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Generative Design and Additive Manufacturing Techniques on the Optimization of Multi-MW Offshore Direct-Drive Wind Turbine Electrical Generators †

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Abstract: New advances in structural optimization techniques and manufacturing methods, such as generative design (GD) and additive manufacturing (AM), are revolutionizing the capabilities to generate high-efficiency and lightweight models in comparison with conventional processes. This study addresses a structural optimization strategy for offshore wind turbine direct-drive generator structures using generative design (GD) and additive manufacturing (AM) techniques. The use of multi-objectives structural optimization processes using GD techniques allows for the exploration of a wide number of unconventional topologies on a tailored, fit-for-purpose strategy, and the implementation of AM methods makes possible the fabrication of complex designs with metallic and composite materials. GD and AM represent a revolution in the field of design optimization, offering flexibility and adaptability while collecting a vast amount of structural analysis data, crucial for a cost-effective approach in the early stages of design projects. The implementation of these techniques demonstrated over 7% weight reduction, a 40% increase in operational range, and a decrease in the cost of manufacturing.

Keywords: offshore wind turbine; direct-drive electrical generator; structural optimization; generative design; additive manufacturing

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1. Introduction

Renewable energy systems are a key factor for the implementation of global sustainable development. Offshore wind energy projects are growing in recent years as a reliable source of sustainable energy, and the implementation of direct-drive powertrain configurations in offshore wind turbines is a dominant choice due to their superior performance. Direct-drive wind turbines are electrical machines with a low rotation speed and high torque. This wind turbine configuration eliminates the use of gear boxes, providing a wide variety of advantages, including a simplification of the system, a significant weight reduction, and a maintenance downtime. These electrical machines can be excited electrically or with permanent magnets (PM), with the permanent magnets direct-drive (PMDD) configuration achieving higher electrical and structural performance. Permanent magnets generators are classified by the orientation of the magnetic flux into three categories: radial, axial, and traverse flux.

A PMDD wind turbine powertrain configuration can be observed in Figure 1. On large wind turbine applications, almost all generators use a radial flux configuration. PMDD wind turbines require stiff generator structures to retain the air-gap clearance between the rotor and the stator against the different loads acting upon the system [1].

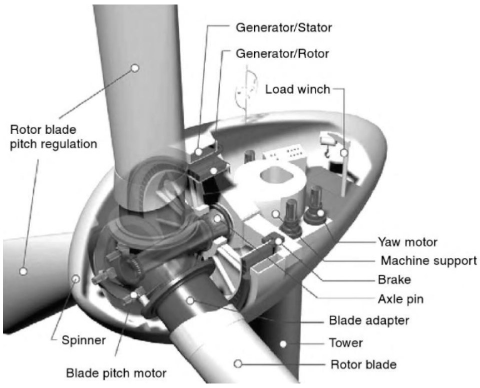

Figure 1. Wind turbine direct-drive system representation [2].

Over 60% of the total mass of PMDD generators corresponds to the inactive material, also known as the supporting structure. High-torque loads acting on these support structures and the requirement to maintain the air-gap clearance between the rotor and the stator involve great challenges on the design process. The exploration of different support structures for PMDD generators has been researched, analyzing structures of simple topologies (discs, cones, and arms), often designed to be manufactured in cast iron. Innovative design optimization techniques such as GD have been utilized to analyze PMDD generators, pushing the boundaries of conventional structural optimization methods and discovering novel topology configurations [3].

Structural optimization processes involve optimization algorithms that can be convoluted for complex topologies, involving a large set of design variables, complicated mesh analysis, multi-objective requirements, and diverse manufacturing constraints. The integration of artificial intelligence (AI) and new design methods allows for the exploration of unconventional topologies. GD is an advanced design technique representing an innovative approach for structural optimization challenges, overcoming certain limitations of conventional topology optimization methods when generating functional solution models. This method creates an iterative model generation in which the process learns and adapts following a combined-objective convergence criterion [3].

