Aerodynamic Performance and Structural Design of 5 MW Multi Rotor System (MRS) Wind Turbines

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Abstract- Multi-Rotor System (MRS) wind turbines provide a competitive alternative to large-scale wind turbines. It addresses many of the drawbacks of large wind turbines including transportation, installation, and maintenance difficulties for large blades. In this work, three different MRS configurations are studied and compared to the NREL 5 MW turbine. A twin, tri, and quad-rotor configurations are scaled-down from the original turbine, such that the total turbine capacity of each configuration is 5 MW. Aerodynamic performance has been calculated using an in-house Blade Element Momentum (BEM) code. A preliminary design for the support structure has been made and analyzed. The deflection slope angle for the tower-top of MRS configurations have values of 0.54°-0.6° as compared to the single-rotor reference turbine with a value of 0.55°. The twin, tri, and quad-rotor configurations provide a total reduction in mass of 25.6%, 16.9%, and 22.5% respectively. Although the inertial and aerodynamic loads decrease as the number of rotors on an MRS increases, but the support structure should be considered before selecting the appropriate number of rotors.

Keywords: Multi-Rotor Systems; Renewable Energy; Structure Analysis; Wind Energy

1. Introduction

With the high demand for energy all over the world, researchers are competing to find new sources of energy or develop existing ones. Renewable energy is of great interest for the cleanliness and sustainability it provides [1], [2]. Wind energy is among the fastest developing industries. It is considered one of the least polluting, most sustainable, and highest efficient energy systems [3]. There is a vast growth in wind energy installations year over year. In the year 2020 alone, a 53% growth in wind energy installations has been achieved compared to the preceding year [4],[5].

To improve the use of wind energy, researchers have innovated new methods and techniques to harvest the power carried in the wind [6]. Some innovations are developed by achieving unconventional methods, for example, airborne wind energy. Where airborne devices like wings [7], kites [8], or aerial vehicles [9] are connected through tethers to ground control units to produce energy through the tension produced by the airborne device to the tether. Other innovations include producing energy through bladeless wind turbines which utilize the vortex formation for wind energy production [10], [11].

However, the conventional way of harvesting wind energy through wind turbines is of the highest efficiency wind energy systems. Research in this area is concerned with improving wind energy production through different control techniques [12], [13], or through innovations that include but are not limited to wind lens technology [14] or applying active flow control over the wind turbine blades [15].

Theoretically speaking, the amount of wind energy produced is directly proportional to the square of the rotor diameter [16]. With that said, producing more wind energy requires enormous-sized wind turbines. The world's current largest wind turbine is General Electric's Haliade-X with a rotor diameter of 220 m and a capacity of 12 MW [17]. This enormous size includes many complications and increases cost. For instance, transportation of a 107 m long blade costs millions of US dollars. Transportation costs generally cost about 10% of the total capital of a wind turbine [18]. In other words, although large-sized wind turbines produce more power, the logistic costs of transportation, installation, and maintenance make it difficult to increase the size of the rotors beyond a certain limit [19].

Multi-Rotor System (MRS) wind turbines first introduced by Honnef in the 1930s produce a solution to the complications of large-scale wind turbines [20]. In this concept, a large-scale wind turbine rotor is replaced with multi-rotors on the same support structure. When this concept was first introduced, it faced many challenges which include the complication of the support structure and yaw control. The technology in the 1930s was not sufficient to address the challenges of the MRS concept, so it fell out of consideration. However, in the past decade with the increasing demand for energy and the state-of-the-art technology in materials science, automatic control, and mathematical modeling techniques, the MRS concept has become a competitor to large-scaled wind turbines.

Competition of the MRS wind turbines with the large-scaled wind turbines comes from the solutions it provides for the logistics costs, and hence, the cost of energy. It has been proven theoretically and experimentally that scaled-down rotors provide a reduced mass of the rotor proportional to the cube of the rotor diameter. For instance, for the same capacity, an n number of rotors MRS wind turbine has a total mass of $\boldsymbol{1/\sqrt{n}}$ compared to a single-rotor [21]. The reduced mass of the rotors means less cost of material and hence less cost of energy. Transportation, installation, and maintenance costs are reduced as well, in addition to reduced complications of transportation of smaller blades. However, the main challenges of an MRS turbine are the complexity of support structure and yawing system. Accordingly, MRS concept is still on the research level and has not been used commercially.

With that being said, research attempts have addressed different considerations in the study of MRS wind turbines. Efforts have been made to study the advancements of MRS over large-scale single-rotor wind turbines. On the aspect of structural analysis and mass reduction, a scaled-down MRS with 5 rotors * 1 MW has shown a 37% mass reduction and 25% cost reduction, compared to a single-rotor with 5 MW capacity [22], [23].

Aerodynamic performance has also been studied to compare MRS to Single Rotor Systems (SRS). Modeling and simulations have been carried out using Computational Fluid Dynamics (CFD) techniques as well as deterministic models to study the MRS systems. All studies have shown improvement in power production depending on the number of rotors and arrangements. CFD simulations have shown an increase in the yearly produced power of 3-5% of different configurations of MRS turbines compared to single-rotors of the same size [24]. One more advantage of the MRS was found to be the quick recovery of the beyond-rotor wake compared to single rotors. This advantage implies better use of the available land in a wind farm by putting the second line of wind turbines at a closer distance [25].

The experimental approach has also proven the advantage of MRS to SRS in power production. Experiments by [26] and by [27] performed independently have agreed on an increase in the yearly power production of each rotor of an MRS of different configurations in the range of 2-7% per rotor, compared to the rotor's original power production if experimented individually.

