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Structural Design Optimization of Doubly-Fed Induction Generators using GeneratorSE

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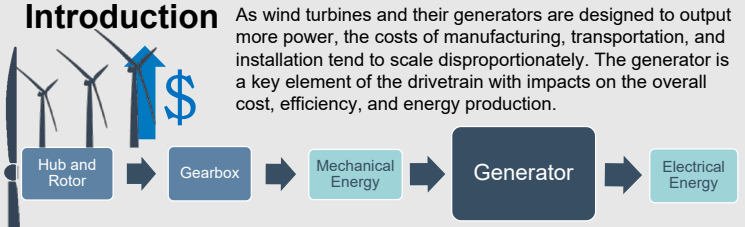
Introduction

As wind turbines and their generators are designed to output more power, the costs of manufacturing, transportation, and installation tend to scale disproportionately. The generator is a key element of the drivetrain with impacts on the overall cost, efficiency, and energy production.



Question: How can we best minimize the cost of energy within the drivetrain?
One solution: Optimize the generators as part of the drivetrain to be more efficient, cheaper, and lighter→ computational tools can aid with the optimal sizing while maximizing efficiency and minimizing mass and cost.

Structural Design

Generator design: A multidisciplinary engineering problem involving electromagnetic, thermal, and structural design.
The generator structural design is identified by important variables that define its geometry: the high-speed shaft, stator, casing, and solid rotor cylinder. The design variables are essential for determining the structural integrity of the generator.

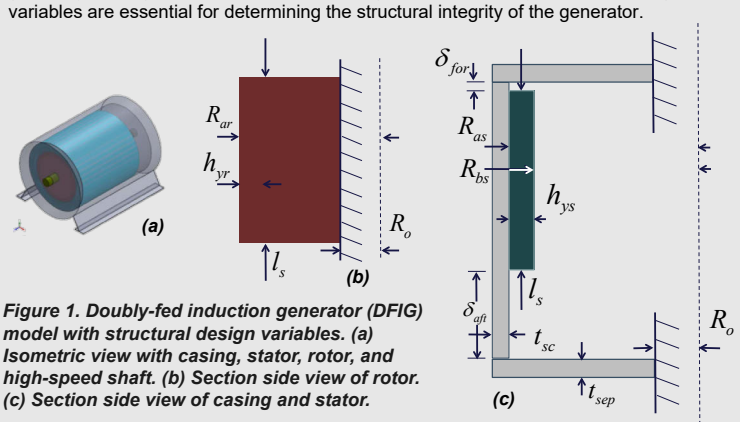


Figure 1. Doubly-fed induction generator (DFIG) model with structural design variables. (a) Isometric view with casing, stator, rotor, and high-speed shaft. (b) Section side view of rotor. (c) Section side view of casing and stator.

The design limits of each variable were determined using GeneratorSE and from commercial generators that range from 0.75 to 10 MW [1]. Constraints are imposed based on deflection limits.

Design Optimization

The following three worst-case loading cases are considered for examining the structural integrity. Deflections, stresses, and the modal response of the components were analytically computed and validated using ANSYS.

1) Normal Maxwell forces acting radially outward (Figure 2a and b)
2) Axial gravitational loading; bending stress and shear stress on the bearing are considered in this case (Figure 2c)

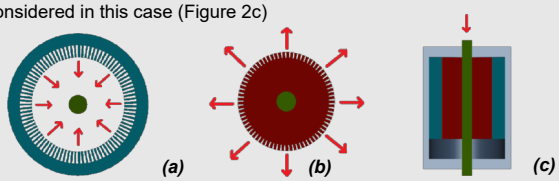


Figure 2. Loading cases. (a) Maxwell load on stator and (b) rotor. (c) Axial gravitational load on entire structure.

3) Torsional deflections due to torque transmitted by the shaft; the defection calculations are derived from [2] and [3].

A range for the first natural frequency of the rotor and shaft was determined using [3]:

$$f_n = \frac{9.87}{2\pi}\sqrt{\frac{EIg}{wl^4}} \quad (1)$$

Where w is a constant distributed load of the rotor and shaft
Min: I is the area moment of inertia of the shaft
Max: I is the area moment of inertia of the rotor for increased stiffness

Finite Element Validation

Optimized structural dimensions were used to create a CAD model in ANSYS (Figure 3). The CAD model was used to validate the analytical model by using the following steps:

- Static structural analyses on the rotor and stator for the three loading cases (six cases total)
- A modal analysis to find the first natural frequency of the rotor and shaft
- A quantitative comparison of the finite element analysis (FEA) and the analytical model.

