A DESIGN OF MULTIROTOR WIND TURBINE

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***Abstract*: The current generation wind turbines are upscaled into multi megawatt range in terms of output power. However, the energy benefit from the turbine is offset by the increased mass and cost. Twenty MW wind turbines are now feasible with rotor diameters up to 200 m, according to a new report from the EU-funded UpWind project in 2011. The question is, how much bigger can wind turbines get realistically? One concept worth considering, and the one that is the subject of this thesis, is to have more than one rotor on a single support structure. Such turbines could have a greater power to weight ratio. Multi-rotor systems also offer the advantage of standardization, transportation and ease of installation and maintenance. In this thesis the NREL 5 MW single rotor baseline wind turbine is compared with a 5 MW multi-rotor wind turbine. The multiple rotors are downscaled using scaling curves keeping the 5 MW baseline machine as reference.**

***Keywords*: Wind Turbine, Multi-rotor, Horizontal axis, Scaling, Aerodynamics, Dimensions.**

I.INTRODUCTION

The increasing awareness of the need for environmentally sustainable energy production has driven the promotion of wind energy conversion systems. Wind is a form of solar power, created by the uneven heating of the Earth's surface. Wind turbines have been developed for over a millennium and are available in various configurations of horizontal and vertical axis. Wind energy conversion systems transform kinetic energy available in the wind into electrical energy. Due to some favorable characteristics such as economic viability, a clean energy resource, low environmental impact, and the potential to cover a large percentage of the energy requirement, this technology has grown considerably in the last few decades. Presently, wind energy accounts for 2.3% of the total U.S. electricity supply. The cost to produce a unit of electricity from the wind has decreased by 80% during the last twenty years [6]. The United Nations has said if greenhouse gas emissions are not cut by 70% within the next 30 years, the world will face detrimental climate system consequences. This necessitates continued research and development in clean energy technologies in order to create more environmentally friendly energy solutions. 1.1 Wind Power Around the World Figure 1 shows the cumulative installed wind capacity in the world up to 2009 which soared above 150,000 MW, while that, just the top ten participating countries' wind turbine installed capacity exceeds that of 2009, in 2010. The potential for wind power has been estimated to be 600 EJ/yr (167,000 TWh) [29]. Wind power is growing at the rate of 30% annually, with a worldwide installed capacity of 198 gigawatts (GW) in 2010 [20], and is widely used in Europe, Asia, and the United States.

II. EXISTING WORK

Most modern horizontal axis wind turbines (HAWT) have the following principle subsystems: i) the rotor-nacelle assembly (RNA), ii) the support structure which includes the tower and the foundation, and iii) the electrical system including cables, transformers, switchgear etc. The RNA is mounted on the tower and has four main components: i) a rotor with two or three blades with a supporting hub to extract the flow energy from moving air and convert it into rotational energy in the shaft, ii) a transmission system to gear up the rotational speed of the shaft, usually consisting of shafts, gearbox, coupling, and a mechanical brake, iii) a generator to convert the mechanical energy into electrical energy, and iv) a controller to supervise the performance of the system. The power output of a wind turbine varies with wind speed and every wind turbine has a characteristic power performance curve. With the curve it is possible to predict the energy production of a wind turbine without considering the technical details of its various components. A power curve for a hypothetical wind turbine the cut-out speed which is the maximum wind speed at which the turbine is allowed to deliver power, limited by engineering design and safety constraints. Power curves for existing machines can normally be obtained from the manufacturer, derived from field tests using standardized testing methods. The process of determination of power characteristics of the wind turbine components and their efficiencies is very complex.

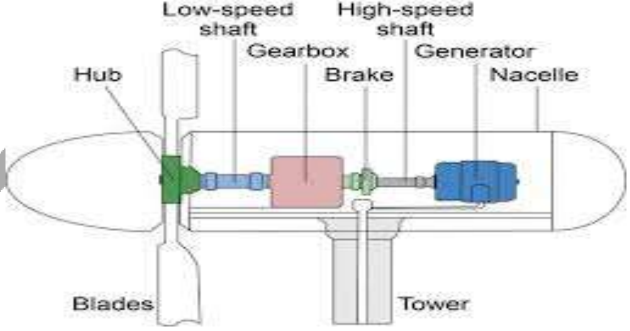

Fig.1 Diagram for horizontal axis wind turbines

III. PROPOSED WORK

The purpose of this thesis is to investigate whether there is any reason to think that a land-based MRWT would be preferable to a single rotor wind turbine with the same swept area. The project focusses on a first level analysis. Specifically, the relative weights and costs of two turbines of the same swept area, one with a single rotor, the other with 3 rotors, are considered. Every effort is made to ensure that this is an" apples to apples" comparison. That is, the same tip speed ratio and same number of blades are used on each rotor, the same type of tower, the same wind speeds, and the same wind shear etc. are used. To do this, a scaling model is chosen. The design stresses are not used as design driver, but the stresses are accounted for.