A combination of the structural and aerodynamic performance of MRS has been carried on in aeroelastic simulations which have proved the advantages of MRS in better power production, combined with better behavior of the support structure dynamics [28]-[30]. The effect of the tip spacing between each rotor of an MRS wind turbine has also been studied to determine the best spacing for better power production per rotor [30].

The authors have partially shared in attempts to compare different configurations of MRS with the same span size [31], and with the same capacity [32]. These comparisons agreed with the results in the literature with advantages of MRS compared to SRS wind turbines. However, in the previous attempts, only the aerodynamic performance was studied with no regard to the structural behavior of the support structure.

So far, up to the authors' knowledge, there is no attempt to determine the optimum number of rotors in an MRS system for a required energy capacity. This work presents a preliminary attempt to study the aerodynamic performance of different MRS configurations, together with a preliminary support structure design and statical structure analysis, in order to have a better judgment on the number of rotors that would fit the best design requirements.

In this work, the NREL 5 MW wind turbine [33] has been compared to three different configurations of MRS with a twin-rotor, tri-rotor, and quad-rotor of the same capacity. Aerodynamic performance has been calculated using an in-house Blade Element Momentum (BEM) code. Then a preliminary design of the support structure has been made for each configuration, where the aerodynamic loads are applied for statical structural analysis. The masses of each component, as well as the total mass and tower deflections, are presented for each configuration for comparison.

The manuscript is organized as follows: section 2 shows the methodology followed for scale-down, aerodynamic loads calculations, and finite element analyses. Section 3 shows the structural design for all configurations. Section 4 shows the results of structural analysis for each configuration and discusses the advantages of MRS concept. Finally, section 5 concludes the main findings of the paper.

2. Methodology

2.1. Scale-Down of the Wind Turbine

The main objective of this work is to study the aerodynamic and structural behavior of MRS compared to SRS of the same capacity. The wind turbine chosen for study is the NREL 5 MW wind turbine [33]. A scale-down has been performed over the wind turbine, in order to study four different configurations of MRS; twin, tri, and quad-rotor, with a total capacity for each turbine of 5 MW. The scale-down has been done so that each rotor would satisfy Equation (1) for wind power [34]:

$$P = \frac{1}{2}\rho A v^3 C_P \qquad (1)$$

Where P is the power, ρ is the wind density, A is the rotor swept area, v is the wind velocity, and CP is the power coefficient. If a single-rotor produces 5 MW of power, then the twin-rotor, tri-rotor, and quad-rotor should produce 2.5 MW, 1.67 MW, and 1.25 MW per rotor respectively. With the wind density, wind velocity, and power coefficient assumed to be constant for all configurations as design parameters, the area of the rotor and hence the rotor diameter can be determined. The diameter (D_n) of a rotor in an MRS wind turbine of n number of rotors, compared to a single-rotor diameter (D) for the same turbine total capacity can be determined through Equation (2):

$$D_n = D * \sqrt{\frac{1}{n}} \tag{2}$$

The rotor diameter of the original NREL 5 MW wind turbine is 128 m. Doing the scale-down as described, the rotor diameters of the twin-rotor, tri-rotor, and quad-rotor are 90.5 m, 74 m, and 64 m respectively.

Similarly, assuming the rotors are manufactured using the same materials, the mass of the rotor will be proportional to the cube of the rotor material. The mass (mn) of a rotor in an MRS turbine with n number of rotors compared to the mass (m) of a single-rotor of the same total capacity can be determined using Equation (3):

$$m_n = m * \left(\sqrt{\frac{1}{n}}\right)^3 \tag{2}$$

Rotor masses were calculated based on equation (3) to determine the total mass reduction for each configuration. The original NREL 5 MW rotor has also been drawn using Solidworks® Computer Aided Drawing (CAD) software. The blades material is assigned as Generic Glass Fiber, A-Glass [35]. The total rotor mass has been evaluated on Solidworks after assigning the material and compared to the original rotor mass of 110,000 kg. After which, the scale-down has been performed on Solidworks with the diameter size of each rotor for each configuration. The same material as the single-rotor configuration has been assigned for all configurations, and the mass has been evaluated. Table 1 shows the calculated mass using equation (3), and the evaluated mass using Solidworks.

Table 1. Rotor Masses for all Configurations

Configuration	Original Mass (kg)	Scaled-Down Calculated Mass (kg)	Solidworks Evaluated Mass (kg)	Deviation (%)
Single-Rotor	110,000	-	109,924	0.07%
Twin-Rotor	-	38,890	38,799	0.24%
Tri-Rotor	-	21,169	20,822	1.6%
Quad-Rotor	-	13,750	13,739	0.08%

With a maximum deviation of 1.6% between the calculated mass and the evaluated mass after assigning the material, the same approach can be trusted for use for the rest of the turbine components, namely the hub and the nacelle. The support structure is evaluated individually after a new design is proposed.

2.2. Blade Element Momentum Method

To calculate the aerodynamic loads on each rotor, the authors have developed an in-house Blade Element Momentum (BEM) code using MATLAB©. In this method, the blade is divided into annular elements with the assumption that there is no interaction between the elements. The loads normal and tangential to the rotor plane for each element is calculated, then numerically integrated to get the rotor loads. The other assumption for classical BEM method is the steadiness of the wind. The main algorithm for BEM is shown in Fig. 1.

