at the blade roots. The blades reduce linearly to chord lengths of 5 m and 7 m at the blade tips. The blades are designed in such a way that the distances between the pivoting line of the blades and the leading edge are kept constant along the blades, which are equal to 2.5m for the upper blades and 3.5m for the lower blades. As a result of the previously mentioned blade configurations, the leading edges are positioned on a straight line, whereas the trailing edges from an inclined line along the blades. The turbine is designed to operate between the mean wind speed of 4 and 25 m/s. Simulation of the operational loads are performed for the following wind speeds: 4.5, 6.5, 8.5, 10.5, 12.5, 14.5,16.5, 18.5, 20.5, 22.5, 25 m/s.
The total power extracted from the wind at 12.5 m/s is 6.47 MW, but electrical power is inevitably lower due to losses. Figure 3 depicts the correspondence between rotational speed and wind speed together with an adjusted power curve of the X-Rotor (with an assumed efficiency of 90%).

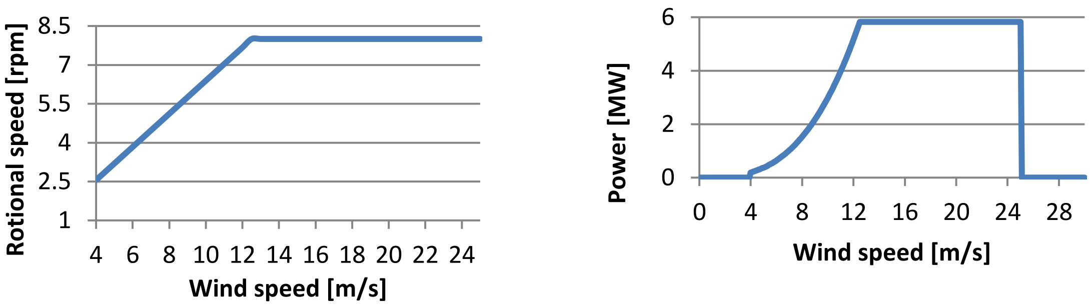

Figure 3: The variation of rotational speed with wind speed

3.2.2 Extreme loads

Extreme loads correspond to the parked position of the turbine, where the 50-year occurrence extreme mean wind speed of 52 m/s is acting and a simultaneous loss of grid connection occurs (DLC 6.2 of IEC 61400-1 [3]). Thus, there is the possibility for the turbine to be caught in a locked position with the wind blowing parallel to the rotor plane. To simulate this situation, Ansys CFX is used. The pre-dimensioning of the cross sections of the blades is performed by imposing the stress in the material not to exceed the allowable value when the structure is subjected to the extreme loads. A partial safety factor of 1.35 is chosen for loads. For the short term verification, the partial safety factor for the material is set to 2.2 [3], and 1.85 for buckling [5].
The blade is divided into 17 elements having 18 sections, starting with NACA 0025 at the root and ending with NACA 0008 at the tip. Pre-dimensioning is performed for each section, where the profile is changing. The bending and edge moments are computed in each section from the Ansys CFX analysis results. Afterwards, for each section a finite element (FE) model of the blade section with a constant cross section is developed, using shell elements.
According to [5] a structure, whose load-bearing laminate consists of unidirectional carbon-fibre reinforcement layers, may qualify, with regard to short-term and fatigue strength, for a simplified strain verification, provided a high laminate quality can be verified. The simplified strain verification states that the strain along the fibre directions shall remain below the following design values:

- tensile strain $\varepsilon_{Rd,t} \leq 0.24\%$
- compressive strain $\varepsilon_{Rd,c} \leq |-0.18|\%$

Dimensions are adopted such that the above strain constraints can be fulfilled together with the stress criteria. Therefore, there will be no need for a detailed fatigue check under these circumstances and the rigidity condition may be fulfilled from the beginning.

