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Design and optimization of multi-MW offshore direct-drive wind turbine electrical generator structures using generative design techniques

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ABSTRACT

The use of generative design as an alternative to typical structural optimization techniques opens the door to new methods of manufacturing. In this study, generative design techniques were used as an automated iterative process with an extensive set of control variables and initial models to explore and optimise the stiffness and weight of different configurations for a 3 MW offshore wind turbine electrical generator structure. With this new approach of adding generative design techniques to a structural optimization process, a 4% reduction in structural mass was achieved. The modification in the structural geometry also help to enlarge the machine's operational range with the consequent growth in energy gathering.

1. Introduction

Electricity as a source of energy is a fundamental factor of modern growth and the development of renewable energy systems is essential to accomplish a sustainable future (IEA, 2019). Wind energy is the most developed and mature renewable energy technology offering a significant an advantage in cost-effectiveness, sustainability, and lifetime costs in comparison with other renewable energy sources (Ostachowicz et al., 2016). Offshore wind resources are higher in energy density, steadier, less turbulent and with fewer land use limitations than onshore. The conditions created by offshore winds generate more efficient environments to develop wind farms than onshore, obtaining over 50% more energy in average. However, offshore wind applications face complex design and planning obstacles due to the open sea's harsh weather conditions and the inaccessibility to the machines for maintenance purposes. Due to the difficulties of access and downtime, minimizing costs and developing lightweight structures with simple installations have become an important area of study. Direct-drive wind turbines have been implemented in offshore wind developments contributing to a wide range of advantages, such as overall mass reduction, simplification of the structure and compactness. In comparison with conventional geared wind turbines, the removal of the gearbox significantly diminishes the number of moving parts, reducing downtime periods and maintenance processes. Direct-drive generators have low operational rotation speeds of around 10 rpm and high torques are developed through the generator structure (Wilson, 2010; Carroll et al., 2015; Márquez et al., 2018). Fig. 1 depicts a typical wind turbine direct driven powertrain configuration with a permanent magnet electrical generator, "PM". In order to excite an AC synchronous generator, different ways exist: including electrical excitation and permanent magnet excitation. Switch reluctance generators are machines in which only the stator is electrically excited. Higher electrical efficiency, reliability, structural compactness, and lower weight make PM machines superior to electrically excited generators. Having said this and with a clear trend showing that the offshore wind energy industry leans towards the use of permanent magnet machines for direct-drive powertrains, also known as "PMDD", and the authors have focused their attention on this configuration.

Different topologies have been researched for the supporting structures of PMDD generators based on simple shape forms such as discs, cones, and arms. These large structures are usually made of cast iron and designed in a modular manner. By dividing the structures in smaller parts is possible to overcome the issues associated with transportation regulations and installation and manufacturing limitations. Fig. 2 shows the typical configurations for direct-drive wind turbine electrical generator supporting structures.

PM generators can be characterised according to the orientation of the magnetic flux as it crosses the existing airgap between the rotor and the stator, as follows,

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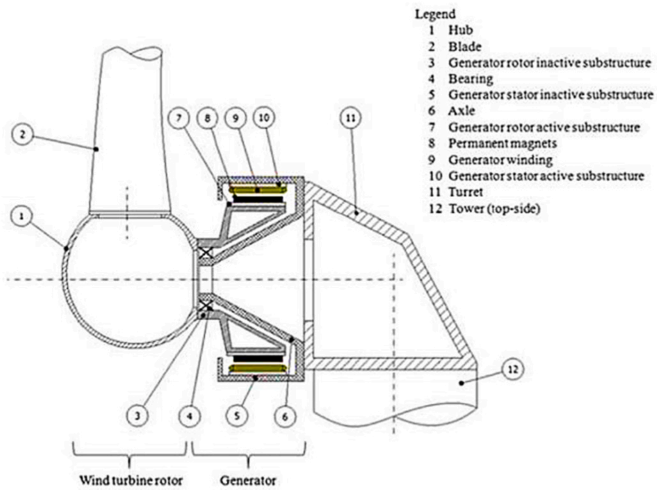

Fig. 1. Direct-drive configuration (Stander et al., 2012).

- radial flux
- axial flux
- transverse flux.

The radial flux, "RF", configuration has been widely used for commercial models (Mueller and Polinder, 2013) and it is the one chosen for this investigation. The topological configuration and the basic components of a PMDD radial flux electrical generator are displayed in Fig. 3.

Most of the research to date has focused on the active material weight reduction, that includes all the electrically active components of the machine, such as copper wiring, back iron and magnets. Nevertheless, the highest mass contribution of PMDD generators, in the order of 2/3 of the total mass, is associated with the inactive material, which corresponds to the electrically inactive parts of the generator (Jaen-Sola, 2017; Jaen-Sola and McDonald, 2014), also identified as the supporting structure.

The design of PMDD radial flux generators involves great challenges due to the high torque loads involved and the necessity to maximize the structural stiffness in order to maintain the airgap open and stable. The generator power output "$\boldsymbol{P}$" can be described by the equation $\boldsymbol{P} = \boldsymbol{T}\,\boldsymbol{\omega}$, where "$\boldsymbol{T}$" is the torque generated and "$\boldsymbol{\omega}$" is the rotational speed. By assuming the generator as a cylinder with surface stress applied, see Fig. 4, the generator torque can be calculated as follows, $\boldsymbol{T} = 2\pi\boldsymbol{\sigma}\boldsymbol{R}^2\boldsymbol{l}$, where "$\boldsymbol{T}$" is the torque produced by the generator, "$\boldsymbol{\sigma}$" is the shear stress, "$\boldsymbol{R}$" is the radius of the air gap and "$\boldsymbol{l}$" is the axial length.

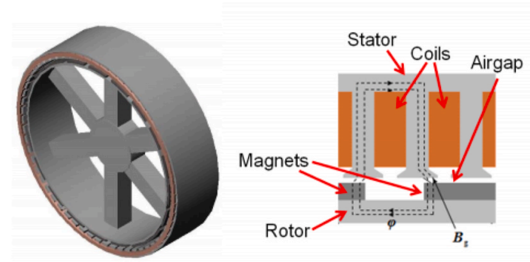

Fig. 3. PMDD radial flux generator (Jaen-Sola, 2017).

The main loads acting over the PMDD generator structure and used in this study are presented in Fig. 5. The normal stress is shown in Fig. 5 (a), and it is due to the effect of the magnetic attraction between the moving and the stationary components. It is the largest with a value in the range of 200–400 kPa. The shear stress is originated in the airgap as one structure tries to slide the other. It is in the order of 25–50 kPa. See Fig. 5(b). The gravitational load with a value of 9.81 m/s^2 is shown in Fig. 5(c) and it is of significant relevance for this type of structure not only during operation but also during transportation and installation.

The modes of deflection of a structure define the degree of

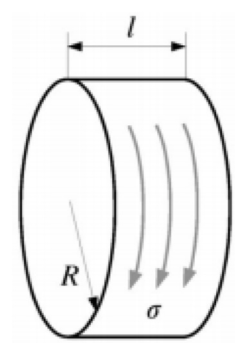

Fig. 4. Generator cylinder model for torque representation (Jaen-Sola, 2017).