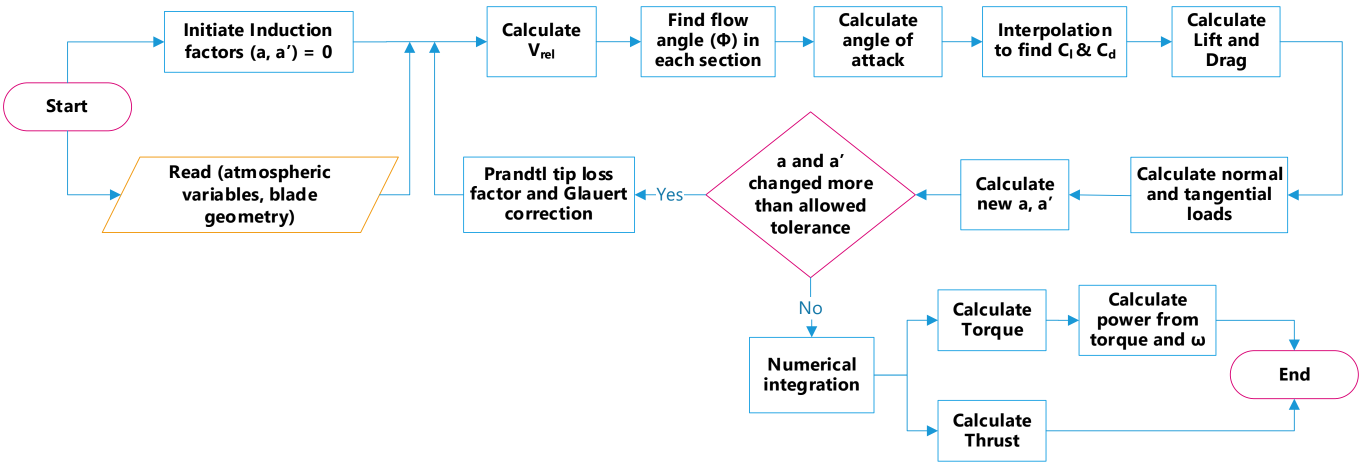

Fig. 1. BEM Flowchart

The in-house code has been verified by the authors by comparing the aerodynamic loads starting from the cut-in wind speed of 3 m/s to the rated wind speed of 11.4 m/s, to the NREL 5 MW definition report [31]-[33].

The code is used for aerodynamic load calculations to be further used for the structural analysis. Thrust and torque loads at the rated wind speed are used for structure analysis, and the power produced is calculated to measure the performance of each configuration.

2.3. Finite Element Analysis

The finite Element Structural Analysis tool on Solidworks has been used for the structure analysis for the support structure of each wind turbine configuration. Although the structural analysis tool on Solidworks is preliminary, the main aim of this work demands only preliminary results to determine a basic understanding of the effect of the number of rotors on the overall performance of MRS wind turbines.

Static structure analysis has been performed using the static solver of Solidworks to calculate the von Mises stress, as well as the tower deflections. An automatic mesh generator has been used to generate the mesh for the tower with blended curvature-based mesh to account for the curvatures in the tower geometry. A fine mesh has been used to account for the medium accuracy of the solver, and it has been checked for quality and interference.

2.3.1. Structure Analysis Verification

To verify the structural solver, a simulation has been performed on the tower of the single-rotor wind turbine. The tower material has been set with Steel of grade AISI 304, to match the mechanical properties recommended in the NREL 5 MW definition report [33]. Dimensions of the tower geometry are shown in Table 2.

Table 2. NREL 5 MW Tower Geometry

Property	Value
Tower Height (m)	87.6
Tower-Base Diameter (m)	6
Tower-Base Thickness (m)	0.027
Tower-Top Diameter (m)	3.87
Tower-Top Thickness (m)	0.019

Y. Shkara et. al. have performed an aeroelastic analysis on the NREL 5 MW wind turbine. They studied the dynamic response of the tower at the rated wind speed of 11.4 m/s. The deflection of the tower-top in the fore-aft (out of plane) direction was found to be a sinusoidal wave within the range of 0.6 m to 1.2 m [36].

In this study, the structural analysis performed is statical, however, the same simulation conditions were used. The same tower properties were created, and the rotor thrust and torque were calculated at the rated wind speed of 11.4 m/s. Rotor thrust and torque have the values of 827.7 kN and 4185.5 kN.m respectively.

The tower mesh has been created with high mesh quality and a total of 65,523 elements. Rotor aerodynamic and inertial loads are placed on the top of the tower as point loads for simplicity, and the tower base was considered to be fixed. The mesh shape for the tower is shown in Fig. 2, and the deflection of the tower in the fore-aft direction is shown in Fig. 3.