A. Multi Rotor Wind Turbines

The current generation of wind turbines have been upscaled into multi megawatt range in terms of output power. In order to find the best locations to harvest wind, it is a natural step to take wind turbines offshore, recognizing onshore environmental impacts and the abundance of better-quality wind resources at sea. For offshore wind turbines, support structures are the main cost drivers (over 40% of the system components cost) and it is vital to extract the maximum effect of the wind. In order to do this either the rotors need to be made larger, or more than one rotor must be used. This conclusion was not arrived at by simply geometrically up-scaling a 5 MW machine. The design was highly modified: the blades are based on a lighter, better design, with unique adaptations to the design of the controls and sensors. Whether such a large wind turbine is economically feasible remains to be seen. illustrates the growth in wind turbine size since 1985. The CoE is defined as the unit cost of energy (in $/KWh) from the wind energy system Manufacturing single blades exceeding 120 m with current technology, offshore erection with current installation vessels and cranes at this scale, transport limitations etc., indicate that single rotor design seems to be uneconomic at very large scale.

$$\mathrm{COE} = \frac{\text{(Total annualized costs)}}{\text{(Annual energy production)}} \qquad (1)$$

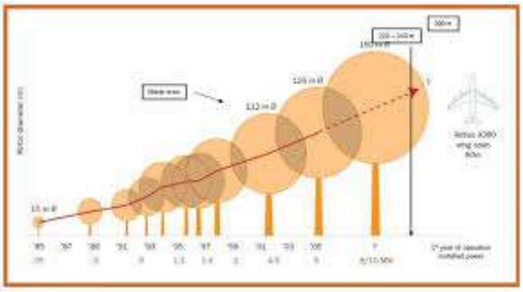

Fig.2 Increasing wind turbine rotor size

B. Modern MRWTs

Henk Lagerweij of Lagerwey Wind has built several MRWTs and has extensive knowledge of key engineering issues such as yawing and rotor interaction. Fig.3 shows a Lagerwey multi rotor system. It employed a tree like structure, which is potentially subject to vibrational problems, especially if extended to a large array, and hence was not very strength-to-weight efficient.

1. Scaling Relationships

Peter Jamieson, in 1995, recognized the scaling principles, implying a fundamental weight advantage of multi rotor systems and developed a case based on commercial data to justify the potential benefit. He put forward his ideas on scaling principles in his book Innovation in Wind Turbine Design, in 2011.

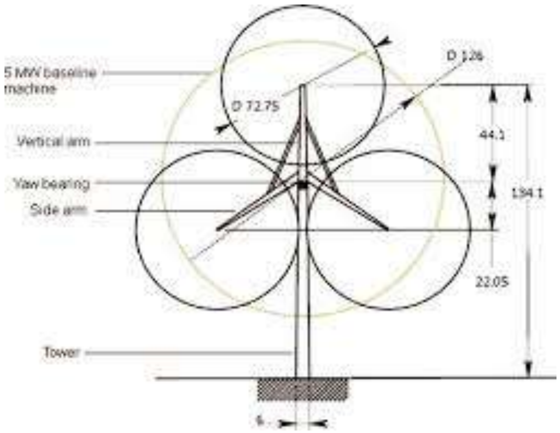

Fig.3 Three rotor Wind turbine

2. Scaling Trends

a. Geometric Scaling

The simplest scaling procedure is to simply multiply the dimensions of an object uniformly by a similar factor. This method is called geometric scaling which is referred to as the 0th order of scaling. The area of any 3D object scales as the square of the length, whereas the volume scales as the cube of the length. Thus, upscaling rotor size by a small fraction (geometric scaling) significantly increases the rotor mass and cost. This relationship, known as the area-volume relationship has been adopted by Jamieson to show that having multiple small rotors, each generating a fraction of the total power proves to be more mass effective than a single large rotor of the same power capacity. The mass advantage is observed in the rotor and drive train components. The above concept is expressed mathematically as K = n d D 3 = nm M = 1 √ n where n is the number of rotors of the MRWT and m is the associated mass and d is the diameter of each rotor of the MRWT, M is the mass and D is the diameter of the single large rotor, and K is the ratio of masses of the two systems . The √ 1 n formula clearly describes the mass advantage (which could mean a cost benefit) of downscaling. In other words, if the rotor diameter is halved, the area (and hence the amount of wind captured) is quartered. However, the mass has decreased to an eighth. Simply put, the mass decreases faster than power with decreasing diameter.