For all sections the position of the internals relative to the leading edge is:

- leading edge reinforcement ends at 1% of the chord;
- spar caps are starting from 15% and ending at 47% of the chord;
- shear webs are equally spaced inside the spar caps;
- the trailing edge reinforcement begins at 99% of the chord.

The locations of the internals are determined by trial. The spar caps are positioned to be far from the symmetry axis so as to achieve maximum bending resistance, but keeping the mass as low as possible. Table 1 represents the details of blades cross sections. The obtained mass for an upper blade is 40500 kg and for a lower one 23384 kg.

Section	NACA profile	Spars thickness upper blades [mm]	Spars thickness lower blades [mm]	Shear webs thickness upper blades [mm]	Shear webs thickness lower blades [mm]	Shell thickness all blades [mm]	Reinforcements thickness all blades [mm]
1	0025	55	20	20	10	5	5
2	0024	53	19.41	19	10	5	5
3	0023	51	18.82	19	10	5	5
4	0022	48	18.23	18	10	5	5
5	0021	46	17.64	17	10	5	5
6	0020	45	17.05	17	10	5	5
7	0019	43	16.47	16	10	5	5
8	0018	40	15.88	15	10	5	5
9	0017	37	15.29	14	10	5	5
10	0016	35	14.71	13	10	5	5
11	0015	30	14.11	10	10	5	5
12	0014	25	13.52	10	10	5	5
13	0013	20	12.94	10	10	5	5
14	0012	15	12.35	10	10	5	5
15	0011	10	11.76	10	10	5	5
16	0010	10	11.17	10	10	5	5
17	0009	10	10.58	10	10	5	5
18	0008	10	10	10	10	5	5

Table 1. Details of blades cross sections components

Based on the above masses the two bladed system shown in Figure 1 has a primary rotor mass of 127768 kg. This mass is in line with masses of existing wind turbine rotors of similar rated power, which is relevant for the CoE comparison in Section 5.

3.3 Fatigue evaluation

The tensile and compressive strains under operational loads at the highest mean wind speed, namely 25 m/s, are lower than those under extreme loads. In such a case, according to existing standards, a detailed fatigue check is unnecessary. Nevertheless, it is recognised that a detailed fatigue check is required and will be undertaken during the next phase of the X-Rotor concept's feasibility analysis, once a full aero-elastic model has been developed.

3.4 Buckling verification

DNV-GL recommends for the stability analysis that the partial safety factor for materials be applied to the mean values of the material stiffness in order to determine the design values of the component resistances. Based on those guidelines a safety factor of 1.85 is obtained [5].

For upper and lower blades FE models are constructed using beam elements. For each of the 17 elements of on each blade an average of the initial and ending section is used for modelling. The extreme load is applied as pressures on each element. For the lower blade a concentrated mass is put at the tip to simulate the nacelle. For the initial control, the buckling eigenvalue analysis, taking into account the first ten modes, is performed. The resulting buckling load factors of the upper and lower blades are computed to be 2.67 and 9.85. These values are so high that the blades will not become unstable under the extreme loads and as such, nonlinear buckling analysis seems to be no longer necessary.

3.5 Modal analysis
Blade modal analysis is performed, in order to control the blades natural frequencies according to the Campbell plot. For each lower blade a concentrated mass without rotational inertia is added at the blade tip, to be able to simulate the nacelle of the secondary rotor. The smallest natural frequencies of the upper and lower blades are respectively 0.59 and 0.52 Hz. Therefore, the resonance phenomenon for the upper and lower blades due to the resulted harmonic rotational peaks of the rotor within the operational wind speeds will be unlikely.