Fig. 2. Mesh of the Single-Rotor Wind Turbine Tower

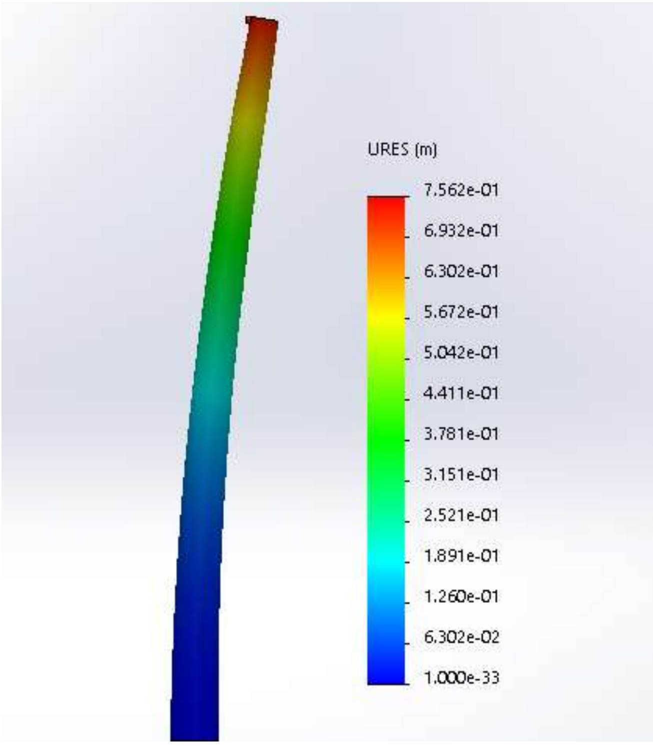

Fig. 3. Side View of NREL 5 MW Single-Rotor Tower Deflection

The maximum deflection at the tower top was found to be 0.756 m, which lies within the range of values of deflection for the fore-aft direction of the reference analysis [36]. Assuming the deflection is linear, the deflection slope angle for the tower-top is approximately 0.55°. This preliminary result can be used for further analyses of the MRS configurations, to get a basic decision for the most appropriate configuration.

3. Structural Design

In this section, the proposed design of the turbine support structure is proposed. Three different configurations of MRS wind turbines are proposed: twin-rotor, tri-rotor, and quad-rotor. The rotors are scaled down from NREL 5 MW turbine, as well as the nacelles and hubs for each rotor.

The main criteria for sizing the support structure are based on two aspects:

The first row of rotors is placed at an elevation corresponding to the single-rotor using the same scaling factor as the rotor diameter.

The deflection slope angle at the tower top of each configuration is the same as the single-rotor tower at the rated wind speed

The tower of the single-rotor turbine is 87 m high. Accordingly, using the same scaling as the rotors, the elevation of the twin-rotor tower is 61.5 m, and the elevation of the first row of rotors for the tri and quad rotors are 50.3 m and 43.5 m respectively. The material used is the same as the single-rotor wind turbine tower, Steel of grade AISI 304. Tower-base and tower-top diameters were determined by fine tuning until the tower-top deflection slope angle lies in the range of 0.55°. And the thickness has been assumed to be constant along the tower and side booms with the value of 20 mm.

The length of side booms and tower extensions has been decided such that the spacing between all rotors (center to center) is 1.05 of the rotors' diameters. Fig. 4 to 6 show the main dimensions of the twin, tri, and quad rotor configurations respectively.

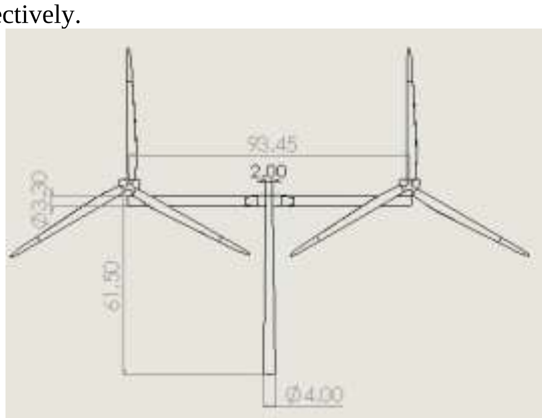

Fig. 4. Dimensions of the Twin-Rotor Configuration

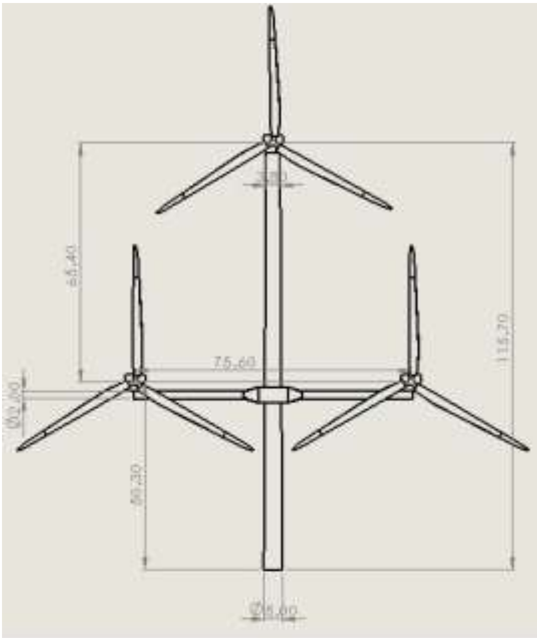

Fig. 5. Dimensions of the Tri-Rotor Configuration

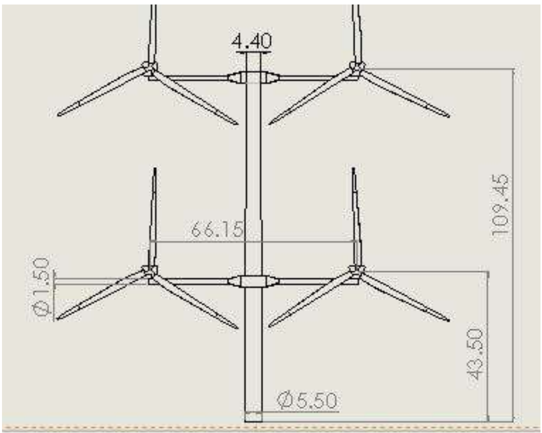

Fig. 6. Dimensions of the Quad-Rotor Configuration

Based on the proposed design, and with the selection of materials for each part as the single-rotor, the masses of each part of each configuration were evaluated. A summary of the masses is shown in Table 3.

Although there is a significant reduction in the masses of the rotors for the MRS configuration compared to the single-rotor, but the support structure cannot be just scaled down. The size of the support structure was determined to accommodate the number of rotors for each configuration. However, the total mass of each turbine configuration when evaluated in Solidworks, there is a mass reduction for the MRS configurations.

