A Lightweight Approach for Airborne Wind Turbine Drivetrains

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Abstract

Buoyant airborne wind turbines are devices capable of harnessing stronger winds at higher altitudes and with their automated and rapidly deployable system they are suited to niche applications such as emergency power generation. Although much of the wind turbine technology for these systems is common with their 'grounded' cousins, an additional design limitation is the requirement for the wind turbine equipment to be lightweight. This paper concentrates on the drivetrain of the wind turbine and the different potential ways of reducing its mass. A buoyant airborne wind turbine with different types of drivetrains, going from gearless to geared systems with distinct gear ratios, has been analysed. Special attention was paid to the mass of the supporting structure of the permanent magnet electrical generator and this was minimized by utilising low density materials, such as composites, in its design. The model showed that a significant reduction in the mass of the drivetrain can be achieved in the gearless case by using materials with a higher ratio of Young's Modulus to density for the electrical machine supporting structure. For the geared systems, mass decrease was less significant as the gearbox mass had also to be considered. ***Keywords:*** **Airborne, lightweight, generator structure, composite materials**

1 Introduction

Airborne wind turbine systems are gathering increasing attention as they are able to capture stronger winds at very high altitudes. There are a plethora of different airborne wind turbine types, e.g. buoyant [1], flip-wing style (Mars) [2] and kite (SkySails power system) [3]. This paper concentrates on buoyant airborne wind turbines, also known as BATs. An example of such a system is the Altaeros turbine, displayed in Figure 1.

Figure 1: Buoyant airborne wind turbine (BAT) [1]

These devices are composed of a high performance fabric shell filled with helium that puts a horizontal axis wind turbine up in the air. High strength tethers keep the turbine in place and send power to the ground station which comprises an autonomous control system and power conditioning equipment. Most of the wind turbine technology for these systems is similar to that of the 'grounded' turbines. However, some further constraints are added to their design. This paper attempts to address the different potential ways of decreasing the mass of the drivetrain. Looking at the turbine equipment, it was identified that the supporting structure of the PM electrical generator was one of the heaviest components. The structure of the generator must be able to:

- Transmit and react torque,
- Maintain a clearance between rotor and stator subject to a magnetic force of attraction between the magnets on the rotor and the steel on the stator,
- Maintain that clearance subject to the radial expansion due to rotation.

Therefore, a suitable design would be one that matches all of these requirements at the lowest possible mass. Having this mind, different drivetrains arrangements were analysed, going from gearless to conventional geared systems with diverse gear ratios, paying special attention to the generator structure that was designed using composite materials.

2 Drivetrain model

This investigation is based on a 100 kW buoyant airborne wind turbine with a swept area of 93.5 m^2 and 5.5 m rotor radius. With a rotor speed of 140 rpm, the low speed shaft nominal torque is 6.8 kNm. As explained, the turbine drivetrain must be as light as possible to be lifted up in the air. Bearing this in mind, a particular number of layouts – comprising gearless and conventional geared with several ratios – have been studied so as to find out the lightest possible layout. In the calculation of the drivetrain mass, the gearbox (if needed) and the generator masses have been considered. Gearbox masses are based on catalogue data for commercially available parallel and planetary gearbox units [4]. As the turbine in question is small in size, high rotor speeds can be achieved without exceeding tip speed limits, which means that geared systems will be operated at small gear ratios. The gear ratio, "i", is defined as:

$$i = {}^{n_1}/_{n_2} \tag{1}$$

where n_1 is the output rotational speed and n_2 is the input rotational speed, both in rpm.

In order to find the mass of the gearboxes, the masses of all the inline gearbox units with a torque output M_{N2}≥6.8 kNm were plotted into a graph and a trendline fitted. It was observed that Equation 2 with a R^2 = 0.8376 presented the best fitting,

$$m = 3.4316\ln(i) + 85.411 \tag{2}$$

where m is the gearbox mass (including the electric motors mounting). By using Equation 2, the mass of the hypothetical gearboxes working at i = 2, 3, 4, 5, 6, 8, 10 was found out. Figure 2 shows the wind turbine topology as assumed in this investigation.