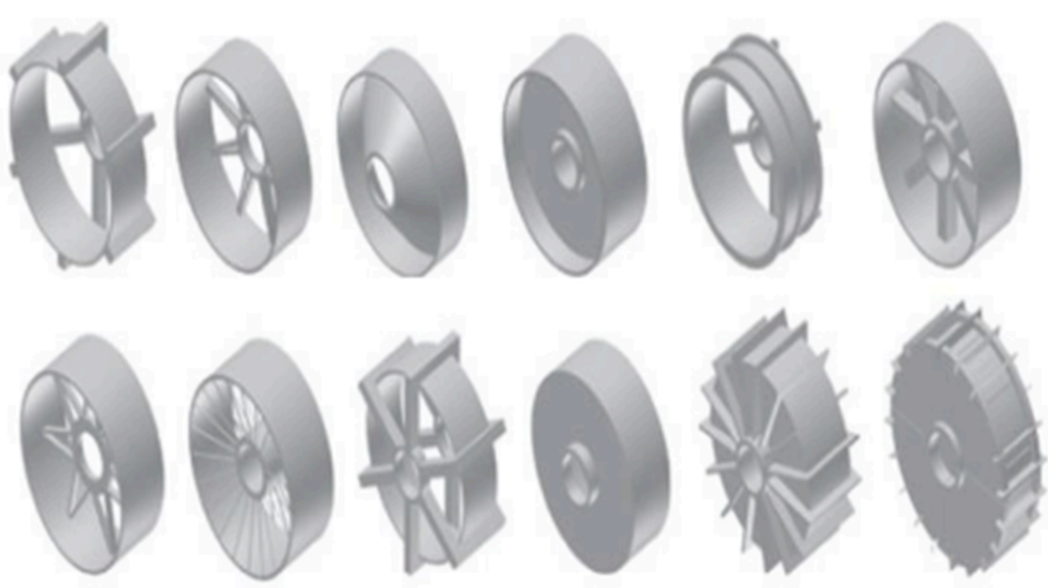

Fig. 2. Conventional direct-drive generator supporting structures (Stander et al., 2012).

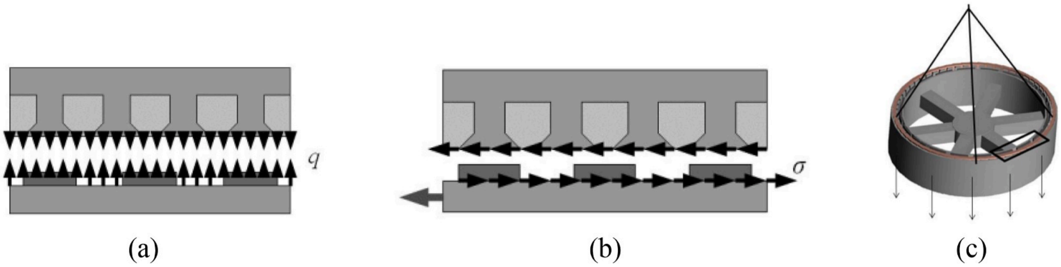

Fig. 5. Main loads at play in a RF electrical machine. (a) Magnetic attraction of the moving and the stationary components; (b) Shear stress; (c) Gravitational loading (McDonald et al., 2008).

displacement of a structural element under a load. The structure can adopt distinct shapes as it can be seen in Fig. 6 according to the operating conditions. In this study, a Mode 0 deflection corresponding to typical working conditions in which the generator structure deforms uniformly in the radial direction, with an expansion of the rotor structure and a compression of the stator structure has been assumed. Mode 1 corresponds to the deflection caused by shaft misalignment whereas Mode 2 shows an ovalizing behaviour and Mode 3 produces a structure with ripples.

However, when a more complex system is considered, for instance a 3-dimensional model, an advanced stress package is necessary. Using computational finite element techniques and generative design methods available in commercial packages (ANSYS 2020; Autodesk Inventor 2021 & Fusion 360) the structural optimization of a PMDD radial flux electrical generator has been addressed. The generative design method represents a revolution in design techniques which compromise an AI-based controlled framework to generate an optimization iteration of design models based on a series of pre-set parameters. The generative design method varies the initial parameters of the design to generate numerous models to satisfy the fitting requirements (Sangeun et al., 2019).

2. Structural optimization strategy

This study focuses on the optimization of the structural mass and

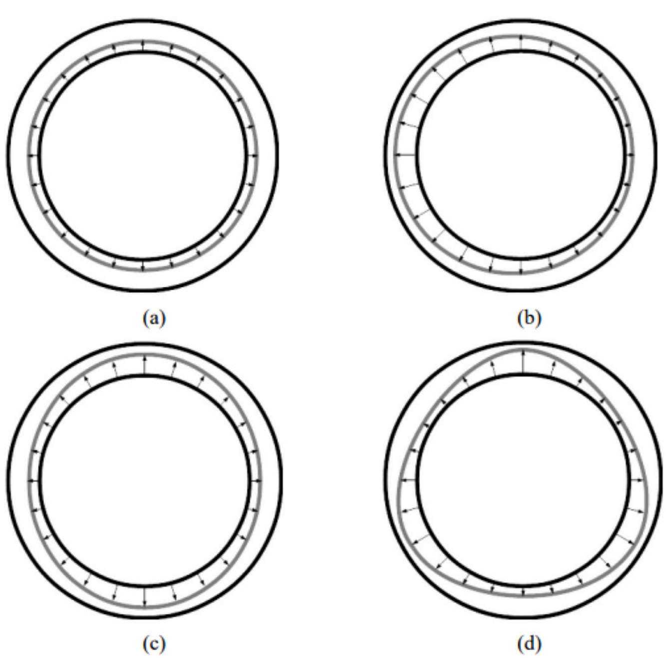

Fig. 6. Generator deflection modes. (a) Mode 0; (b) Mode 1; (c) Mode 2; (d) Mode 3 (Jaen-Sola, 2017).

stiffness of a multi-MW offshore wind turbine electrical generator rotor based on the research and results obtained by Jaen-Sola et al. in (Jaen-Sola et al., 2018) & (Jaen-Sola et al., 2020), using a generative design method. The structural optimization algorithm was developed by considering the convoluted nature of the process followed in this study. See Fig. 7. The main procedure is the generative design process in which different initial models were used applying different sets of variables and boundary conditions. The initial models were addressed from a general perspective, i.e., solid cylinder, to a more targeted-oriented model, in this case known as the preoptimized disc structure.

