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Design of direct-drive wind turbine electrical generator structures using topology optimization techniques

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Abstract. Reducing the structural mass of low speed multi-MW electrical machines for renewable energy purposes have become an important object of study as with the drop in mass a substantial decrease in the machine capital cost can be achieved. Direct-drive wind turbine electrical generators need very robust and heavy supporting structures able to cope with the demanding requirements imposed by the environment and the forces and moments transmitted by the wind turbine rotor in order to maintain the air-gap clearance open and stable. It is estimated that at least 2/3 of the total machine mass corresponds to the supporting structure. The main aim of this investigation is to minimize the structural mass of a 3 MW direct-drive wind turbine permanent magnet electrical generator, which dimensions have been previously optimized, making use of topology optimization techniques. Easy to manufacture structures made of cast iron capable of complying with the requirements were generated for both rotor and stator.

1. Introduction

Global energy consumption has experienced an important increase since the last century especially in emerging countries, such as China and India. The same trends are shown for the world's population and economic growth [1]. However, the fact that these three factors are highly correlated makes difficult to tackle the problem of climate change. With almost 80 % of the electricity demand worldwide coming from the combustion of conventional fossil fuels [2], the level of greenhouse gases, released to the atmosphere is causing significant changes in the Earth's mean temperature.

Taking into consideration this clarifying fact, governments have turned their attention on renewable energies. Wind energy is one of the most developed and mature clean technology and has an important role to play in the fight against global warming. Wind resources tend to be greater and steadier offshore and therefore large scale renewable energy projects will be developed further away from shore. In this context, where the offshore wind sector is becoming a key player, a huge effort is being made worldwide with the main aim of quickly reducing its high levelized cost and making it capable of competing with conventional electricity production technologies. Offshore wind turbines are placed in harsh environments where the wind speeds tend to be higher, the air has high humidity and salt content, foundations and substations are subject to wave and tidal current loading and access can be limited by wave height. Some of the manufacturers' considerations for wind turbine design are low maintenance requirements, easy access to important components, high capacity factors and assembly with the lightest and cheapest possible crane.

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Drivetrains are the area of biggest variation and improvement in wind turbine design. Conventional wind turbines are usually formed by a gearbox, a medium or high speed generator and a power converter. Gearboxes have a limited lifetime that in most cases does not reach the expected wind turbine lifetime. It is normal to replace them at least once in the course of the wind turbine lifetime [3]. It is considered that the higher the number of gearbox stages, the higher the gearbox failure rate [4]. Consequently, manufacturers are studying new methods to replace or just to eliminate the gearbox by introducing the direct-drive concept. Direct-drive wind turbines present a number of advantages that make them suitable for offshore purposes. Among them, the removal of the gearbox stands out. With it expensive gearbox matters can be avoided. Moreover, the decrease in the number of moving parts, such as bearings, represents a significant reduction in downtime periods, for example for oil replacement. However, this concept also introduces new challenges as the loads from the wind turbine rotor are directly transmitted into the electrical generator and with a large torque input a machine of considerable dimensions and robustness is needed to deal with such a harsh environment and keep the air-gap open and stable.

In [5], Polinder presents an overview of the available generators for wind turbines and their trends. A good insight of the types of wind turbine generators used in the present day as well as their advantages and disadvantages is given in this comprehensive study. Electrical generators for direct-drive wind turbines are AC synchronous machines that can be electrically or permanent magnet excited. Permanent magnet generators can be considered superior to electrically excited machines as they are more compact, they are more efficient and have lower weight. These generators do not need external electric excitation since their rotor poles are made of permanent magnet material. The overall efficiency of the machine and the energy capture rate then increases as there are no I_f^2R losses. Besides, the lack of slip rings improves the machine's reliability.

Permanent magnet generators are often characterized by the orientation of the magnetic flux as it goes across the air-gap, as follows: radial flux, axial flux and transverse flux.