The twin-rotor, tri-rotor, and quad-rotor have a mass reduction of 25.6%, 16.9%, and 22.5% respectively compared to the total mass of the single-rotor turbine.

Table 3. Mass Summary for All Configurations

	Mass (kg)			
	Single- Rotor	**Twin- Rotor**	**Tri- Rotor**	**Quad- Rotor**
Support Structure	302,953	238,685	345,635	331,047
Blade	17,740	6,272	3,414	2,217
Hub	56,704	19,983	10,580	7,088
Rotor	109,924	38,799	20,822	13,739
Nacelle	240,076	84,607	44,795	30,009
Total Mass	652,953	485,497	542,486	506,039
Mass Reduction	--	167,456	110,466	146,913
Mass Reduction %	--	25.6	16.9	22.5

4. Results and Discussion

The aerodynamic loads for each configuration have been evaluated using the BEM in-house code. Then these loads together with the inertial loads been used for the structural analysis.

4.1. Aerodynamic Loads

After verification of the BEM code, simulations have been performed for each rotor of the MRS configurations to evaluate the aerodynamic loads and power produced. Fig. 7 and 8 show the aerodynamic thrust and torque load per rotor resepectively, and Fig. 9 shows the power produced per turbine for all configurations.

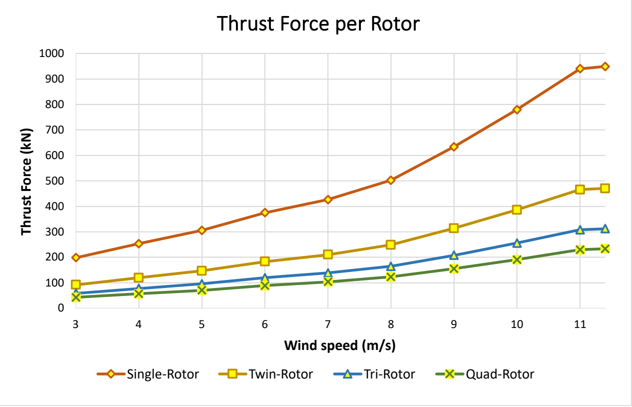

Fig. 7. Thrust Force Per Rotor for All Configurations

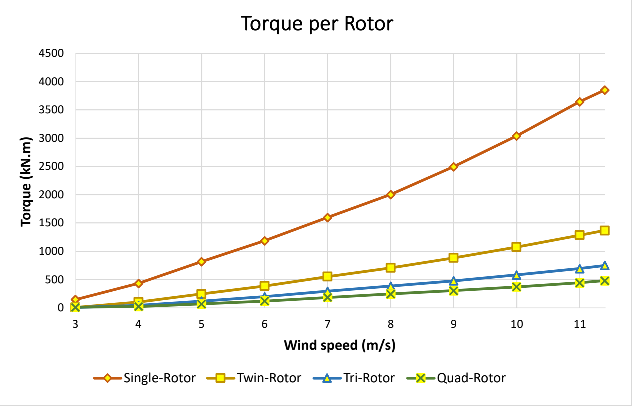

Fig. 8. Torque Per Rotor for All Configurations

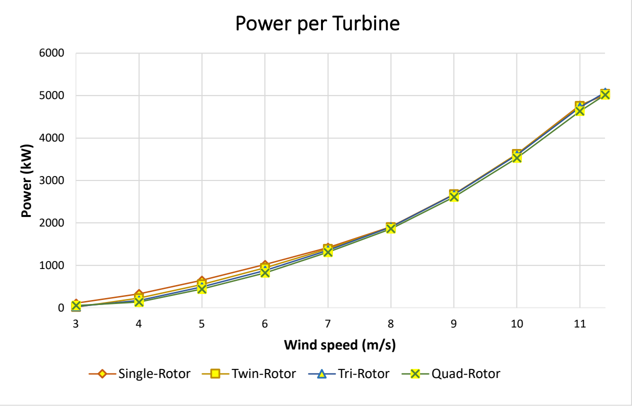

Fig. 9. Power Produced Per Turbine for All Configurations

The results show that there is a significant decrease in the aerodynamic loads as the number of rotors increases, although the total produced power per turbine is almost identical. The maximum thrust and torque per rotor at the rated wind speed of 11.4 m/s is used later for the structural analysis.

4.2. Structural Analysis

Solidworks structural analysis solver has been used to study the tower deflections for each configuration. The aerodynamic loads and inertial loads for each rotor are placed on each support structure assuming there is no aerodynamic interaction between the rotors.

4.2.1. Twin-Rotor Configuration

The support structure for the twin-rotor configuration is studied for structural behavior. The structure is meshed on the Solidworks automatic mesh generator, as a blended curvature-based mesh. The loads are placed as point loads at the ends of the side booms, in a static structure analysis manner. The Mesh shape for the twin-rotor support structure is shown in Fig. 10, and the simulation conditions are shown in Table 4.