Due to the complexity of the structural optimization algorithm numerated blocks and arrows were used in Fig. 7 to explain the flow of the methodology and the steps followed. It explains where a model is dismissed, and its procedure ends with each iteration while using the feedback in the next generation of models. The fitness-based selection process of the genetic algorithm is based on different criteria, such as structural compliance, mass reduction percentage, topology complexity or computing processing ineffectiveness. The structural optimization process is described as follows:

1. Initial specifications: Wind turbine specifications and design parameters identification as defined in Tables 1 and 2 based on the research and results obtained by Jaen-Sola et al. in (Jaen-Sola et al., 2018) & (Jaen-Sola et al., 2020).
2. Solid cylinder model approach: A solid cylinder model is used as an initial model in the structural optimization algorithm. With the aim of observing the different results generated by the process, a more general strategy for the generative design control variables was employed.
3. Solid cylinder results and dismissed model justifications: At this stage the results obtained need further optimization and control over the generative design variables, highlighting the requirement of human input in during the process. The used of a solid cylinder for the process is dismissed justifying the causes, and the results obtained are used to provide feedback for the next generation of models.
4. Solid cylinder with variable shaft support approach: Feedback from the first generation of results of the structural optimization algorithm is applied to modify the initial model following a fittest-based selection process.
5. Solid cylinder with variable shaft support results and model dismissed justification: As described for step 3, the generative design results are assessed and used as feedback for the next generation of models.
6. Preoptimized disk & cone structures approach: Based on the observation of the generative design results of the initial iterations, a preoptimized model approach is used for the process based on the research and results obtained by Jaen-Sola et al. in (Jaen-Sola et al., 2018) & (Jaen-Sola et al., 2020).
7. Preoptimized conical structure results and model dismissed justification: The generative design results are assessed, and the cone model dismissed due to its complexity.

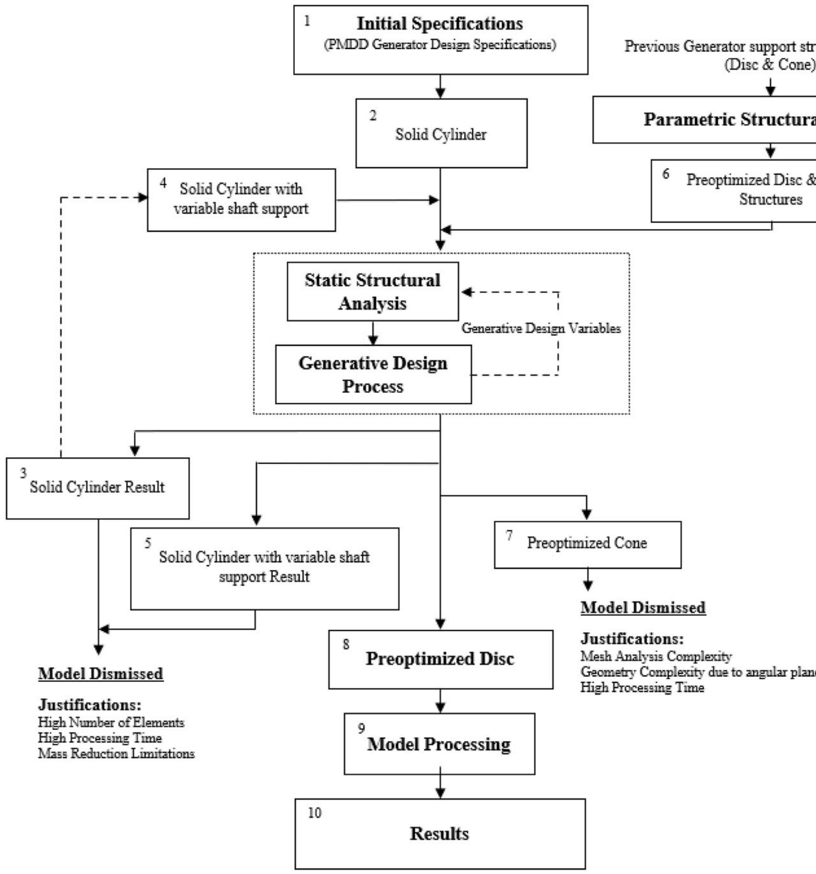

Fig. 7. Structural optimization algorithm.

Table 1
Physical properties of structural steel.

Young's modulus "E"	2.1×10^{11}Pa
Poisson's ratio "ν"	0.3
Density "ρ"	7850 kg/m^3

Table 2
PMDD generator design parameters.

Rated power	3 MW
Generator excitation	Permanent magnet
Permanent magnet topology	Radial flux
Drivetrain	Direct-Drive
Rotational speed	14 rpm
Axial length "l"	1.2 m
Rotor internal radius "R"	2 m
Shaft radius "r"	0.625 m
Airgap length "z"	0.0005 m
Pole pairs	60

8. Preoptimized disk structure results analysis and fittest model selection: The generative design results are assessed, and the selection of the disk structure results is stated as the fittest group.
9. Preoptimized disk model processing: Once the fittest generation of results is selected as the models generated for the disk structure, an individual solution is selected among the generated models and processed for a final exhaustive analysis and discussion of the results.
10. Final results analysis and conclusions: The final results of the selected model are addressed and discussed.

A 3 MW PMDD radial flux machine has been chosen for this study where 3 main loads are considered (see Fig. 8). These are, the normal stress applied uniformly on the cylindrical outer surface due to magnetic attraction, the shear stress produced by the effect of having one stationary component classically made of cast iron, such as the stator, involving one rotating component with permanent magnets attached to its outer surface, such as the rotor, only separated by a small airgap, and gravity. A Mode 0 deflection representing typical operating conditions was assumed for this analysis, which corresponds to a uniformly distributed deformation throughout the structure. A finite element

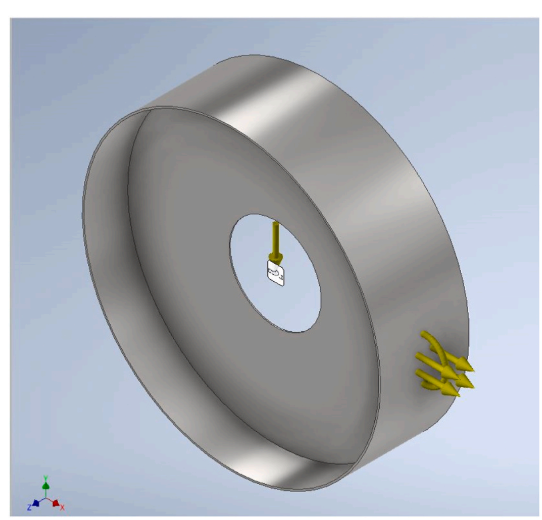

Fig. 8. Rotor structure loads and fixed support under working conditions.

analysis and a generative design approach have been implemented using Autodesk Inventor 2021 and Ansys 2020 R2. Table 1 lists the physical properties associated with the structural material used in this investigation while Table 2 describes the electrical machine design parameters. As it can be seen, cast iron has been selected as structural material for this 3 MW PMDD radial flux generator which rotates at a constant speed of 14 rpm and has a radius of 2 m, an axial length of 1.2 m and an airgap length of 5 mm. Number of pole pairs is 60 (Jaen-Sola et al., 2018).