Most of the permanent magnet commercial models have a radial flux configuration with magnets mounted onto the surface of an inner rotor spinning within the stator's armature [6]. It is possible to estimate the mass of the supporting structure, also known as inactive material, of radial flux electrical machines at an early design stage. The excessive weight of the generator structure was highlighted by Hartkopf *et al*. who claimed that 2/3 of a direct-drive radial flux electrical machine mass corresponded to the inactive material [7]. Mueller, McDonald and MacPherson claimed in [8] that at multi-megawatt ratings the inactive mass of a direct-drive axial flux machine it is almost 90 % of the total mass. Several studies have been written on this regard presenting different approaches that can be utilised when designing this type of machines in order to minimise their structural mass [9][10][11].

Although many different types of structures can be assumed to characterize permanent magnet machines, see figure 1, disc and arm structural models, are more common due to their relative simplicity.

Figure 1. Typical rotor and stator structures [12]

McDonald [9] defined several methods for estimating the structural mass of the machine so as to cope with uniform deflection (Mode 0) and used arm and disc models to relate the mechanical and the electromagnetic design in radial flux machines and to calculate radial, axial and tangential deflections in the structure. Although there are a number of forces at play in the machine, in an early stage of the

design process it is considered appropriate to take into account only the normal component of the Maxwell stress as it is the largest force by far.
Bearing this in mind, this investigation is centred on minimising the mass of the inactive material of a 3 MW direct-drive wind turbine radial flux permanent magnet electrical generator using topology optimization techniques.

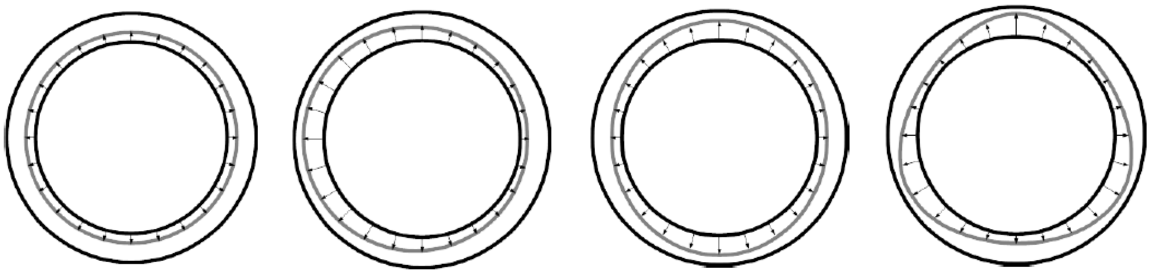
2. Modes of deflection

An ideal structural design for an electrical generator would involve a lightweight low-cost structure capable of maintaining the air-gap between the rotor and the stator open. Therefore, the variable to consider is strain in place of stress. Deformation can be different at different parts of the components forming the electrical machine. Consequently, it cannot be assumed that local and global deflections are one and the same. In [13], the authors noted that localized contact can eventually happen because of:
Mode 0: Relative radial expansion of the rotor or radial compression of the stator.
Mode 1: Relative displacement of the rotor and stator.
Mode 2: Distortion of either or both of the circular surfaces into ellipses (known as ovalizing).
Mode n: Distortion with ripples, n peaks around the circumference.
In general, the total change in air-gap clearance, δ (= δ_{r} + δ_{s}) can be expressed as a function of circumferential angle around the machine's axis, θ, by equation (1),

$$\delta(\theta) = \sum_{0}^{\mathrm{n}} \delta_{\mathrm{n}} \sin n(\theta - \varphi_{\mathrm{n}}) \tag{1}$$

where $\delta(\theta)$ is the change in air-gap clearance at angle θ, δ_{n} is the amplitude of component n, φ_{n} is the phase angle of component n, and n is the number of peaks, hence:
n = 0 for deformation of mode 0 (Figure 2(a));
n = 1 for mode 1 (Figure 2(b));
n = 2 for mode 2 (Figure 2(c));
$n \geq 3$ for mode 3 (Figure 2(d)) and higher.
Often the air-gap deformation is dominated by a uniform mode 0 component with amplitude, $\bar{\delta}$, and a higher order component with amplitude δ_{Δ} and hence equation (2) can be modified:

$$\delta(\theta) = \bar{\delta} + \delta_{\Delta} \sin n(\theta - \varphi_{\mathrm{n}}) \tag{2}$$