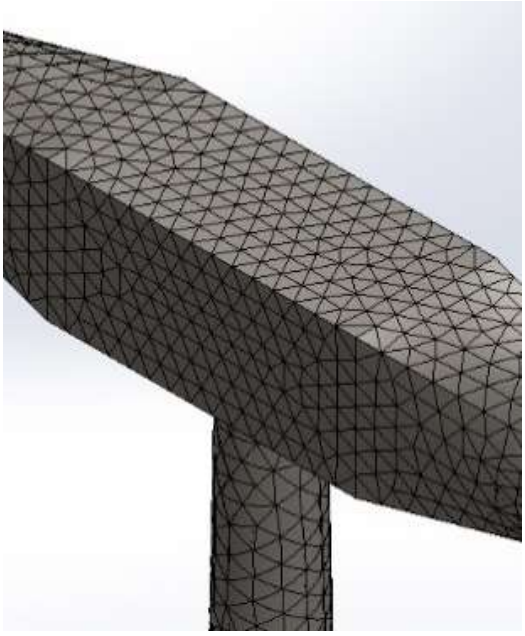

Fig. 10. Mesh of the Twin-Rotor Wind Turbine Tower

Table 4. Simulation Parameters for the Twin-Rotor Configuration

Parameter	Value/Status
Wind Speed (m/s)	11.4
Rotor Thrust (kN)	470.31
Rotor Torque (kN.m)	1,368.5
Rotor Mass (kg)	38,799
Nacelle Mass (kg)	84,607
Mesh Elements (-)	36,571
Tower-base Fixation	Fixed Support
Simulation Type	Static

The support structure deflections are shown in Fig. 11 for the from view of the structure, and in Fig. 12 for the side view.

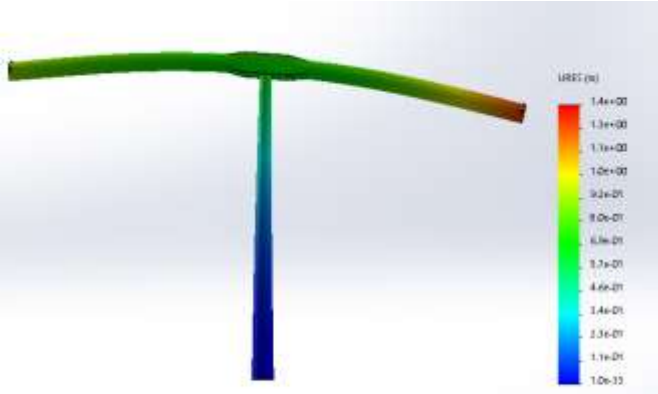

Fig. 11. Twin-Rotor Support Structure Deflection - Front View

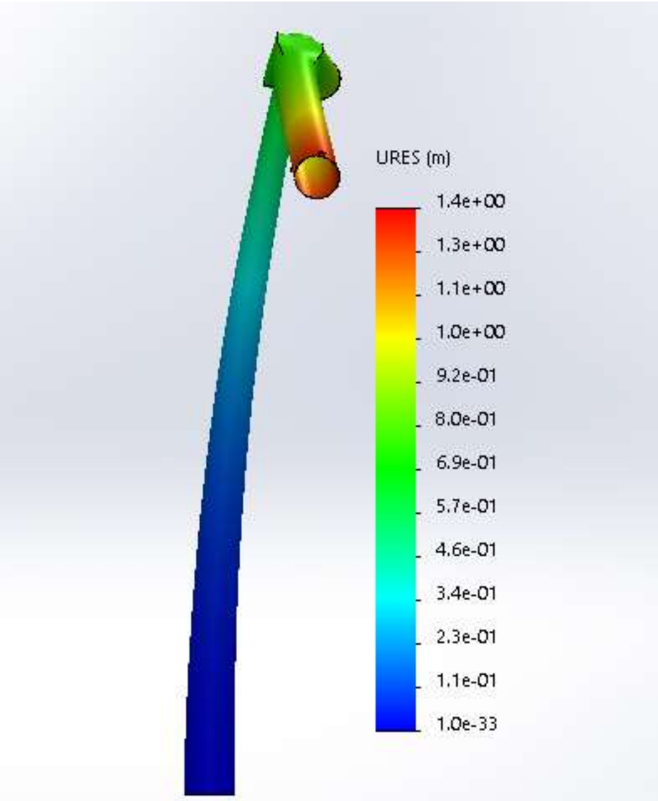

Fig. 12. Twin-Rotor Support Structure Deflection - Side View

The maximum fore-aft deflection at the tower-top for the main tower is 0.66 m, while at the height of the tower 61.5 m, the deflection slope angle is 0.6°. This slope angle is only 0.05° different compared to the single-rotor tower. The side-boom maximum deflection is 1.4 m relative to the tower base, however, relative to the tower-top the deflection is 0.74 m which is within the accepted range of values.

It is also noted that in the in-plane direction, the right side boom is deflected more than the left one. This can be explained by the imposing of the rotor and nacelle weights, with the rotor torque which is in the same direction as the inertial loads. As opposed to the left side boom where the torque is in opposite direction to the inertial loads. Improvements to this design can be achieved by using supporting beams or guy wires. However, as a preliminary design, the deflections are within the acceptable range compared to the single-rotor.

4.2.2. Tri-Rotor Configuration

Similarly, the analysis has been performed on the tri-rotor configuration support structure. Simulation conditions are shown in Table 5. The maximum aerodynamic loads from the BEM simulations have been used to act on the tower top for the static structural analysis.

Table 5. Simulation Parameters for the Tri-Rotor Configuration

Parameter	Value/Status
Wind Speed (m/s)	11.4
Rotor Thrust (kN)	312.06
Rotor Torque (kN.m)	749.9
Rotor Mass (kg)	20,822
Nacelle Mass (kg)	44,795
Mesh Elements (-)	58,544
Tower-base Fixation	Fixed Support
Simulation Type	Static

Results for the support structure deflections are shown in Fig. 13 for the front view, and Fig. 14 for the side view of the tri-rotor configuration support structure.

The maximum deflection in this configuration is at the tower top with a value of 1.1 m. The total height of the tri-rotor main tower is 115.7 m. This means that the deflection slope angle is 0.54°, almost the same value as the single-rotor tower.

This comparable value of the tower top deflection slope ensures the effectiveness of the proposed structural design of the tri-rotor configuration.