A generative design simulation study follows a range of pre-set parameters and initial conditions. See Table 3. In this case, the loads acting over the PMDD generator structure are 400 kPa for the normal stress, 30 kPa for the shear stress and 9.81 m/s^2 for the gravitational load (Jaen-Sola and McDonald, 2014). A deflection limit corresponding to 10% of the airgap length was also imposed (0.5 mm). This is to avoid a potential increase in the magnetic attraction load that can put the structural integrity of the whole machine at risk. The rotor structure was fixed to the shaft.

In the generative design process, the software uses the information of the static structural analysis, generating an iteration of topologies which comply respecting the limit of deflection of 0.5 mm in the airgap. The initial geometry mesh settings, boundary conditions and response constraint method define the path that the iterative process will follow while generating different models. Different approaches were assessed during this process using different initial models, boundary conditions and manufacturing constraints.

2.1. Preliminary analysis using a complete solid cylinder

A solid cylinder structure was used as an initial approach to give freedom to the software to develop a first and general iteration of models. With this, the study shows a trend by the results and based on this information other initial structures are proposed too. This approach did not include any dynamic features. Making use of the physical dimensions given in Table 2, a solid cylinder with a mass of around 100,000 kg was set as initial model. The range of percentage of mass reduction was set to 80–85%, resulting in an unacceptable time of computation due to the high number of elements and calculations. See Fig. 9 for the initial visual results obtained for the solid cylinder and Table 4 for the initial numerical results achieved for models with hexahedral meshes with different levels of refinements.

Different mesh analysis variables were used for the process to obtain the different results, in particular the mesh sizing tools in Ansys (see Table 5). These tools are resolution of the mesh, with a set of parameters from 1 to 9; transition, controlling the change in element size, fast or slow; and span angle center, with the options of coarse, medium or fine. Setting these parameters we could obtain a coarse mesh, 50,000 to 100,000 elements for a preliminary, quicker process (Fig. 9 (a)); or on the contrary, obtaining a fine mesh, 500,000 to 1,000,000, where a more specific result was targeted having a time-consuming process. The manufacturing constraint tools in Ansys help to drive the generative design process towards a desire solution. As a rotational piece of machinery, the rotor structure needs to have a cyclic symmetry in order to have a good inertia performance. This constraint tool adds more control input parameters to drive the iterative process changing the process algorithm and generating a topology that satisfy a cyclic symmetry around a selected axis (Hendrickson and Chan; Jaisawal and Agrawal, 2021).

This preliminary study highlighted the need for the use of a simplified initial model. Fig. 10 shows an example of the different iterations for the preliminary analysis of the generative design process and how the software creates the topology throughout the different iterations following the initial set of parameters and boundary conditions to produce the result shown in Fig. 9 (b).

After the initial results, a simplification of the initial approach was addressed by adding to the boundary conditions the variable of the shaft fixed support position and width. An exclusion geometry was added in the generative design process, with a shaft boundary condition as a variable along with the outer cylinder face where the active material is mounted onto. An exclusion geometry is one that the piece of software will not be able to modify in any way during the study. A representation of an exclusion geometry can be seen in the preliminary solid cylinder approach Fig. 9, highlighted in red. Although the result of the preliminary study shows the mid-span position for the shaft support structure as the predominant result other possibilities were explored. Reductions in the structural mass were obtained but some limitations were encountered in model generation where the iterative generative design process was ending without a successful result and where the control methods weren't as efficient as the other approaches to arrive to a valid result. An approach with an offset position of the shaft support from the centre can be seen in Fig. 11, where the shaft support was set on one of the edges and where the width of the shaft was set with the different parameters (50 mm, 75 mm & 100 mm).

In the preliminary results it can be seen a tendency of the generated models to build up on a plane perpendicular to the shaft axis and more precisely the greater mass reduction of generated models with a central shaft fixed support (Fig. 12 & Fig. 13).

Another example of topology creation in the generative design process can be seen in Fig. 13, where different control methods (a) and (d) were used. The outcomes achieved showed that the use of a manufacturing cyclic symmetry constraint can help to reduce the total mass in a considerable manner while forcing the software to keep the symmetry.

The cyclic symmetry manufacturing constraint of the generative design process was considered for the study having a significant influence on the generation of models due to the rotational nature of the structure. The balance of mass around the axis of rotation improves the inertia of the structure. This constraint helps to generate models with a given value of symmetry as a variable.

An important observation was made about the complex nature of the generative design process followed. On top of the numerous initial variables available, the iterative process did not follow a linear response. A reduction in the initial condition known as mass to retain target did not imply aa decrease in the resultant structural mass. Therefore, as a linear approach could not be used, a manual genetic algorithm approach was applied using the generative design variables described in Table 3. A genetic algorithm constantly modifies individual solutions, selecting the fittest results, and using them as the parents for the next generation of solutions. After different generations of variable modifications and combinations, the process evolves toward an optimized model.

Table 3
Generative design variables.

Boundary Conditions Solid Cylinder	
Shaft fixed support position	central, side
Shaft fixed support width	full width, 50, 75, 100 (mm)
Mesh Analysis	
Number of elements	100,000–1,000,000
Type of elements	tetrahedral, hexagonal
Size of elements	Automated
Adaptative sizing	yes, no
Resolution of mesh	1–9
Transition	fast, slow
Span angle centre	coarse, medium, fine
Generative Design Process	
Convergence rate	5%
Number of iterations	10–500
Response constraint	mass to retain target (%), mass to retain range (%), generative design displacement limit (0.5 mm)
Manufacturing constraint	cyclic symmetry
Time of computation	30–360 (minutes)

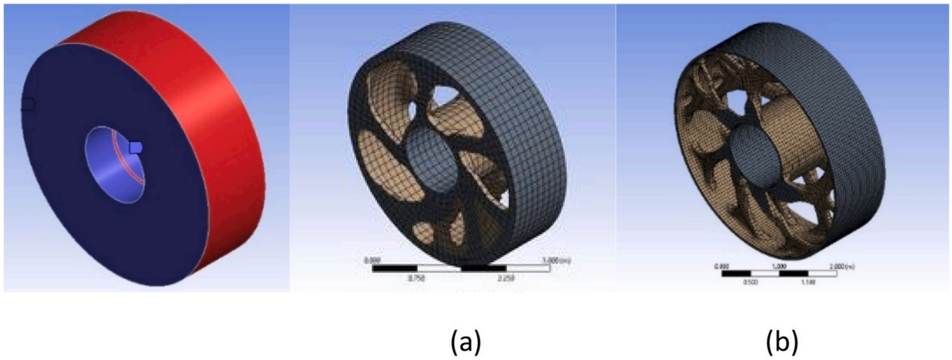

Fig. 9. Preliminary solid cylinder approach highlighting exclusion geometries (left); Initial results: (a) & (b) (right).

Table 4
Preliminary solid cylinder approach. Initial results: (a) & (b).