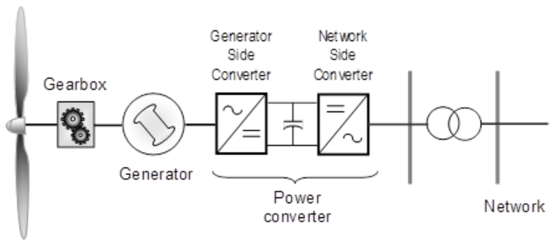

Figure 2: Wind turbine topology

The electrical generator mass involves the mass of winding copper, permanent magnets, steel (rotor and stator yokes, stator teeth), supporting structure and others (casing, bearings, mountings). The breakdown of masses for the 100 kW direct drive generator is shown in Figure 3.

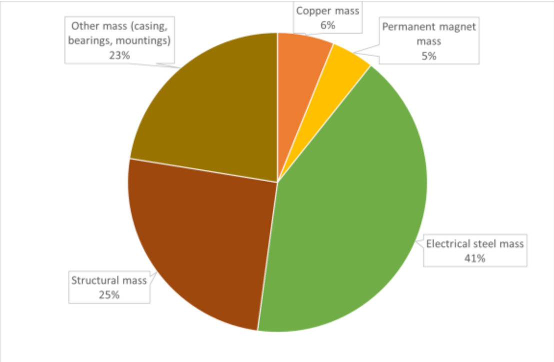

Figure 3: Breakdown of mass for the direct drive generator

Generator masses are based on basic electromagnetic design and torque scaling, with the addition of modelling the mechanical design to cope with forces within the generator. An electrical shear stress of 30 kPa is assumed for all designs. The size of the generator ranged from R=0.42 m for the direct drive case to R=0.19 m for a geared turbine with a drivetrain operating at gear ratio 10.

2.1 Generator assembly

The electrical machine supporting structure was designed to support the major loads present during generator's operation. It was considered that the structure must be able to withstand these forces without deforming more than 10% of the airgap size in any direction. Taking this into account, 2 different types of materials, those that are isotropic, such as steel, and those that are orthotropic, such as composites, were looked at. Making use of finite element techniques, also known as FE techniques, both types of structures were evaluated[5]. A comparison between these two revealed that the composite structure is able to perform as well as the steel structure. In addition, the structure made of composite materials was lighter than its counterpart made of steel.

2.1.1 Steel structure

The generator supporting structure is assumed to be made with discs. For all generators, the structure was CAD modelled and the major dimensions, t_c and t_d, thickness of the cylinder and the disc, respectively, varied so as to reduce the structural mass while meeting deflection criteria. The assemblies were constrained at the shaft and studied using a quad mesh of 5mm size. It was considered that all the structures were made of steel. The following are the material characteristics used for the steel models: density, ρ=7850 kg/m^3, Poisson's ratio, v=0.3 and Young's modulus, E=2.1x10^5 MPa. The structures were studied for mode 0 deflection (constant deflection around the airgap cylinder) with a normal expansion load of 400 kPa being applied to the outer face of the rim, as shown in Figure 4, for the rotor case. In the stator's case, the pulling out load was applied to the inner face of the cylinder[6].

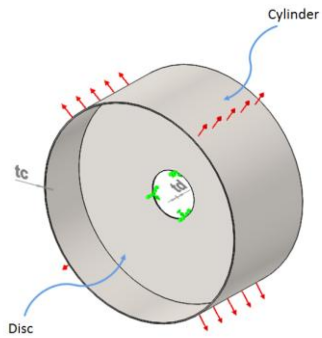

Figure 4: Disc rotor structure under normal stress

The FE analyses carried out highlighted that the highest deflection in the rotor structure takes place at the edge of the rim. With an airgap size of 2.1 mm, a cylinder thickness, t_c, of 5 mm and a disc thickness, t_d, of another

5 mm were required to comply with the deflection criteria in the gearless case. For the rest of the cases, big thickness variations were not needed as for the drivetrain operating at a gear ratio of 10, the thickness of the disc could be kept at 5 mm, whereas the cylinder thickness could be only decreased 3 mm.