b. Dynamic Scaling

In a scaling scenario, physical quantities such as load, size, weight etc. vary with the scale factor. In dynamic scaling, let pre-numbers be defined as relations between these physical quantities such that the pre-numbers do not vary with the scale factor. For example, limiting stress is one such pre-number in strength-to-weight problems. Thus, stress can be used as the design driver, which allows modifying dimensions and offers flexibility relative to the geometric scaling method as it depends on material properties. This method is referred to as the 1st order of scaling. This method of scaling was not used for the project.

C. Aerodynamic Interactions

One of the important factors of wind turbine design is the aerodynamics. A multirotor system will require a careful analysis of the aerodynamics due to the interaction of rotors in an array in the same wind field. Smulders, et.all showed through tunnel testing that for two adjacent rotors with no overlap, the average power output of a two-rotor system is slightly higher than that of two single rotors, especially if the spacing of the tips is very small. This is true for the situation of co-rotation as well as counter-rotation. The effects are due to wake rotation, more specifically of the interaction of wake vortices. As regards the forces on the two-rotor system, the test results concluded that the contribution of the axial forces keep the up-wind rotor systems headed out into the wind. If the distance between the rotor plane and yawing axis is too large then the side forces working on the plane tend to turn the rotor out of the wind. The paper suggests that rotors placed adjacent to each other give slightly higher average output power. It should be noted that, these tests were done on 20 cm diameter rotors. Wind tunnel tests conducted by Southwest Research Institute (SwRI) for Ocean Wind Energy Systems (OWES) on a seven-rotor array of 400 W capacity each showed similar results. It was determined that rotor spacing of as little as 2% of the rotor diameter resulted in little or no blade interaction. These results strengthen the case for multi-rotor arrays being feasible without detrimental aerodynamic interactions.

IV. DESIGN PROCESS

In this chapter the structural design process of the support frame, the preliminary yaw system and the tower is presented. The key phases of the design process discussed are the objective of the design, the loads and configurations, the scope of the research, and the iterative design process of the whole structure. The scope of the design is as follows:

A. Design Requirements

The main objective is to design a support structure for the 5 MW MRWT and compare the weight and cost of the entire system with the NREL 5 MW baseline wind turbine. In order to maintain a consistent basis of comparison the following specifications are kept same as the NREL 5 MW baseline wind turbine: same tower, three bladed rotors, rotor TSR 7, 90 m hub height, 11.4 m/s rated wind speed, 0.14 wind shear exponent.

B. Design Specifications

1. Materials

The material chosen is structural steel alloy ASTM A992 with a minimum yield strength of 345 MPa and minimum tensile strength 448 MPa. It has density 7850 kg/m3, Young’s modulus 200 GPa and shear modulus 77 GPa which is less than the material used in the NREL machine, but comparable and only increases the safety factor. Keeping a safety factor of 1.8 the limiting stress for the design is 190 MPa.

2. Design Conditions

The wind regime for load and safety considerations is divided into the normal wind conditions, which will occur frequently during normal operation of a wind turbine, and the extreme wind conditions that are defined as having a 1-year or 50-year recurrence period, as defined in the fundamental wind turbine design standard, IEC The MRWT is modeled for simplified versions of two IEC design conditions (static analysis with steady wind model)

- **Operating at rated power:** This is called the Normal Turbulence Model (NTM).
- **Stationary at maximum wind**: This is the Extreme Wind Speed Model (EWM). The 50-year EWM is chosen for this design.

C. Structural Scheme

The structure will need to withstand bending moments due to thrust from each of the rotors and will also have to support the weight of the RNA corresponding to each of the rotors. Regardless of the specifics, the goal is to hold each of the three smaller RNAs in a manner such that the maximum stresses are within allowable design code limits, the overall mass of the framework is low enough so that the system is not heavier than the 5 MW baseline machine, and also not to be too complex. The yaw 35 bearing will be assumed to be at the 90 m level on the tower. The design will require several iterations for optimization of the tower top structure. Two configurations of rotor positions are considered as shown in Figure 4. The structural scheme is based on the concept design by Honnef. The geometric center of the rotor areas is at 90 m hub height for both cases. The swept area of the MRWT is shown in comparison with the NREL baseline machine. Adopting results from the Smulders and OWES tests, radial spacing between rotors is 5% diameter.