(a)	(b)
Coarse mesh (hexagons) Full shaft length support Structural mass (18,574 kg)	Fine mesh (hexagons) Full shaft length support Structural mass (14,574 kg)

Table 5
Generative design solid disc with offset shaft support initial parameters for (a), (b), (c).

(a)	(b)	(c)
Fine mesh (hexagons) No manufacturing cyclic symmetry constraint Edge width (50 mm) Structural mass (10,363 kg)	Fine mesh (hexagons) No manufacturing cyclic symmetry constraint Edge width (100 mm) Structural mass (10,156 kg)	Fine mesh (hexagons) Manufacturing cyclic symmetry constraint (6) Edge width (100 mm) Structural mass (9991 kg)

2.2. Preoptimized model approach

Following the observations of the solid cylinder approach (see Table 6), a second approach was carried out using preoptimized models. The generator sub-structures have been preoptimized following a parametric static structural analysis with Autodesk Inventor 2021. A structural parametric study was accomplished in (Jaen-Sola et al., 2021; Jaen-Sola and Mcdonald, 2016). By modifying the values of the wall thicknesses of the sub-structures, see Fig. 14, disk cylinder and cone cylinder support structures, the mass was minimised while complying with the stiffness requirements. The parametric results for both sub-structures were represented employing contour plots for ease of visualisation and the obtention of the preoptimized models. See Figs. 13 and 16 (Jaen-Sola et al., 2018, 2020).

The mesh settings represent the relations of the different elements and nodes generated during the FEA and, therefore, an appropriate configuration was assessed to obtain accurate results from the study. Different designing adaptive analysis procedures were used to refine the solutions such as local mesh control on stress points and h-refinements which consists in changing the size of the elements in relation to stress and location (Zienkiewics et al., 2014).

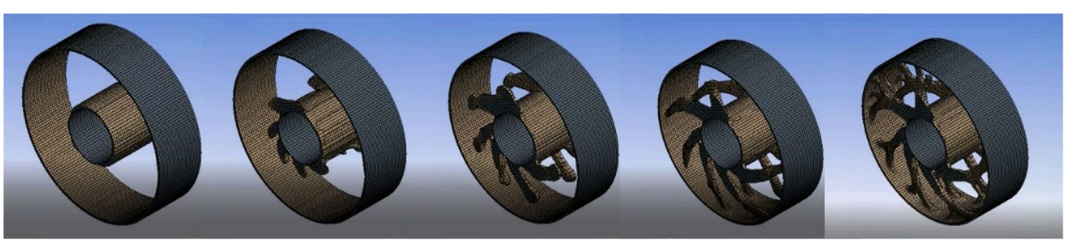

Fig. 10. Generative design process, preliminary solid cylinder approach (b).

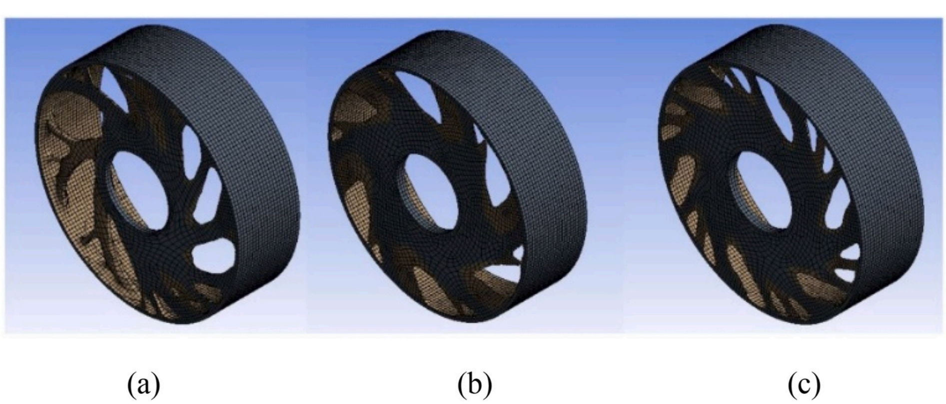

Fig. 11. Generative design solid disc with offset shaft support models (a), (b), (c).

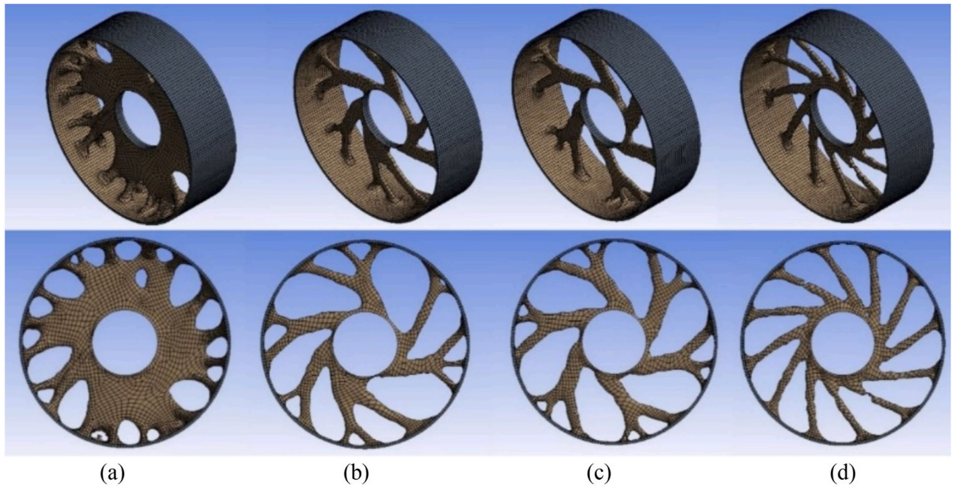

Fig. 12. Solid cylinder generative design process models with central fixed support (a), (b), (c), (d).

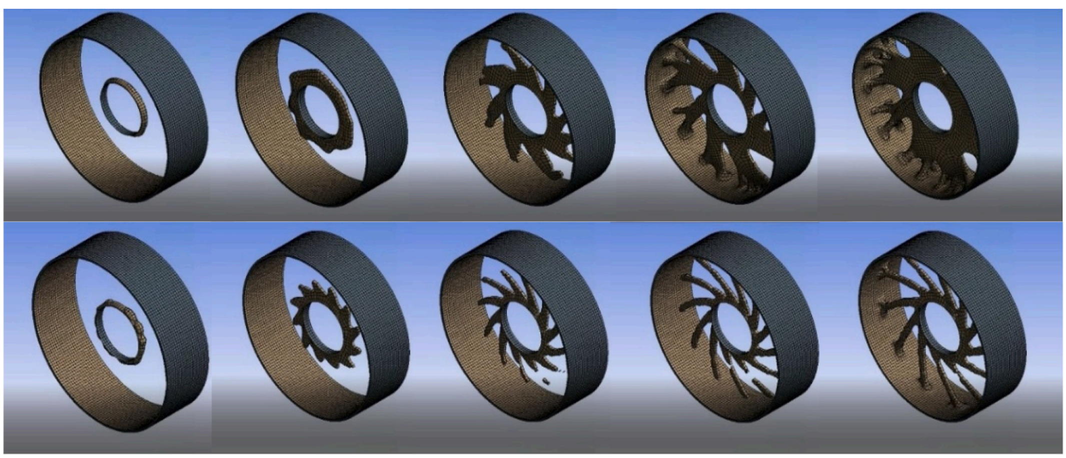

Fig. 13. Generative design process. Solid cylinder generative design process (a) Top lane; Solid cylinder generative design process (d) Bottom lane.