For the stator structure, the highest deflection concentrated in the midpoint of the rim, right in between the two disc supporting structures. Variation of dimensions was made following the same pattern as for the rotor. It means that the same thicknesses used for the cylinder and for the disc of the rotor were utilised for the sub-structures of the stator.

2.1.2 Composite structure

The composite structure was designed in ANSYS Mechanical APDL[5], using carbon/epoxy as structural material and SHELL281 as element. The material properties utilised are as follows: E_1=203 GPa, E_2=11.2 GPa, G_{12}=8.4 GPa, v_{12}=0.32, ρ_c=1600 kg/m^3, δ=5x10^{-6} m and θ=1.96x10^{-11} m. Where E corresponds to the Young's modulus, G is the shear modulus, v is the Poisson's ratio, ρ_c is the density, δ is the distance between fibres and θ is the cross-section area of a single fibre.

As known, composite materials are anisotropic and non-homogenous. A lamina, also called ply or layer, is a single flat layer of unidirectional fibres arranged in a matrix, which serves to protect and bind the fibres together, as well as to transfer the loads. A laminate is a stack of plies of composites. Each layer can be set at different orientations and can be made of distinct material systems.

The cylinder sub-structure and the disc sub-structure were modelled separately and then joined together by merging their nodes. The disc sub-structure was designed utilising a mosaic pattern fibre orientation as used by Morozov's *et al*. in his model for flywheels[7]. The cross-section area of the disc was kept constant at a thickness, $t_{d,c}$=0.01 m. 8 plies of 1.25 mm were combined together to form the disc structure utilising the midplane as a reference.

The front surface of the disc was divided into different areas as shown in Figure 5. The same fibre layout as understood from Morozov's flywheel model was employed. The main purpose of this new model is to avoid stress concentrations by spreading them out throughout the whole structure. In order to orientate the fibres as desired, 4 different cylindrical coordinate systems were created. The fibres of the distinct areas were placed respect to these frames. In addition, certain key zones were reinforced using smear layers of the same material so that the stiffness of the structure could be improved. A secure bond between the reinforcing fibres and the base element is assumed by ANSYS and the motion of the reinforcing fibres is determined solely by the motion of the base element as the relative movement between the mentioned components is not allowed[8]. This was considered as a good way of incrementing the structural stiffness without adding extra mass. However, the FE analyses results showed that the influence of this reinforcement on the performance of the overall rotor and stator structures was minor as the major factor to be considered in the design of the generator structure is the fibre layout and the percentage of the 0/90/45/-45 plies of the cylinder