Traditional topology optimization (TO) offers a guidance for weight-reduction operations, indicating the areas of the optimization volume domain where mass can be removed. On the contrary, GD can produce functional models generating mass around a certain optimization volume domain. Figure 2 is a representation of different optimization volume ranges and boundary conditions for a structural optimization process, where "Ω_{mat}" represents the volume of the material, "Ω" and "Ω_0" are the different optimization volume domains, and "Γ_{mag}" is the surface where the magnetic loads are applied [4].

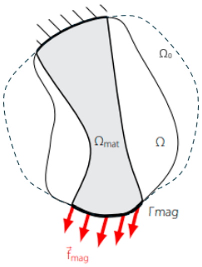

Figure 2. Representation of different optimization volume ranges for a structural optimization process [4].

A complex structural optimization often requires a multi-objective strategy; for PMDD generators, the main objective is to keep the air-gap clearance between the rotor and the stator within a limit value while maximizing the stiffness of the structure and reducing the total mass. Therefore, the primary criterion of the multi-objective optimization strategy must be minimizing the displacement normal to the surface of the air gap. A representation of this function using a strain equation is described in Equation (1), where "Ω_{mat}" represents the volume of the material, "ε" represents the strain, "u" is the displacement, and "σ" is the density [4]:

$$\min \int_{\Omega_{mat}} \varepsilon\left(\vec{u}\right)^T \sigma\left(\vec{u}\right) d\Omega_{mat} \tag{1}$$

Advanced structural optimization using GD methods commonly generates complex innovative model results, which are often impossible to produce with conventional manufacturing processes such as casting or machining.

Additive manufacturing (AM) is a fabrication process that adds material layer-by-layer to generate a model instead of the subtracting material method of conventional manufacturing. AM allows for the fabrication of complex structures, reducing production time and manufacturing costs for small batches and opening the door for innovative capabilities on structural optimization techniques, such as unconventional geometries, hollow cavities, or internal lattice structures. Metal AM also offers high-performance material properties due to the high-temperature sintering in comparison with other manufacturing processes like casting [5].

The combination of advanced structural optimization flexibility with the capabilities of new manufacturing methods represents an innovative approach for complex systems, such as the design of PMDD generator structures.

2. Methodology

This study focused on the exploration of new approaches for the optimization of PMDD generator structures, new advances in manufacturing technology, and innovative design techniques. The case study generator chosen is based on the previous knowledge obtained from [3], where a multi-objective structural optimization strategy was developed for a 3 MW offshore wind turbine generator using GD techniques. Due to the limitations of AM on size regarding the build envelope of current machines, a scale down of the generator structure has been considered following the study [1], where a comparison between different size generators (3 MW and 100 kW) is developed using different materials. The 100 kW generator structure, with a rotor diameter of approximated 0.5 m, was selected to fit in the maximum 3D printing build envelope offered by the metal AM machine SLM NXG XII 600, with a build envelope of 600 × 600 × 600 mm.

The structural optimization strategy has been developed following the methodology established in [3], including a static structural and a modal analysis, with a scaled-down generator model for a wind turbine of 100 kW. Figure 3 is a representation of part of the process of the generative design method in ANSYS.

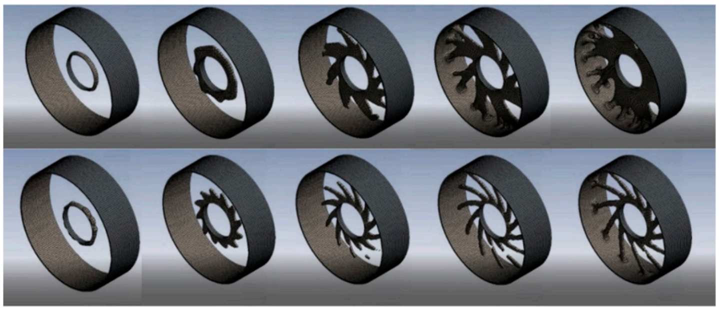

Figure 3. Structural optimization process using generative design techniques [3].