Table 6
Solid cylinder generative design process models (a), (b), (c), (d).

(a)	(b)	(c)	(d)
Fine mesh (hexagons)	Fine mesh (hexagons)	Fine mesh (hexagons)	Fine mesh (hexagons)
No manufacturing cyclic symmetry constraint	No manufacturing cyclic symmetry constraint	Manufacturing cyclic symmetry constraint (6)	Manufacturing cyclic symmetry constraint (12)
Mass to retain target (50%)	Mass range to retain (45–70%)	Mass range to retain (45–70%)	Mass range to retain (45–70%)
Structural mass (17,835 kg)	Structural mass (10,524 kg)	Structural mass (11,119 kg)	Structural mass (10,192 kg)

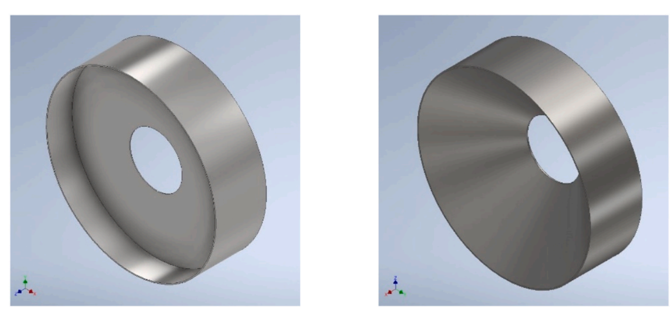

Fig. 14. A view of disk and conical rotor structures (left & right respectively).

The mesh convergence criterion has been targeted at a 5% convergence rate to satisfy a sufficient accuracy of the results. The mesh study for the parametric static structural analysis were set as seen in Table 7.

On the conical rotor parametric structural optimization contour plot displayed in Fig. 15, where the cone wall thickness in mm is on the vertical axis and the cylinder thickness in mm is on the horizontal axis, one can see that the optimum topology complying with the deflection limit of 0.5 mm, is at 21 mm for the cone thickness and 24 mm for the cylinder thickness with a resultant structural mass of 5298.30 kg. The use of the cone structure in the generative design process produced a number of different models as it can be seen in Fig. 14, however, this topology approach was finally dismissed due to the complexity of the process and the extensive computational times derived from the mesh behaviour. Limitations in the process of generative design for curved surfaces in comparison with the disc structure were observed.

Table 7 lists the design parameters employed in design process and the numerical results achieved. Once again, the use of manufacturing cyclic symmetry played an important role and help to reduce the mass as well as keeping a well balance mass distribution across the structure. This model retrieved a mass of 4288.40 kg.

Hexagonal mesh element configuration is recommended for an optimized process, yet, tetrahedron elements work better on curved

Table 7
Parametric static structural analysis mesh study.

Mesh Settings	
Average Element Size	0.080
Minimum Element Size	0.100
Grading Factor	1.500
Maximum Turn Angle	60.00 deg
Rotor Disk Structure Mesh	
Elements	175435
Nodes	324029
Rotor Cone Structure Mesh	
Elements	345953
Nodes	593428

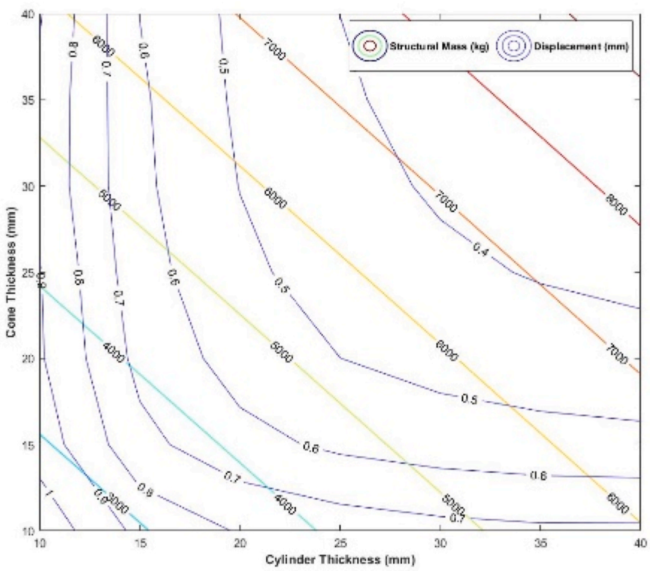

Fig. 15. Static structural optimization of the rotor with conical cylinder support.

planes due to their multiple plane angles. Converting the mesh of the conical structure into hexahedrons involves reducing the size of mesh elements, increasing the total number of elements and raising the computation time. See Fig. 17.

The use of the preoptimized disk model produced more efficient results in the generative design process due to the avoidance of the curved conical surfaces. On the rotor disk parametric structural optimization shown in Fig. 18, the optimum topology corresponds to 15 mm for the disk thickness and 22 mm for the cylinder thickness with a resultant structural mass of 3953.80 kg.

At this stage, it is worth highlighting that the difference in mass between the preoptimized structures is around 1,300 kg. This means that for the same loading conditions and constraints, a conical structure needs much more mass than a disk structure to comply with the previously imposed deflection limit. The design parameters and the structural mass results for the conical structure are summarized in Table 8. Details for the disk structure are given in Table 9. The acquired models showed that a further reduction of nearly 150 kg in the structural mass is possible. Moreover, a simplification of the topology for manufacturing purposes as it is shown in model (e) can be achieved. With the optimum model identified shown in Fig. 19(e), the optimization process can continue.

A representation of a generative design process with a flexible initial set of parameters can be seen in Fig. 20, which produces a complex and an organic type of configuration difficult to manufacture. In this Figure, the importance of the use of initial appropriate variables and control methods in the generative design process is highlighted. With a well-defined set of preliminary parameters and constraints as well as an optimum preselected geometry, more efficient results can be obtained (see Fig. 21).

As stated in the optimization algorithm presented in Fig. 7, the next step is to check the dynamic behaviour of the proposed structure through the use modal analyses. Nonetheless, a limitation in the analysis of the structure of the generated models was identified. Due to the high number of facets existing in the model, the computational requirements became too large. See Fig. 19 for further details. Different approaches and commercial pieces of software were assessed to reduce and simplify the number of facets.

After a number of attempts, Autodesk Fusion 360 was selected and used to process and clean the generative design model created by ANSYS applying different methods as described in Table 10.

The best-optimized simplification of the generative design model can be shown in Fig. 22, where the number of facets was reduced on the elements with their surface on the same plane. However, it was not possible to simplify the facets on curved surfaces without deforming the initial geometry.