(a) (b) (c) (d)

Figure 2. A rotor deforming into the air-gap towards a stator

(a) Mode 0, uniform deflection, $(\boldsymbol{\theta}) = \bar{\boldsymbol{\delta}}$
(b) Mode 1, eccentricity, $(\boldsymbol{\theta}) = \bar{\boldsymbol{\delta}} + \boldsymbol{\delta}_{\Delta} \boldsymbol{sin}\ (\boldsymbol{\theta} - \boldsymbol{\varphi})$

(c) Mode 2, ovalization, $(\boldsymbol{\theta}) = \overline{\boldsymbol{\delta}} + \boldsymbol{\delta}_{\Delta}\boldsymbol{sin2}\,(\boldsymbol{\theta}-\boldsymbol{\varphi})$
(d) Mode 3, $(\boldsymbol{\theta}) = \overline{\boldsymbol{\delta}} + \boldsymbol{\delta}_{\Delta}\boldsymbol{sin3}\,(\boldsymbol{\theta}-\boldsymbol{\varphi})$

3. Structural optimization

Structures are more prone to deform following certain patterns depending on their geometric configuration. In [10] Jaen-Sola and McDonald optimized a generator structure made of cast iron model by first finding the minimum radial and tangential stiffnesses needed to comply with the structural requirements of the rotor and the stator sub-structures (disc and cylinder) and second by minimizing the thicknesses of the said sub-structures until a limit in deflection previously stated was reached (10 % of the air-gap length). The optimized rotor structure presented in [10] was formed by a disc sub-structure with 56 mm of thickness and a cylinder sub-structure with a thickness of 40 mm. The stator structure was composed by two discs of 40 mm thickness each and a cylinder with a thickness equal to 25 mm. See Figure 3.

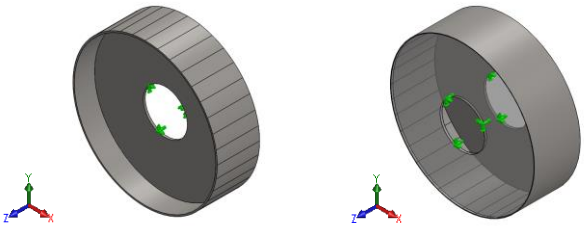


Figure 3 (Left) Rotor structure showing constraints; (Right) Stator structure showing constraints

The characteristics of the entire machine are as follows,

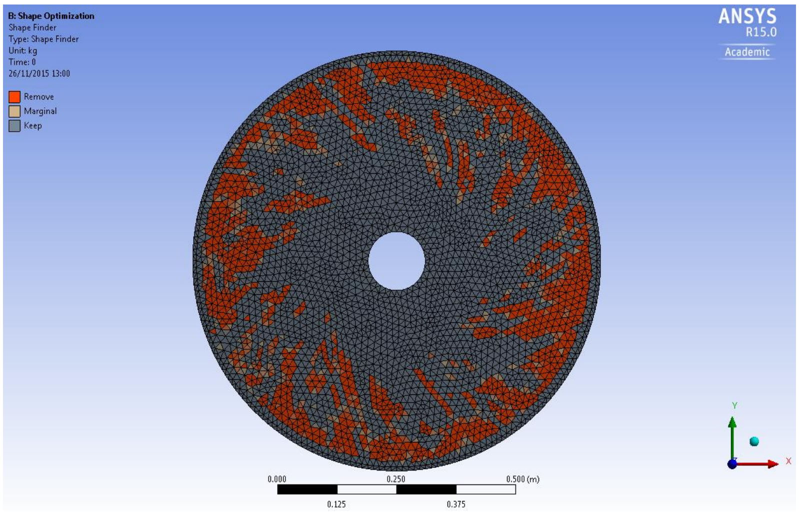
- Power rate, 'P' = 3 MW
- Structural material density, 'ρ' = 7,850 kg/m^3
- Axial length, 'l' = 1.2 m
- Rotor radius, 'R' = 2 m
- Air-gap, 'g' = 0.005 m
- Rotor yoke height, 'h_{ry}' = 0.04 m
- Aspect ratio = 0.6
- Magnet height, 'l_m' = 0.017 m
- Magnet width, 'b_p' = 0.1 m
- Flux density, 'B_r' = 1.02 T.