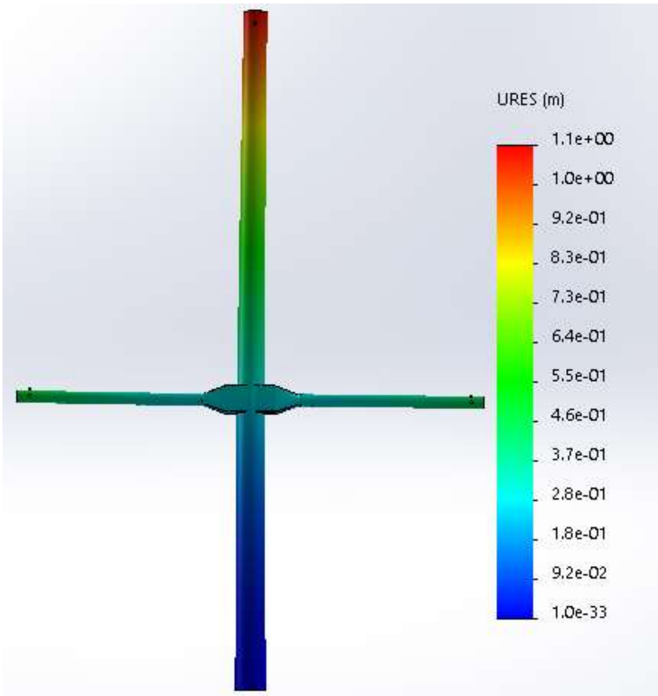

Fig. 13. Tri-Rotor Support Structure Deflection - Front View

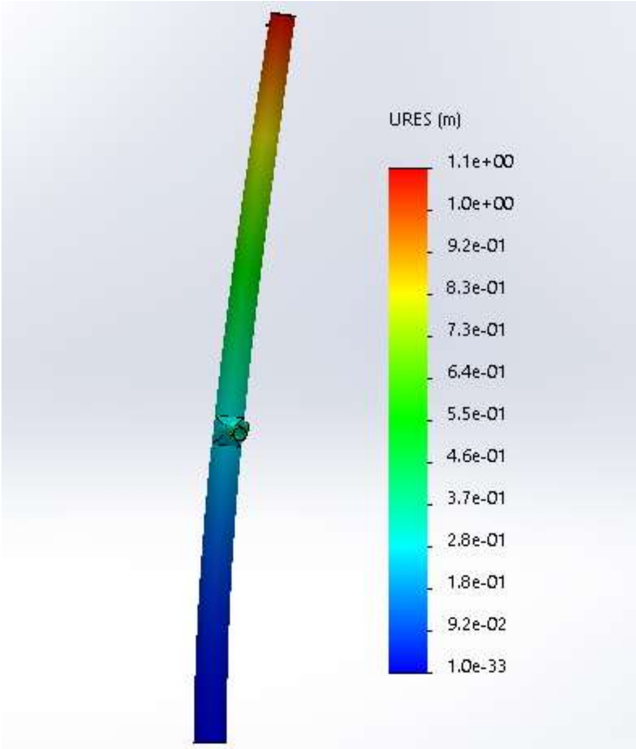

Fig. 14. Tri-Rotor Support Structure Deflection - Side View

4.2.3. Quad-Rotor Configuration

Finally, the quad-rotor configuration support structure is analyzed in the same manner as the previous configurations. The tree-shaped tower is meshed, and the loads are put as point loads. The simulation conditions are shown in Table 6.

Table 6. Simulation Parameters for the Quad-Rotor Configuration

Parameter	Value/Status
Wind Speed (m/s)	11.4
Rotor Thrust (kN)	233.37
Rotor Torque (kN.m)	481.6
Rotor Mass (kg)	7,088
Nacelle Mass (kg)	13,739
Mesh Elements (-)	71,386
Tower-base Fixation	Fixed Support
Simulation Type	Static

The rotor thrust and torque were used from the results of the BEM simulations. The maximum values of the loads at the rated wind speed of 11.4 m/s were used for the analysis. Structural analysis results for the quad-rotor configuration are shown in front-view and in side-view in Figures 15 and 16 respectively.

The tower-top maximum out of plane direction is 1.1 m, with a main tower height of 109.45 m. The tower-top deflection slope angle is 0.57°, compared to 0.55° of the single-rotor tower. Again, the reduced aerodynamic and inertial loads of the quad-rotor configuration have played a major role in the good structural behavior of the support structure.