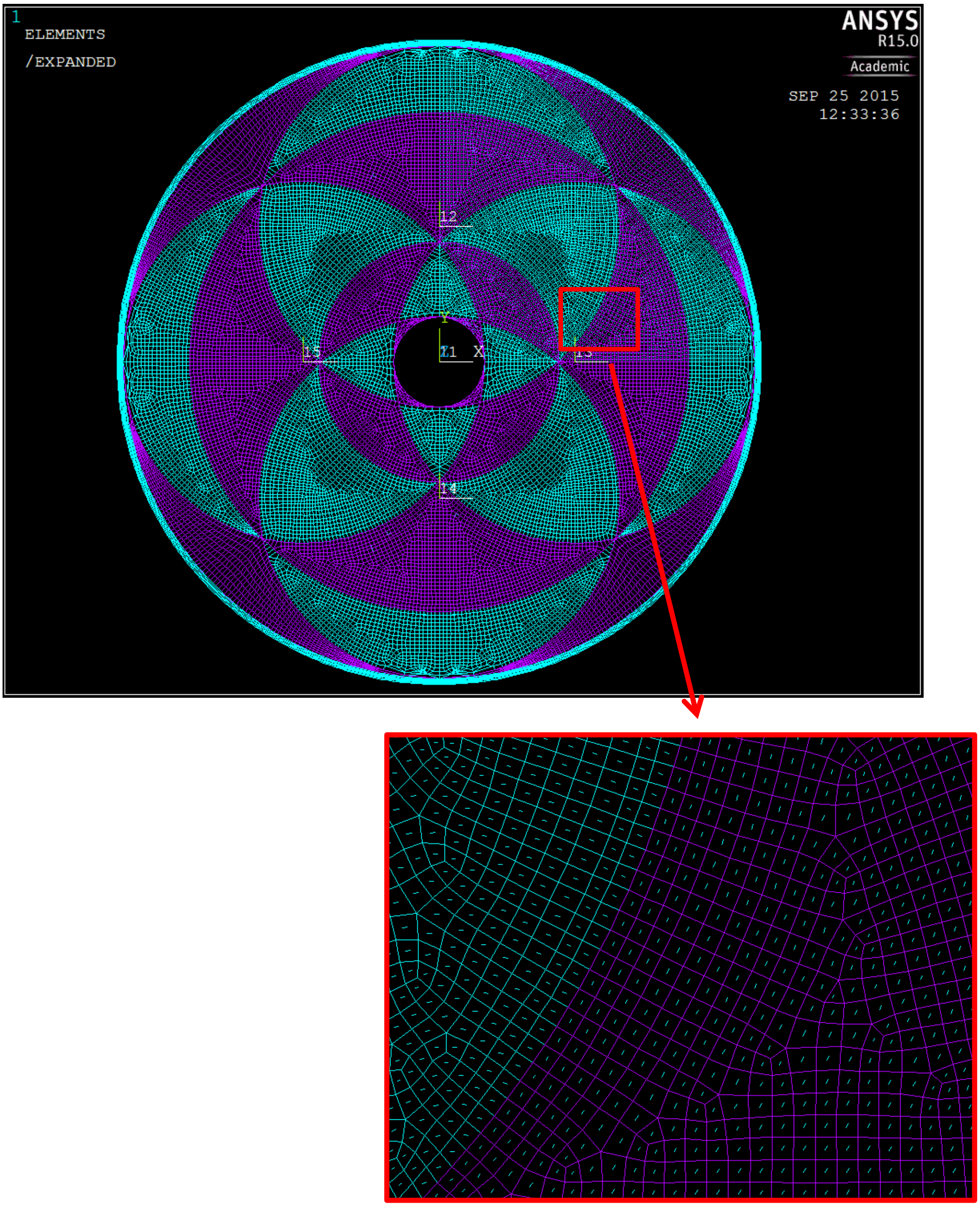

Figure 5: Detailed view of the composite rotor disc structure based on Morozov's model[7]

sub-structure. When modelling the rim, it was intended to keep the laminate symmetrical and balanced, to avoid warpage and shear.

Looking at the stress concentrations, the sub-structure was designed. 14 plies were needed this time, using the bottom plane as a reference, with the following layout: $[(90)_2/(\pm45)_2/0]_s$, with the subscript "$_s$" meaning that the laminate is symmetrical. Two plies at 90° and 2 mm of thickness, two plies placed at 45° with 1.5 mm thickness, another 2 plies at -45° with 0.7 mm thickness and 1 ply at 0° with a thickness of 1.7 mm were utilised to compose one half of the cylinder width. Various finite element studies were carried out to find out the best arrangement for the fibres of the rotor cylinder sub-structure observing the need of using a symmetric layout with 0 degrees plies at the mid-plane and a higher percentage of 90 degrees plies at the edges. The rotor structure was analysed using a 5 mm quad mesh that had to be refined at the very sharp edges. Again the model was constrained at the shaft and the normal load placed on the outer surface of the rim. See Figure 6 for a detailed view of the rotor structure radial deformation (U_x=0.208x10^{-3} m) caused by the mentioned load for the gearless drivetrain. As it happened for the steel structure, the highest deformation was observed to take place at the edges of the rim.