For this paper two models were studied and further optimized, one at a small scale, which helped validate the usefulness of the ANSYS tool, and one at a large scale. With a uniform radial expansion load of 400 kPa (Mode 0) and a tangential load of 30 kPa applied on the outer face of the rotor's rim sub-structure and on the inner surface of the stator's cylinder sub-structure and a gravitational load applied globally according to the Y axis, the shape optimization studies were carried out.

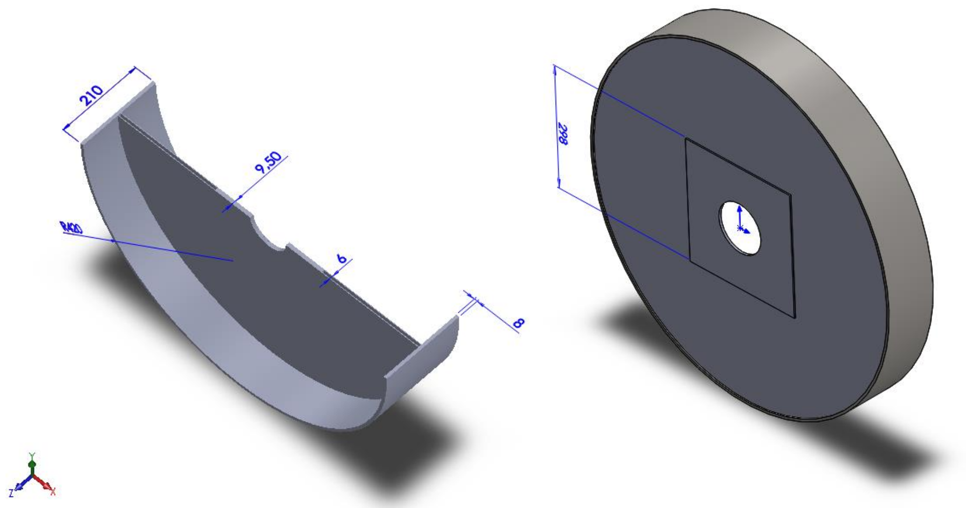
3.1. Small scale disc structure optimization

Multiple methods can be used to estimate the minimum required stiffness and structural mass of an electrical machine [9]. For this investigation, the authors considered appropriate to optimize first the machine volume by finding the minimum required stiffness and thicknesses of the sub-structures forming the rotor and the stator [10] to then carry out topology optimization studies that can further contribute to minimize the mass while maintaining the overall stiffness. This paper is focused on the mass reduction of a linear elastic structure subject to a particular set of boundary conditions, where the overall stiffness is a constraint, and loading. Topology optimization, also known as shape optimization, can be categorized as compliance-based or stress-based. Compliance-based is a well-known and mastered technique [14], whereas stress-based has been typically avoided due to numerical issues caused by the behaviour of local stresses identified as the singularity phenomenon. Although, the research trend shows a clear appetite for the development of the stress-based method, a compliance-based optimization approach was used as it fits better to the application presented in this paper.