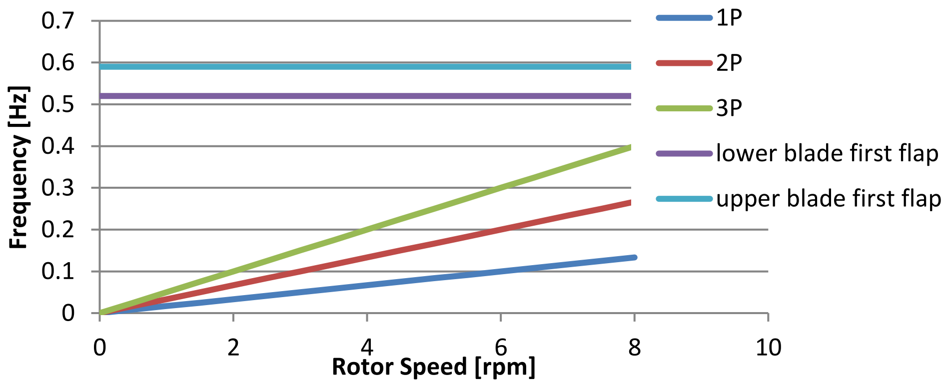

Figure 4: Campbell plot of rotor blades

4. O&M Cost Analysis

The O&M costs of existing offshore wind farms make up approximately 30% of the levelised cost of energy for a given offshore wind farm [6]. The X-Rotor offshore wind turbine has the potential to reduce the O&M costs for a number of reasons. The primary reason is the X-Rotor does not contain either of the two components that contribute most to offshore wind turbine downtime in existing wind turbines, namely the gearbox and/or a multi-pole generator. Secondly the X-Rotor does not require a jack up vessel for drive train failures, substantially reducing O&M vessel costs. The following subsections outline the methodology and results obtained from comparing the X-Rotor O&M costs to the O&M costs for existing offshore wind turbines.

4.1 O&M Cost Modelling Method
In order for X-Rotor O&M costs to be compared to existing offshore wind turbines the O&M costs for the X-Rotor must first be calculated. A comparison to O&M costs for existing wind turbine types can then be carried out. To ensure a like for like comparison a hypothetical site was used for each wind turbine type in the comparison. The hypothetical site is located 50km from shore and contains the same environmental (wind speed and sea state) conditions for each turbine type.
To calculate the O&M costs for the X-Rotor the same methodology and O&M cost model from [6] were used. The O&M model chosen for this analysis was the one reported in [6, 7]. The model is a time based simulation of the lifetime operations of an offshore wind farm. Failure behaviour is implemented using a Monte Carlo Markov Chain and maintenance and repair operations are simulated based on available resource and site conditions. The model determines accessibility, downtime, maintenance resource utilisation, and power production of the simulated wind farms. The outputs of the model for this work

were the operations and maintenance costs for a hypothetical wind farm located 50km offshore consisting of 100 X-Rotor offshore wind turbines.
The O&M cost model and model inputs were adjusted to represent the X-Rotor as detailed in the following paragraphs.
The model inputs for the X-Rotor O&M cost modelling described above included:

a) Site wind speed and sea state data
b) Wind turbine component failure rates
c) Wind turbine component repair times
d) Wind turbine component repair costs
e) Wind turbine component number of technicians required for repair
f) Vessel operating parameters and costs

Further detail on each input is provided below:

a) The site wind speed and sea state data were taken from reference [6, 9]. Data included wind speeds, wave height and wave period data from the FINO platform in the North Sea.

b, c, d, e) The wind turbine component failure rate, repair times, repair costs and "number of technicians required for repair" inputs came from field data. They were obtained from an empirical analysis of existing operational wind turbines as detailed in [6,9,10]. Inputs b, c, d and e were assumed the same for a number of the wind turbines components that are common between the X-Rotor and existing wind turbines, for example, tower, blades, pitch system etc. Examples of X-Rotor O&M model input differences from existing wind turbines are the gearbox failure rate, repair times, repair costs. Those inputs were removed, while the generator failure rate, repair times, repair costs were doubled (as a conservative estimate to represent the two lower rated generators). Additionally, the failure rate, repair times and repair costs of the X-Rotor power take off were added and assumed to be the same as a wind turbine transformer.

f) Vessel costs were assumed the same as [6].