D. Blade Deflection

B Blade deflection is an important parameter to consider in the design of the spaceframe. The maximum out-of-plane deflection for the NREL machine is approximately. Truss type support frame deflections 5.5 m at rated wind speed under dynamic loading. Blade deflection depends primarily on the blade stiffness. It varies as the cube of the diameter, just as weight and cost. This makes the blade tip deflection of the downscaled MRWT rotor to be in the range of 1-1.5 m.

E. Comparison with Existing Method

The most suitable method to evaluate new technology is to set it alongside existing state of the art technology and conduct a side by side comparison. Here we are assuming the tower cost and/or structure remains constant. Comparison is carried out for single rotor replaced by multi rotors, along with associated parts such as drive trains, generators and nacelle. In these entire multi rotor wind turbines large single rotor is replaced by number of small rotors of equivalent area. Counter rotating wind turbine emphasis on improving performance through reuse upwind rotor wake.

V. RESULT

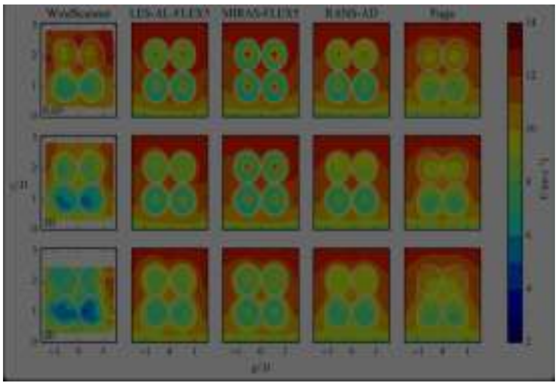

Fig.4 multi-rotor wind turbine

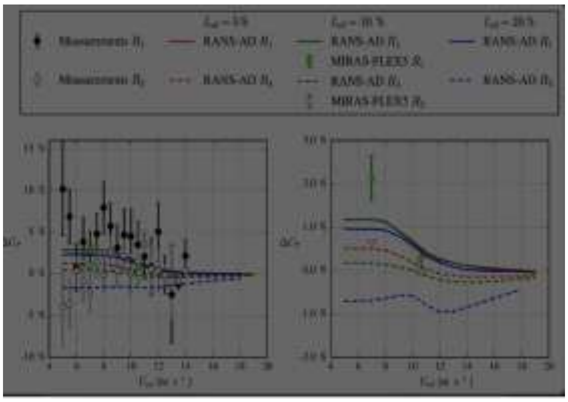

Fig.5 Graphical Representation

P = Power output, kilowatts

Cp = Maximum power coefficient, ranging from 0.25 to 0.45, dimension less (theoretical maximum = 0.59)

ρ = Air density, lb/ft3

A = Rotor swept area, ft2 or π D2/4 (D is the rotor diameter in ft, π = 3.1416)

V = Wind speed, mph

k = 0.000133 A constant to yield power in kilowatts. (Multiplying the above kilowatt answer by 1.340 converts it to horse- power [i.e., 1 kW = 1.340 horsepower]).

VI.CONCLUSION

One of the most important areas to study in the MRWT design is the aerodynamics. It is assumed for this work that the aerodynamics is unaffected by a closely spaced rotor array in a wind field as suggested by Smulders, et al. and the OWES tests. Yawing of an MRWT goes hand in hand with aerodynamics and also merits further study. It is possible to use time series outputs from FAST as inputs to SAP at chosen locations on the geometry. This would be a good start to understand the complex 3-d nonlinear dynamics of a MRWT. The frame will be subject to asymmetrical loads, shear, yawing etc. Other IEC design conditions should be accounted for to ensure complete, safe design such as extreme operating gust (EOG), extreme turbulence model (ETM), extreme direction change (EDC), extreme wind shear (EWS). Other environmental conditions such as rain, hail, snow, ice, earthquakes, humidity and temperature should be studied too. Different loading scenarios would have to take into account in future studies such as startup, shutdown and braking. The MRWT design developed here uses a most basic approach to modeling MRWT RNA components. Other researchers may develop new ideas from the outline presented here. The main purpose of the MRWT is to reduce the overall cost of the machine. Despite the present limitations and the scarce literature available, the design provides useful predictions and allows inferences about the behavior of the system. With increased versatility, MRWTs could become useful in some applications.

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