A preliminary approach of the capabilities of AM has been integrated into the structural optimization strategy using manufacturing constraints such as overhang angle and build direction. Moreover, a simulation of the AM process has been assessed using Fusion

360. Due to the wide number of commercial AM machines offered in the software and the different setup configurations available, the parameters have been assessed to optimize the AM process for the application. The AM machine SLM NXG XII 600 has been selected to maximize the build envelope and build-up rate of a large-size component, in this case, a PMDD generator support structure. These parameters are described in Table 1.

Table 1. Parameters for a selective laser melting process of additive manufacturing simulation in Fusion 360.

Setup		**Statistics**	
Machine	SLM NXG XII 600	Layer count	3060
Build envelope	600 × 600 × 600 mm	Building height	153.000 mm
Build-up rate	1000 cm^3/h	Support volume	47.044 cm^3
Spot size	80 µm	Production time	49 h 44 min
Material	AlSi10Mg		
Support method	Automatic Bar Support		
Overhang angle	45 degrees		

3. Results and Discussion

A scaled-down model of the wind turbine generator of 3 MW has been constructed to be assessed according to the AM limitation of current machines. The model generated for the 100 kW PMDD generator has been used to develop an AM simulation in Fusion 360 in order to obtain a preliminary assessment on the use of AM in combination with GD structural optimization methods. Figure 4 shows a selective laser melting process for AM using Fusion 360, with the representation of different printing layers throughout the process.

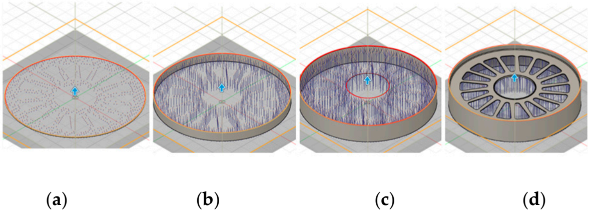

Figure 4. Selective laser melting process (SLM) of additive manufacturing simulation in Fusion 360: (**a**) Layer 101 (5.05 mm); (**b**) Layer 801 (40.05 mm); (**c**) Layer 1501 (75.05 mm); (**d**) Layer 2001 (100.05 mm).

In order to have a preliminary assessment of the process, the material selected is AlSi10Mg due to the accessibility to information on the energy consumption of the AM process provided in [6]. In Figure 5**,** we can observe an energy Sankey diagram for the AM process of SLM using AlSi10Mg, representing the complexity of the AM process where just 26% of the total energy consumption is used printing the part for a part of 5.5 cm, with a total energy used of 103.29 MJ. This highlights the importance of consideration at the design stage of the manufacturing process as part of the optimization strategy. An estimation for the 100 kW model of 0.5 m of diameter states that a component of similar complexity that is ten times bigger would consume five to seven times more energy [7].

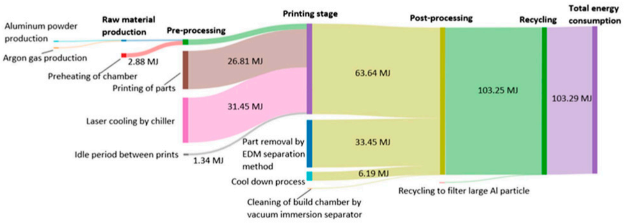

Figure 5. Energy Sankey diagram for an additive manufacturing SLM process of a single part of AlSi10Mg [6].

4. Conclusions

Integrating the flexibility of advanced design techniques such as GD with the capabilities of new manufacturing methods such as AM represents a revolution in the exploration of high-performance structures. Combining these innovative approaches offers a complete analysis of the structure from the design development to the manufacturing process. This study shows that using these novel processes could achieve cost-efficient results and improvements on lead times for small batches for new topologies of PMDD generator structures in comparison with conventional processes.

The design challenges associated with PMDD generators require the most advanced design and analysis techniques, and the exploration of new materials and manufacturing processes is needed for more sustainable and efficient renewable energy systems.

GD is a flexible, highly adaptable, and intelligent analysis process that allows for us to discover unconventional structures while offering an interactive design environment. The analysis of complex topologies, hollow cavities, internal lattice, or thin-reinforced walls, generates novel paths to design fit-for-purpose efficient structures. The rapid development of AM makes possible the fabrication of these original topologies and the accessibility to different materials, both metals and high-performance composites.

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