Once all model inputs were adjusted to represent the X-Rotor, the O&M cost model was populated and utilised to determine the X-Rotor O&M costs. The results were then compared to O&M costs for 4 different existing wind turbine types at the same hypothetical wind farms. The four existing wind turbine types for comparison are detailed in Figure 5. Results of the comparison are shown in subsection 4.2.

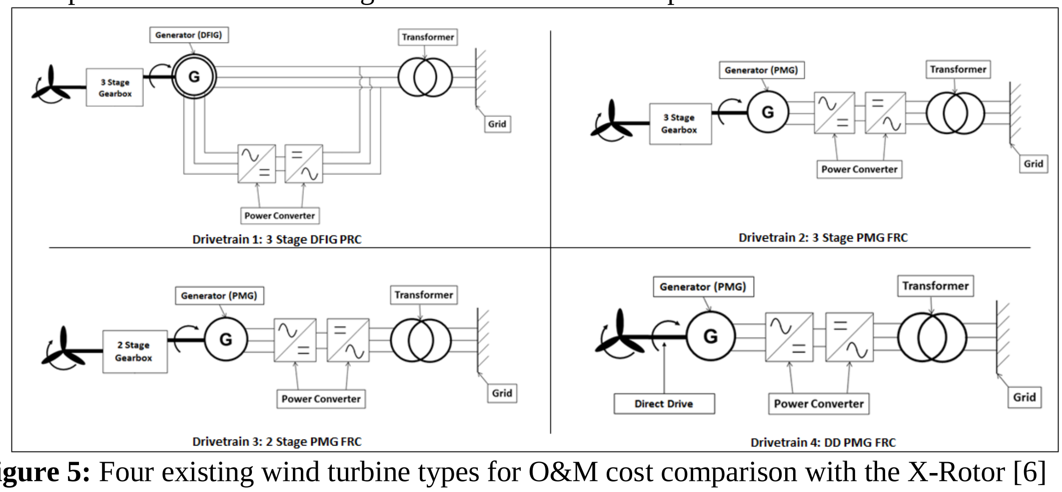

Figure 5: Four existing wind turbine types for O&M cost comparison with the X-Rotor [6]

4.2 Comparison of O&M costs

Figure 6 shows the O&M cost comparison between the X-Rotor and the 4 existing wind turbine types described in the previous section. When compared to the average O&M cost of existing wind turbine types the X-Rotor has ~43% lower O&M cost. It can be seen that the X-Rotor has ~55% lower O&M costs than the worst performing existing wind turbine type (3 Stage DFIG) and ~25% lower O&M costs than the best performing existing wind turbine type (DD PMG). It is expected the X-Rotor O&M costs will be further reduced once future work is carried out on the modelling methodology to capture additional X-Rotor inputs. At the moment conservative assumptions were made for all uncertainties in model inputs, for example around failure rates, repair times, repair costs etc. A conservative approach was adopted to ensure X-Rotor O&M cost benefits were not over estimated.

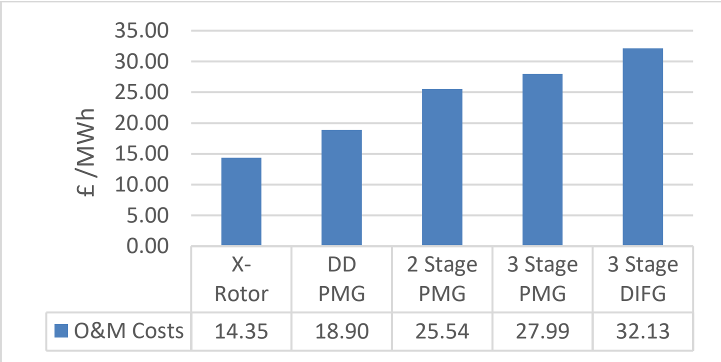

Figure 6: Comparison of O&M costs with existing wind turbine

5. CoE Comparison

In order to complete an early stage CoE comparison between the X-Rotor and existing offshore wind turbines, inputs from the CoE equation for existing turbines were compared with the same inputs for the X-Rotor. The CoE inputs for comparison in this paper are O&M costs and turbine costs, all other costs are assumed the same for the purpose of this comparison.