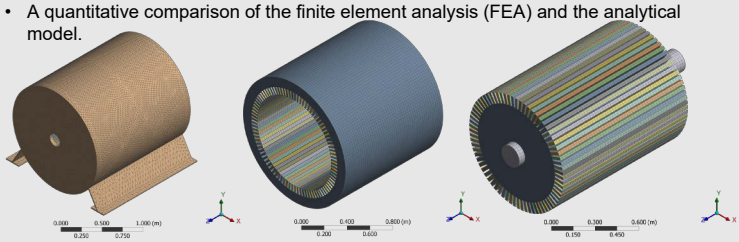


Figure 3. Isometric renderings of DFIG CAD: (a) the stator casing, (b) stator, and (c) rotor and shaft

Results

The total weight of the generator was confirmed by the CAD model as follows:

- GeneratorSE total weight: 17.04 tons
- CAD model total weight: 17.42 tons

These results present a 2.1% difference.
The deflection results (Table 1) between the analytical model and the FEA differ by less than 20% for the normal component of Maxwell stress on the rotor and stator (Figure 4).

Table 1. Comparison of Structural Deflections and Stresses: Analytical vs. FEA

	Analytical	FEA	Δ%**	δ_{allow}
Radial Def Rotor	2.92E-04 mm	2.50E-04 mm	17.0	0.286 mm
Radial Def Stator	0.0027 mm	0.0033 mm	-19.0	0.286 mm
Axial Def Rotor*	0.00145 μm	1.90 μm	-99.9	2.42 mm
Axial Def Stator*	0.48 mm	0.89 mm	-46.2	3.43 mm
Torsional Def Rotor*	6.49E-4°	0.97E-4°	-93.3	0.05°
Torsional Def Stator*	1.56E-4°	0.34E-4°	-95.4	0.05°
Bending Stress Casing (Gravity)*	36.6E+6 Pa	106E+6 Pa	-65.0	136E+6 Pa
Shear Casing (Gravity)*	1.90E+6 Pa	4.36E+6 Pa	-56.5	136E+6 Pa

*The axial, torsional, and stress derivations (Table 1) in the analytical model require ongoing development.

** $\Delta\% = \frac{x_{analytical} - x_{FEA}}{x_{FEA}} * 100\%$

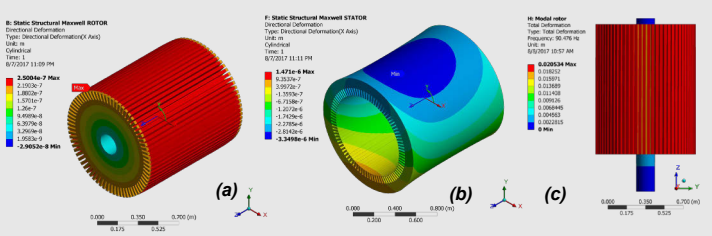


Figure 4. FEA results. (a) Structural static analysis of Maxwell load on rotor and (b) stator. (c) Modal analysis of rotor and shaft.

Natural frequency was found to be between 36.1-680 Hz from the analytical model and 90.48 Hz from the modal analysis (Figure 4c).

Conclusion and Future Work

The DFIG structure was optimized with the objective function of cost, a direct function of mass. The structural dimensions were validated with FEA. The percent difference between the analytical and finite element model for the radial rotor and stator deflections were found to be 17 and -19, respectively. For this application, a percent difference of less than 20% is within a reasonable margin of error. Additionally, the natural frequency from the modal analysis was found to be 90.48 Hz, which is within the bounds predicted by the analytical model. The results suggest that our analytical model correlates with the FEA in some areas but requires further development. In the future, this work could be replicated for other generator types and a detailed cost analysis could be performed.

References:
[1] L. Sethuraman and K. Dykes. 2017. *Generator SE: A Sizing Tool for Variable-Speed Wind Turbine Generators* (Technical Report). NREL/CP-5000-66462, National Renewable Energy Laboratory (NREL), Golden, CO (US). https://www.nrel.gov/docs/fy17osti/66462.pdf.
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