In the case of the stator, the same disc sub-structures were applied. Nevertheless, the geometry of the stator is completely different to that of the rotor. The configuration with the two discs helps to make the overall structure stiffer and therefore reduce the deflection. But as composites are orthotropic materials, the fibre

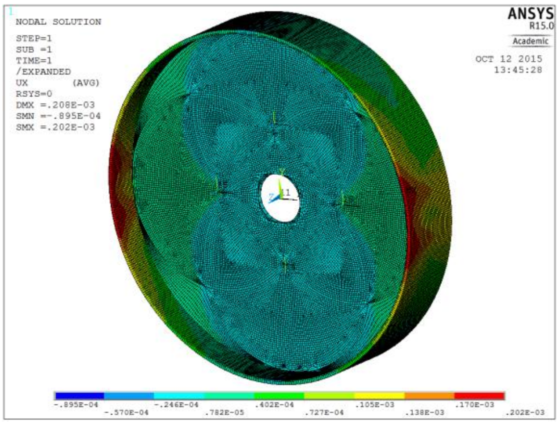

Figure 6: Rotor composite structure highlighting deformation in radial direction

layout must be accordingly aligned to take advantage of the material properties and also take advantage of the structure geometry. As it happened with the rotor, the cylinder sub-structure showed a huge influenced on the stiffness of the whole structure. This time 20 plies were necessary. The layout as follows: $[(90)_2/(0)_4/(\pm45)_2]_S$. Employing the bottom plane as a reference, 2 plies of 0.5 mm at 90°, 4 plies of 1.6 mm at 0°, 2 plies of 0.5 mm at -45 degrees and another 2 plies of 0.5 mm at 45 degrees each were applied to form one half of the cylinder thickness. The FE studies highlighted that the highest deformation localises in the middle of the rim structure, right in between the two disc structures as it happened with the structure made of steel. See Figure 7 for a view of the stator structure radial deflection (U_x=0.205x10^{-3} m) produced by the normal stress for the direct driven generator.

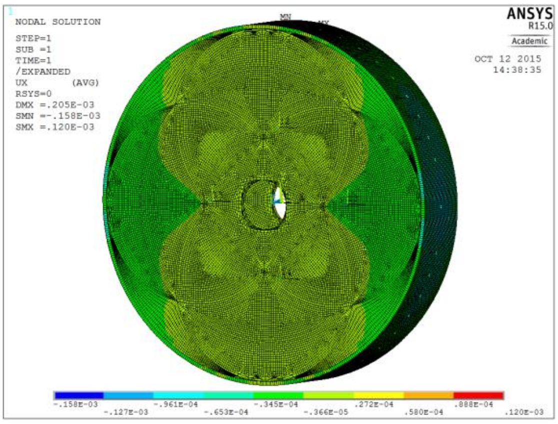

Figure 7: Stator composite structure highlighting deformation in radial direction

3 Drivetrain mass comparison

A comparison between drivetrains mass having generator supporting structures made of either isotropic material (steel) or orthotropic material (carbon/epoxy) was carried out. The obtained results were plotted against the gear ratio as illustrated in Figure 8. A breakdown of mass for all the generator models is shown in Figure 9. It was seen that the use of composites helps reducing the mass of the