- Cost of energy savings from O&M

As seen in section 4.2 the X-Rotor has lower O&M costs than each of the four existing wind turbine types. 55% lower O&M costs than the 3 Stage DFIG configuration, 49% lower than the 3 stage PMG, 44% lower than the 2 stage PMG and 25% lower than the DD PMG configuration. Based on O&M costs making up 30% of the overall cost of energy [6] the previously mentioned O&M costs saving equate to X-Rotor CoE savings of 17% when compared to the 3 stage DFIG configuration, 15% when compared to the 3 stage PMG configuration, 13% when compared to the 2 stage PMG configuration and 7% when compared to the DD PMG configuration. On average across all 4 existing wind turbine types, the X-Rotor achieves a 13% CoE savings through O&M cost reductions. It should be noted that all O&M cost savings presented in this section are based on the assumption that failure rates, failure costs, number of technicians required for repair and downtimes of components that are used in both the X-Rotor concept and existing turbines are assumed the same.

- Cost of energy savings from turbine costs

Turbine capital costs and turbine component costs for the 4 existing turbines shown in Figure 5 are provided in [11]. For the X-Rotor turbine cost comparison it is assumed that outside of the gearbox and generator all other turbine costs are the same as the existing turbines. This assumption is based on the fact that outside of the gearbox and direct drive generator the main difference between the X-Rotor and existing wind turbines is the X-Rotor's novel X shaped rotor. As shown in Section 3, the mass of the X-Rotor has been determined to be in the same region as that of existing direct drive turbines. Based on this mass similarity, it has been assumed that costs will be similar. In reality, the assumption may be a conservative estimate because no twist is required in the X-rotor blades, simplifying the production process. Assuming the cost difference is driven by the removal of the requirement for a gearbox and multi-pole generator the capital cost savings from the X-Rotor compared to the cost of the 4 existing turbines range from 5% for the DFIG and 32% for the DD PMG with an average of 17% across all 4 drive trains. Based on [12] indicating turbine costs make up 30% of the overall cost of energy it can be seen that the X-Rotor turbine costs saving compared to the average capital cost of existing turbines is ~5%.

- Total cost of energy savings

When comparing the 4 existing turbines with the X-Rotor it was found that for the existing turbine types the lowest capital cost has the highest O&M cost and vice versa. For example, the 3 stage DFIG configuration has the highest O&M cost but the lowest turbine cost. Consequently, to calculate the total CoE savings from the X-Rotor compared to the average of the 4 other drive train configurations the addition of the average cost of energy saving from O&M and the average cost of energy saving from turbine costs does not provide a true indication of the overall CoE savings. Instead, each of the four drive train types must have their O&M cost saving and capital cost saving added together individually before an average can be taken. When the O&M and turbine cost saving are added for each of the four turbine types the CoE saving from the X-Rotor compared to the other drive train types ranged from 22% to 26% with an average of 24%. It should be noted that all CoE savings presented in this section are based on the assumption that outside of the differences outlined earlier in Section 4 and 5, all costs remain equal between turbine types compared.

6. Conclusion

This paper describes a novel offshore wind turbine concept known as the X-Rotor. Possible design configurations are outlined and structural and O&M analyses are completed. Four existing wind turbine types are compared to the X-Rotor in terms of O&M costs, turbine costs and overall CoE. This work found that the X-Rotor can provide:

- O&M cost savings of up to 55% compared to existing wind turbines
- turbine cost savings of up to 32% compared to existing wind turbines
- CoE savings of up to 26% compared to existing wind turbines

Further work in this area will focus on obtaining greater certainty in the modelling carried out to date and optimising the design of the X-Rotor concept in terms of dimensions, angles, number of blades and number of secondary rotors.

7. Acknowledgements

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