In this Section, the shape optimization add-on tool available in ANSYS Workbench is introduced. Both small and large scale generator structures have been looked at. An optimization study of a small scale generator structure made of cast iron was run first in order to verify the usefulness of the said tool. Moreover, the creation and analysis of a small scale model at first instance was considered good practice and it could be utilized for other purposes in the future. A 100 kW electrical machine with 0.42 m radius, 0.21 m axial length, 2.08 mm air-gap, 140 rpm rotor speed and 6.8 kNm torque was assumed. With a radial expansion load of 400 kPa and a tangential load of 30 kPa applied on the outer face of the rotor rim structure and a gravitational load applied globally according to the Y axis, the shape optimization study was made. After constraining the structure at the shaft, a fine tetrahedral mesh was produced, and as it can be seen, the red elements, which are mostly placed within the disc sub-structure, are the ones that can be removed. See figure 4(a).



(a)



(b)

Figure 4 Rotor structure shape optimization; (a) Rotor structure highlighting the elements to be eliminated; (b) Cut-outs of the optimized rotor structure (dimensions shown in mm)

Linking the result to a CAD model in SolidWorks with the same dimensions and material characteristics a handmade removal of material was carried out always taking into consideration the deflection limit, which in this case corresponds to 0.208 mm. An elimination of 6 mm of material could be done for the disc as seen in figure 4(b). The same procedure was followed for the stator acquiring similar data. In this case, the radial expansion load of 400 kPa was directed inwards and applied to the inner surface of the stator's rim. The tangential load of 30 kPa was applied to the inner face of the stator too, whereas the gravitational load was again applied globally following the Y-axis. Having a 6 mm cylinder thickness and 12 mm thickness discs, a removal of 7.5 mm of material from each disc, as it was done with the rotor, could be accomplished. The total mass for a solid cast iron generator structure being able to withstand the mentioned loads without deforming more than as stated, is 313.22 kg with 114.76 kg for the rotor and 198.46 kg for the stator. After further optimization using the ANSYS shape optimization tool an overall reduction in mass of about 15 % can be achieved. The final structural mass would be 266.7 kg with 91.1 kg for the rotor and 175.6 kg for the stator. At this point, it must be highlighted that during the topology optimization process, the elimination of certain areas of the rotor disc sub-structure contributed to decrease the overall deformation. This allowed a further reduction of the disc thickness from about 10.5 mm to 9.5 mm with the consequent mass saving.

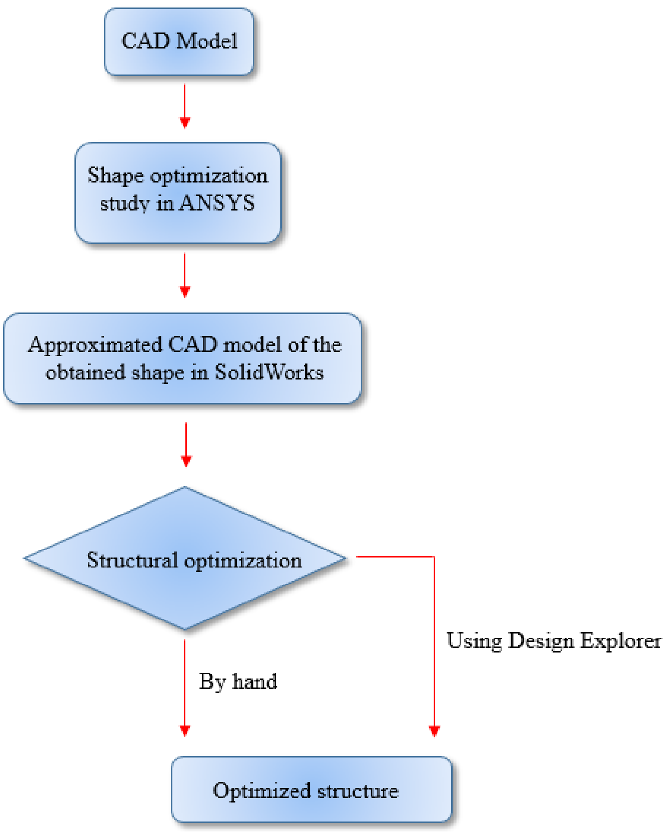


Figure 5 Flowchart of the structural topology optimization process

Figure 5 shows a flowchart of the structural topology optimization process as it was followed. Two different ways of approaching the structural optimization can be tracked: by hand or using the Design Explorer ANSYS tool, coupled to the CAD model in SolidWorks. ANSYS DesignXplorer parametrizes the problem and then analyses the effects of varying those parameters in the whole domain. After a correlation study the most relevant input parameters are identified for further study. The first procedure was used to optimize the small scale model, whereas the second was utilized to optimize the large scale one. Models with relative simple shapes can be easily optimized by hand. However, when the shapes are more complex, the use of an instrument that standardizes the process as DesignXplorer does is necessary.