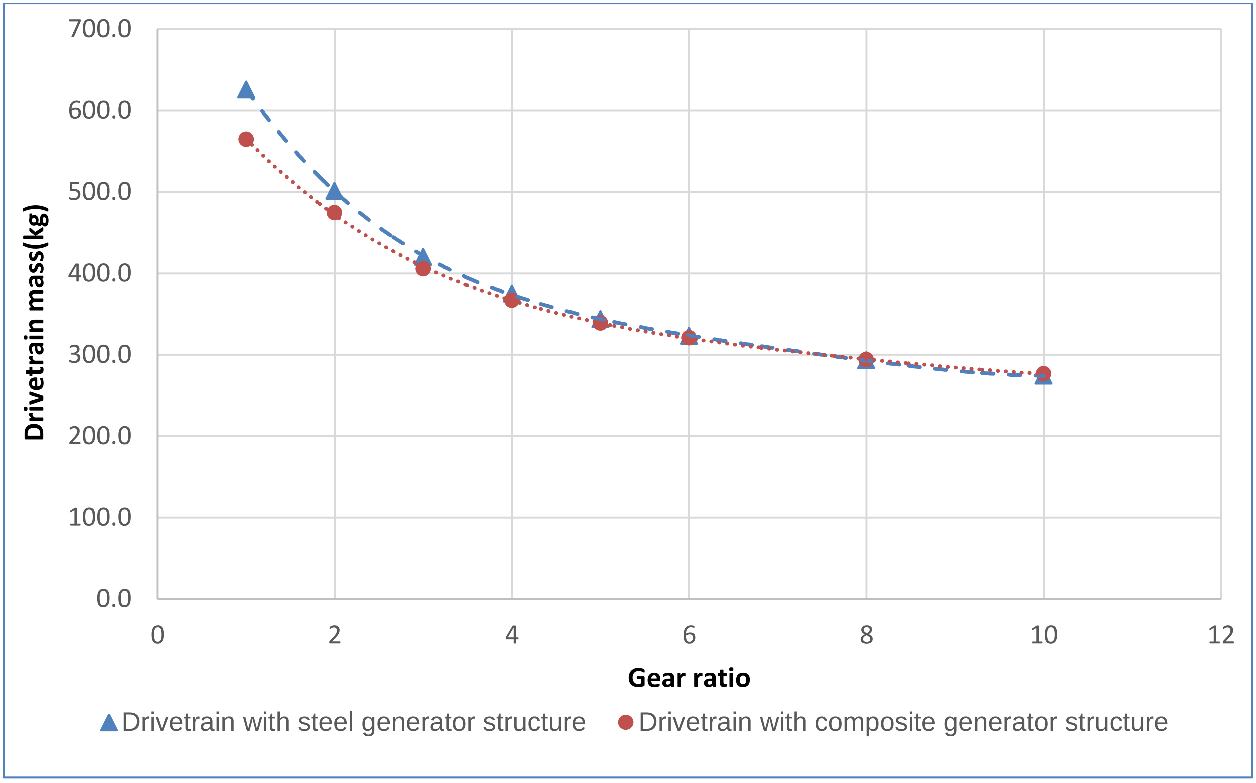

Figure 8: Total drivetrain mass (mass of gearbox and generator) plotted against gearbox ratio for steel and composite generator supporting structures