As fixed geometry parameters must be preserved in the different parts of the structures such as the shaft support or the outer face of the cylinder deformation on these faces was not allowed. The result obtained on the generative design process for the preoptimized disk structure was used as a topology reference to manually approximate a model. Following the pattern shown and the shape of the cavities in the

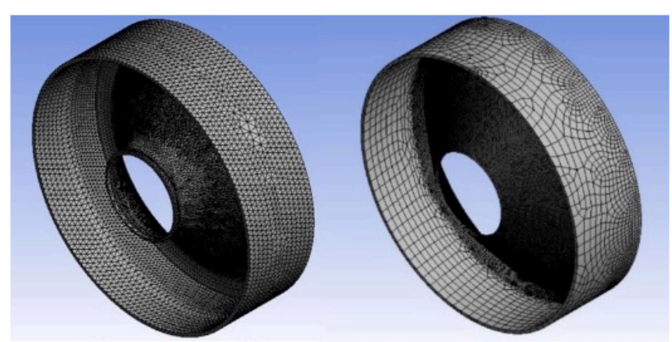

Fig. 17. Conical structure highlighting mesh distribution.

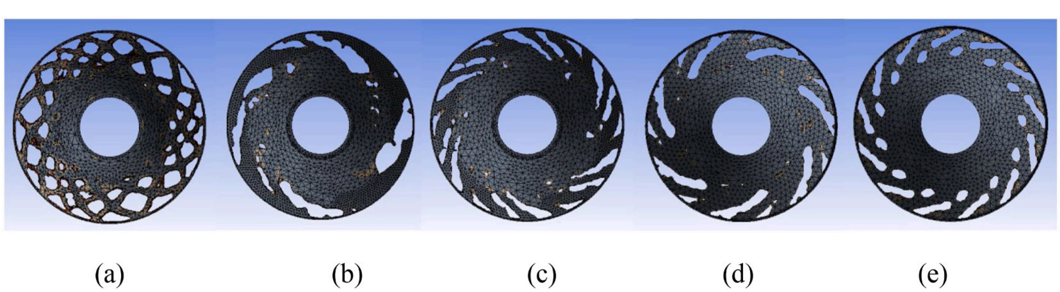

Fig. 16. Preoptimized conical structure generative design process (a), (b), (c), (d), (e).

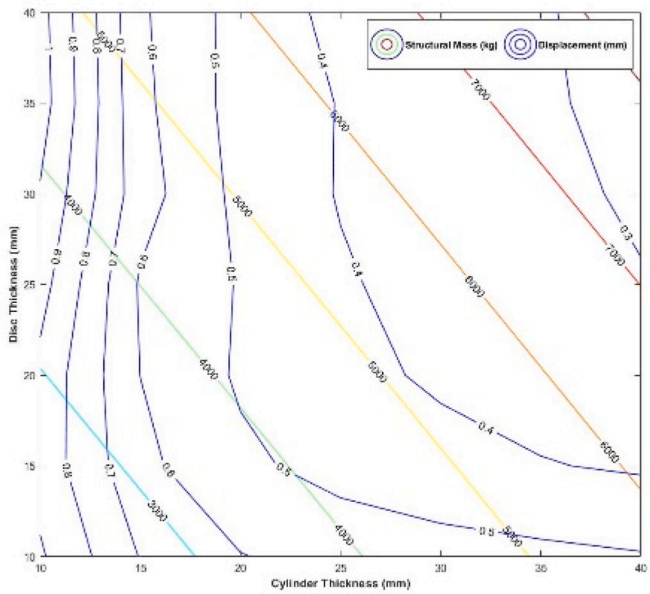

Fig. 18. Static structural optimization of the rotor with disk cylinder support.

disk a model was produced as it is displayed in Fig. 23. The built model based on the result obtained from the generative design process achieved a decrease in mass in comparison to the generated model while maintaining the displacement/deflection limit of 0.5 mm. Minimizing the mass throughout the whole process employed, starting with 3953.80 kg (parametric preoptimized disc), reducing it to 3805.70 kg (generative design model result), and achieving a final structural mass of 3801.60 kg (generative design-built model).

Table 11 summarizes the design-built model results.

3. Conclusion

The combination of using generative design techniques with conventional structural optimization techniques represent an innovative method to the field of structural wind turbine generator analysis. The results achieved for the structure in question during the generative design process open the door to a distinct perspective of the optimization of multi-MW offshore wind turbine electrical generators as a wide range of structural configurations can be discovered and evaluated. The generative design technique used as an optimization tool introduces new methods of structural assessment, cost saving options and allows gathering a significant amount of relevant information in the early stages of the design process. It could be seen how more efficient designs could be acquired if the software is supported with enough design detail at an early stage. The complexity of the method could be optimized in future research in relation to the human input in the generative design variable control method, the decision making through the development of the process, and the fittest-base criterion for population of results selection.

The use of a solid cylinder during the initial stage gave a good idea of the potential models and configurations that could be generated. Nonetheless, the large percentage of mass to reduce, the high number of elements (millions of elements were employed), and the iterative nature of the generative design process (an average of 50 iterations per process) resulted in computational time restrictions and results efficiency issues. It could be also observed that the generative design process worked

Table 8
Preoptimized cone generative design process (a), (b), (c), (d), (e).

(a)	(b)	(c)	(d)	(e)
Adaptative mesh Manufacturing cyclic symmetry constraint (3) Mass to retain target (50%) No generative design displacement constraint Structural mass (3919.7 kg)	Adaptative mesh No manufacturing cyclic symmetry constraint Mass to retain target (75%) Generative design displacement limit (0.5 mm) Structural mass (4689.9 kg)	Adaptative mesh Manufacturing cyclic symmetry constraint (6) Mass to retain target (75%) Generative design displacement limit (0.5 mm) Structural mass (4640.9 kg)	Adaptative mesh Manufacturing cyclic symmetry constraint (7) Mass range to retain (75%) Generative design displacement limit (0.5 mm) Structural mass (4641.6 kg)	Adaptative mesh Manufacturing cyclic symmetry constraint (13) Mass to retain target (75%) Generative design displacement limit (0.5 mm) Structural mass (4288.4 kg)

Table 9
Preoptimized disk generative design process models.