3.2. Large scale disc structure optimization

Having demonstrated the utility of this ANSYS instrument, it was utilized once again to further optimize the 3 MW large scale model. In this case, different outcomes were obtained for the rotor and the stator structures compared to those of the small scale model. Using the sub-structures thicknesses and machine's characteristics provided in Section 3 and with the structure loaded as specified, the shape optimization analysis was made revealing that the elements to be removed are not only within the disc sub-structure but also in the outer surfaces. In addition, they tracked a certain pattern, as observed in figure 6 that can be utilized to eliminate the material in a standard way making the structure easier to manufacture.

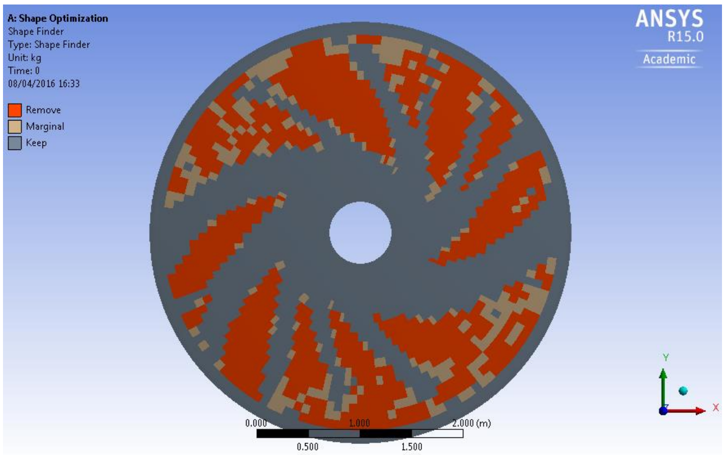


Figure 6. Rotor Structure Shape Optimization

Considering the data retrieved from the shape optimization study, a model in SolidWorks was modified as seen in figure 7 trying to standardize the shape of the clusters of elements to be removed. Then, by linking this model, through a parametric design table, to the ANSYS DesignXplorer tool, the dimensions and the number of those shapes could be altered. Keeping in mind the deflection limit (in this case it is 0.5 mm), the optimum number of gaps was found to be 9. The size of the shapes was maximized so that the maximum amount of material could be taken out. A total number of 57 iterations were necessary to find out the optimum profile for the rotor structure. Figure 7 shows the variables as changed in the DesignXplorer study with l_r = 1,265 mm, R_s = 135 mm, R_m = 2,345 mm and R_l =1,240 mm.

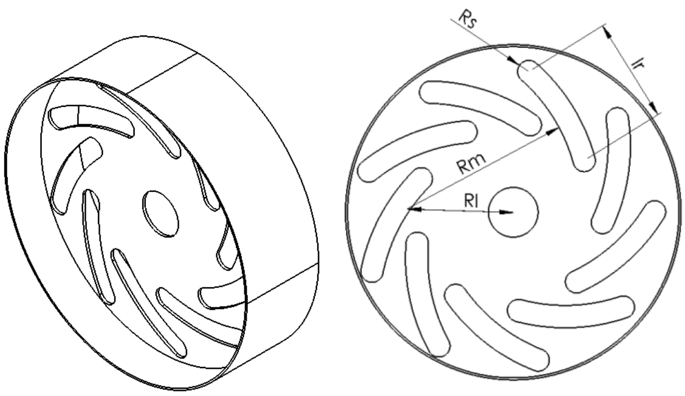


Figure 7. Design Explorer Optimization (Large Rotor Structure)

For the stator structure a similar methodology was followed although a different shape was acquired from the study, as seen in figure 8. The shape was approximated as shown in figure 9 with the optimum found at D_s = 1,400 mm and d_s = 1,150 mm with 5 circular holes. A total number of 23 iterations were needed so as to figure out the optimum values of the two variables.