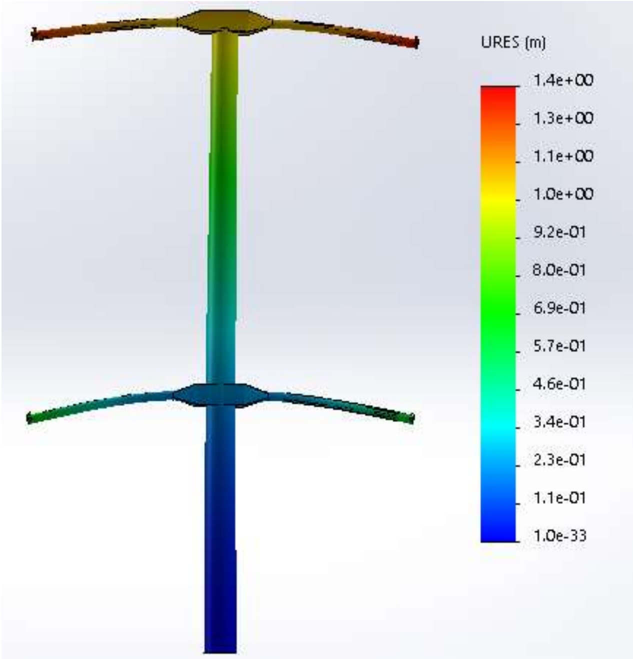

Fig. 15. Quad-Rotor Support Structure Deflection - Side View

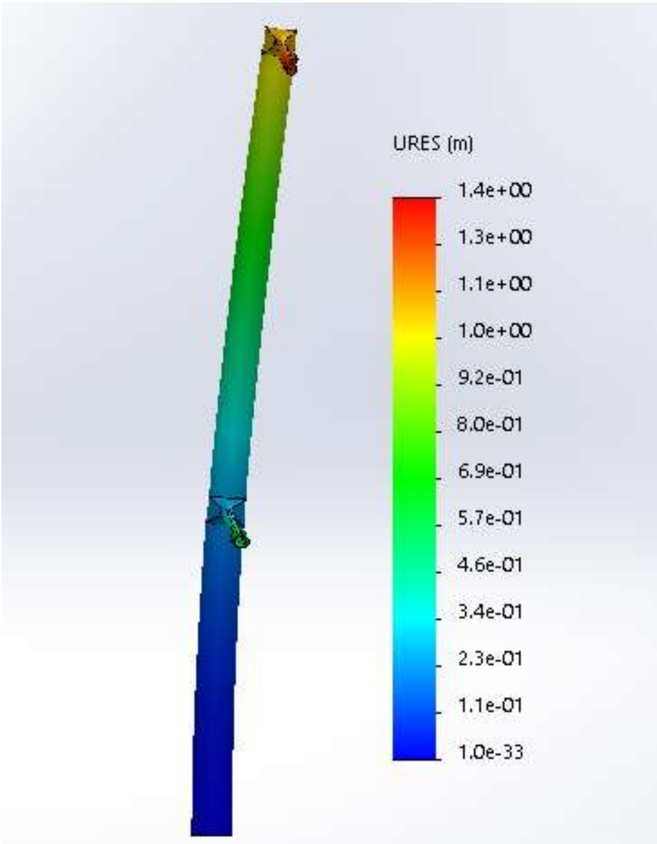

Fig. 16. Quad-Rotor Support Structure Deflection - Side View

The side-booms have also been behaving the same as the previous MRS configurations. The maximum deflection of the upper side booms is 1.4 m relative to the tower base, which means only 0.3 m relative to the deflected tower-top.

5. Conclusions

In this work, three different multi-rotor system (MRS) wind turbines are investigated for their aerodynamic performance and structural behavior. The NREL 5 MW wind turbine is scaled-down to twin, tri, and quad-rotor configurations such that the total turbine capacity of each configuration is the same as the reference turbine with a value of 5 MW.

The MRS configurations have shown a significant decrease in the aerodynamic loads as compared to the single-rotor. The masses of the rotors and nacelles have also been decreased drastically. This decrease can reduce the total cost of energy (CoE).

However, the support structure is one of the challenges of the MRS turbines. A structural design for the support structure for each configuration has been proposed, and the total mass of the turbine has been evaluated. Although the size of the structure has increased to accommodate all the rotors in each turbine configuration, but the total mass of the turbine was reduced by 25.6%, 16.9%, and 22.5% for the twin, tri, and quad-rotor configurations respectively.

A preliminary structural analysis has been performed on each configuration to assess the quality of the structural design. The main factor of comparison was the deflection slope angle, compared to the reference single-rotor tower with a deflection slope angle of 0.55°. The results for the MRS configurations gave values of 0.6°, 0.54°, and 0.57° deflection slope angles for the twin, tri, and quad-rotor configurations respectively. The values are comparable to the reference wind turbine, and further improvements can be achieved by optimizing the support structure, using support beams, or guy wires. The side booms have been found to behave differently from each side of the turbine since the right side is subject to an imposed rotor torque and inertial loads. Unlike the left side where the torque counteracts the rotor and nacelle weights. A guy wire or a support beam will also be useful in this case.

The approach in this study was to use the reference turbine tower as a guide for the support structure. Based on this approach, increasing the number of rotors does not always improve the overall weight of the turbine. The rotor and nacelle masses decrease as the number of rotors increases; however, the support structure size increases as well and hence the total mass should be judged. The total mass of the tri-rotor is greater than that of the quad-rotor configuration, so, a compromise between the number of rotors and total mass should be addressed thoroughly in the design. Nevertheless, there is always a mass reduction in the MRS wind turbine compared to an SRS wind turbine.

Further improvements to this work can be achieved by studying the aerodynamic interaction between rotors to get more accurate results. Also, optimization to the support structure, using different materials, or different rotor arrangements can improve the results.

Nomenclature

Abbreviations

BEM	Blade Element Momentum
CAD	Computer Aided Drawing
CFD	Computational Fluid Dynamics
CoE	Cost of Energy
MRS	Multi Rotor System
NREL	National Renewable Energy Laboratory
SRS	Single Rotor System

Symbols

a	Axial Induction Factor (–)
A	Rotor Swept Area (m^2)
a’	Tangential Induction Factor (–)
c	Chord Width (m)
Cd	Coefficient of Drag (–)
Cl	Coefficient of Lift (–)
CP	Coefficient of Power (–)
D	Diameter of SRS Rotor (m)
Dn	Diameter of MRS Rotor with n Rotors (m)
m	Mass of SRS rotor (kg)
mn	Mass of MRS Rotor with n Rotors (kg)
n	Number of Rotors in MRS Turbine
P	Power (W)
v	Upstream Wind Speed (m/s)
Vrel	Relative Wind Speed (m/s)
ρ	Air Density (kg/m^3)
φ	Flow Angle (°)

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