(a)	(b)	(c)	(d)	(e)
Fine mesh Manufacturing cyclic symmetry constraint (6) Mass to retain target (50%) No generative design displacement constraint Structural mass (4082.2 kg)	Fine mesh Manufacturing cyclic symmetry constraint (6) Mass to retain target (45%) No generative design displacement constraint Structural mass (4039.4 kg)	Coarse mesh Manufacturing cyclic symmetry constraint (6) Mass to retain target (80%) No generative design displacement constraint Structural mass (4493.0 kg)	Medium mesh Manufacturing cyclic symmetry constraint (18) Mass range to retain (45–70%) Generative design displacement limit (0.5 mm) Structural mass (4631.6 kg)	Fine mesh (hexagons) Manufacturing cyclic symmetry constraint (18) Mass to retain target (55%) Generative design displacement limit (0.5 mm) Structural mass (3805.7 kg)

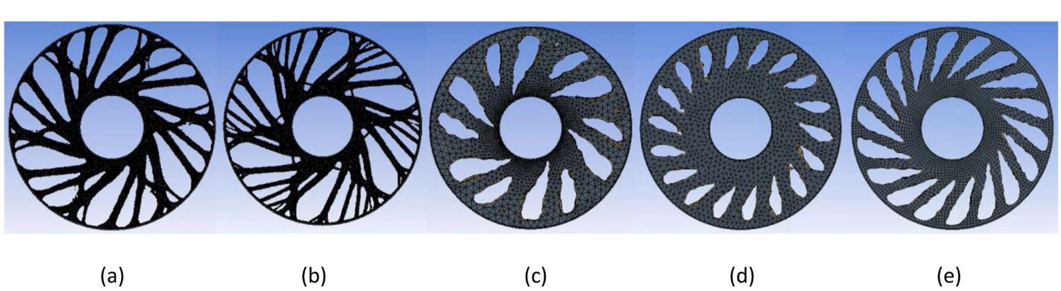

Fig. 19. Preoptimized disk generative design process models.

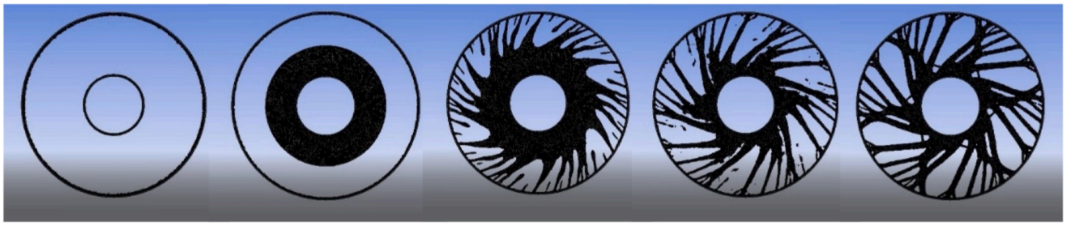

Fig. 20. Preoptimized disk generative design process, (b).

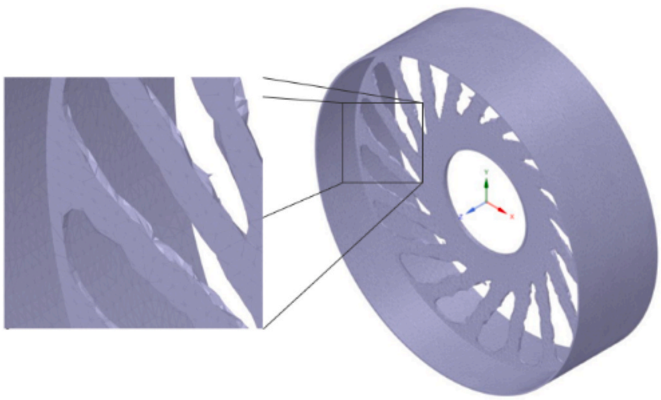

Fig. 21. Preoptimized disk generative design model highlighting facets.

Table 10
Generative design model processing methods.

Method	Error
Triangles to Quad Mesh	Mesh Conversion Error
Number of Facets Reduction	Geometry Deformation & Loss of Dimension Constraints
Merge Facets	Geometry Deformation & Loss of Dimension Constraints
Smooth Geometry	Geometry Deformation & Loss of Dimension Constraints
Fix Sharp Edges	Remeshing Errors
Shrink-Wrap	Remeshing Errors
Overconnected Facets	Remeshing Errors

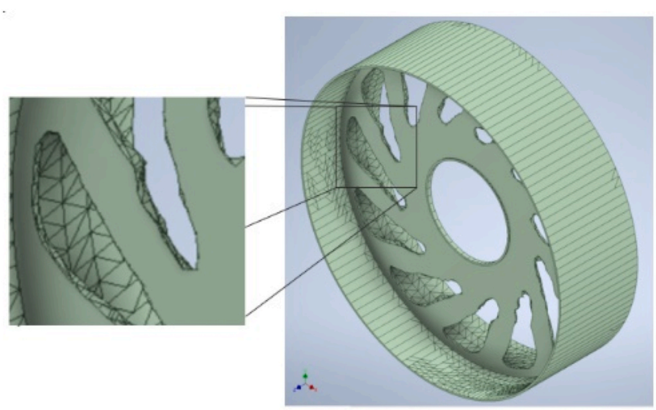

Fig. 22. Preoptimized disk generative design model processing.

more intuitively with the disk structures than with the conical structures due to the complexity of curved conical faces. The reason why the generative design process produced more efficient results for the disk structures resides in the software limitations related to mesh analysis

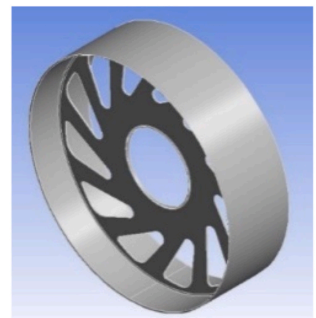

Fig. 23. Preoptimized disk generative design-built model.

Table 11
Preoptimized disk generative design-built model results.

Total Mass	3801.6 kg
Von Mises Stress	45.99 MPa
Displacement	0.4897 mm
Convergence Rate	3.448%

and topology generation for complex curved planes. For the conical structures, the parametric topology optimization technique gave more efficient results than the automated generative design process, by just applying human intuition in the iterative parametrical structural optimization process. During the evolution of the structural optimization algorithm, the generated model results of the solid cylinder and cone structure are dismissed applying the fittest-based assessment of a genetic algorithm due to the limitations found and the different levels of complexity. One criterion used for fittest selection of the generated models, and as an example of the influence of human input, is the generative design control method of symmetry constraint. Regardless of the fact that symmetry is not an initial requirement, it was observed that the families of results with a cyclic symmetry used as a control method generate models with more efficient mass reduction and simpler topologies.

A manual approximation of the generative design outcome was generated with Autodesk Inventor 2021 closely following the parameters of the generated model as a reference. The machine operating range achieved with the final structural configuration expands from the initial 14 rpm to rotor speeds of 18 rpm, with the consequent improvement in the energy harvesting of the system. It can be concluded that an efficient rotor disk structural model with an optimum mass can be generated through generative design techniques. A significant improvement in the modelling stage is introduced by this iterative process that allows the visualisation of models as they are generated. With this approach one can tailor the properties of the structure according to the required specifications. This study proved that the working range boundaries of offshore wind turbine generators can be pushed further into higher and potentially lower rpm for larger energy harvesting efficiency. Generative design is a powerful optimization technique and together with the development of additive manufacturing processes along with the use of non-traditional materials and the prospect of computer-aided modelling provide the necessary flexibility to solve the issues that the wind energy industry is currently facing in the field of multi-MW electrical machine design.

CRediT authorship contribution statement

Daniel Gonzalez-Delgado: Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Pablo Jaen-Sola:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Erkan Oterkus:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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