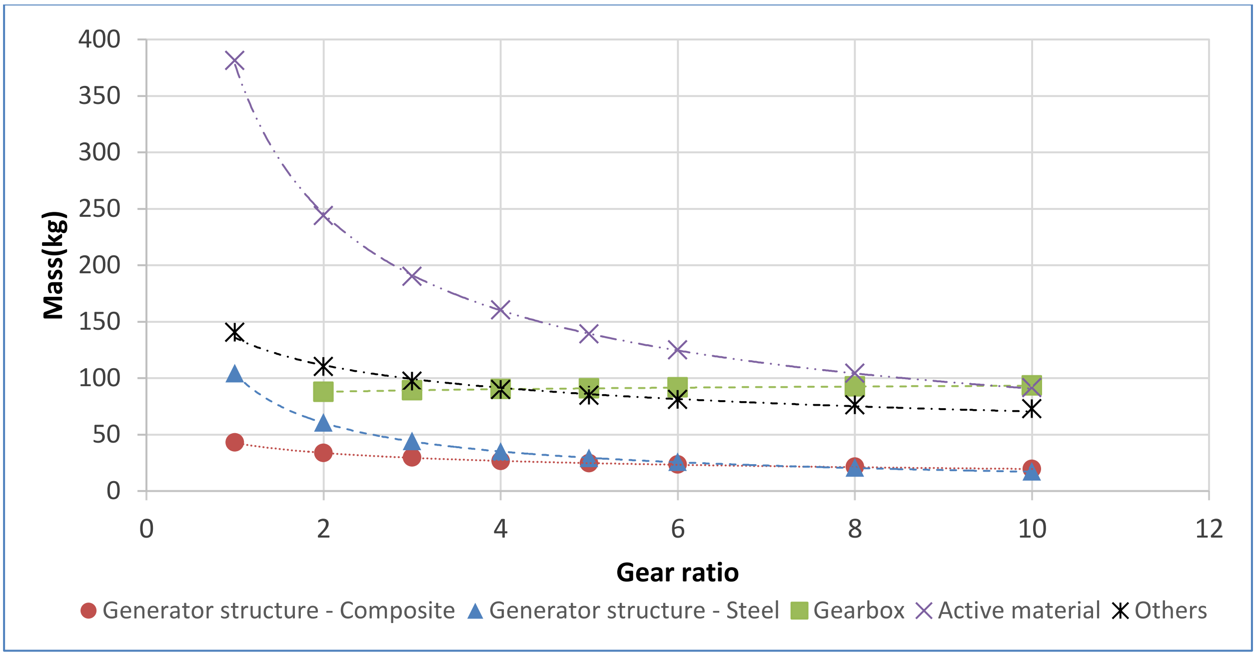

Figure 9: Breakdown of mass for the generator models

overall drivetrain mass, especially in the gearless case, where the difference between the arrangement composed by steel supporting structures and the drivetrain made with composites is 62 kg. This gives an overall mass decrease of almost 10%. By utilising this lightweight model, the shroud size could be reduced and the required amount helium diminished. Other options would include going for larger blades or increasing the efficiency of the generator itself by adding more permanent magnet material.

The gap narrows down as the gear ratio increases. As understood, the lowest mass is given for the drivetrain operating at gear ratio 10 and having the generator supporting structure made of steel. Nevertheless, it is important to notice that in direct drive machines, the electrical generator is directly coupled to the hub, which means that no gearbox is needed in the drivetrain. This leads to increases in the efficiency, availability and reliability of the system and a reduction in noise levels. These benefits must also be considered when selecting the most appropriate drivetrain layout.

On the other hand, it is important to notice that this paper concentrates on disc structures, as they are relatively simple to model and describe but other geometries, such as the one defined in [9], are also available. This patent obtained by SIEMENS AKTIENGESELLSCHAFT, displays several direct drive wind turbine configurations where both the rotor and the stator structures are composed by a rim and two thin disc/conic supporting sub-structures that enhance the stiffness of the overall machine. This type of generator shape will be considered in future investigations.

4 Conclusions

Buoyant airborne wind turbines are devices consisting of a buoyancy system which lifts a lightweight horizontal axis wind turbine up in the air so the stronger winds blowing at higher altitudes can be captured. In this paper, different drivetrain arrangements, from gearless to conventional geared systems, have been analysed in order to find out the lightest configuration. It was observed that the supporting structure of the electrical machine is one of the heaviest components that could be redesigned using materials with a higher Young's modulus to density ratio, such as composites. Making use of carbon/epoxy, a generator structure made with discs was designed. Both rotor and stator disc sub-structures had a mosaic pattern fibre layout with a smear layer of reinforcement. The rotor and stator structures were tested under a normal expansion loads placed on the rim sub-structures. The results obtained were compared with those acquired for their counterparts made of steel. The study revealed that the composite generator structure performs as well as the steel structure under the mentioned load. At the same time, a considerable reduction of the overall structural mass was achieved, as it could be seen for the gearless case, where the mass difference was 62 kg. This means a 10% drop in the overall weight.

Despite of the reduction in mass of the drivetrain achieved by the implementation of composite materials, the lightest configuration corresponded to the arrangement with a steel generator structure and a gearbox operating at a ratio of 10. Finally, it is important to notice that neither the steel structure nor the composite one have been tested under torque loads. The combination of normal and torque loads will be presumably dangerous and it will force us to increase the thickness of the components forming the electrical machine structure, adding up more mass. The influence of the torque load on the structural design of the machine will be considered in future research, as well as other geometries that could enhance its structural performance.

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