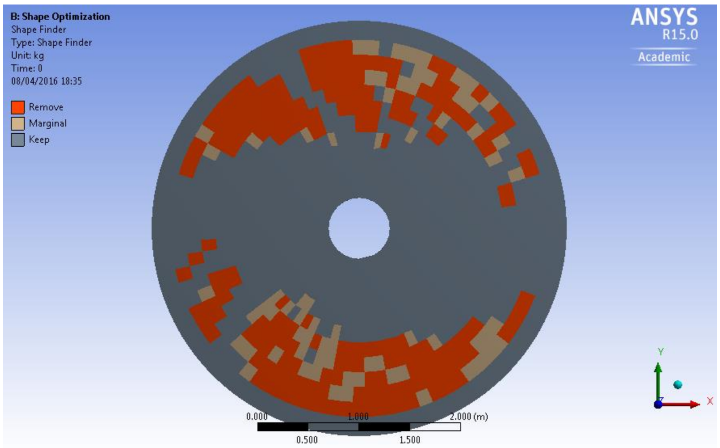


Figure 8. Large Scale Stator Structure Shape Optimization

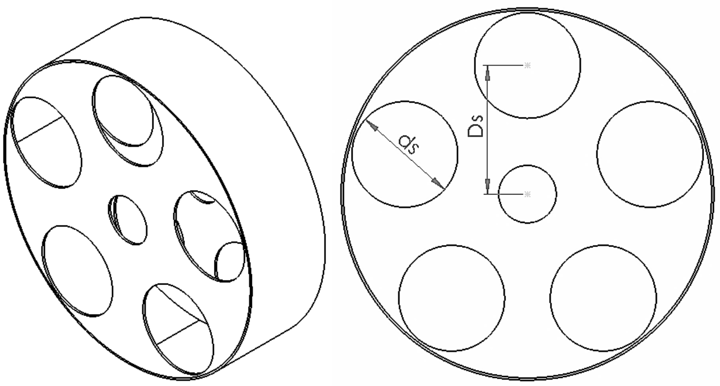


Figure 9. Design Explorer Optimization (Large Stator Structure)

If the mass of the resultant generator structure is compared with a solid disc structure (overall mass of 19,260 kg with 9,809 kg for the rotor and 9,451 kg for the stator [10]) capable of supporting the already said loads, a difference of almost 38 % is achieved. With a total mass of 12,000 kg with the rotor accounting for 5,694 kg and the stator for 6,306 kg a substantial drop in mass was achieved.

4. Discussion and conclusions

Further optimization of the rotor and stator disc structures of a 3 MW direct-drive wind turbine electrical machine was accomplished using finite element techniques. A small scale model was studied first in order to check the usefulness of the shape optimization tool. This previous analysis revealed that substantial mass savings can be obtained. In addition, it was noted that during the optimization process the elimination of certain areas helped to reduce the overall deflection. This allowed a further reduction of the thickness of the entire sub-structure with the consequent decrease in mass. A comparison between a solid structure and the topology optimized structure showed a total mass difference of 15 % in favour of the latter. Once the utility of the said instrument was checked, a topology optimization study of the 3 MW machine structure was carried out. A large drop in mass of about 38 % was achieved by removing material following a certain pattern that facilitates the manufacturing of the structure. With the Design Explorer tool that allows the parametrization of the problem connected to a CAD model in SolidWorks, it was possible to visualize the key areas to be removed, the physical changes made in each study and predict their effect in the whole structure. Looking at the results obtained and the relatively low complex shapes that can be acquired tracking this methodology, the authors recommends its use for additional structural optimizations. More static and dynamic integrated designs can be achieved by using the proposed technique.

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