Structural Design Optimization of Doubly-Fed Induction Generators using GeneratorSE

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Abstract

Larger wind turbines, generating more electricity, increase costs disproportionately for manufacturing, transportation, and installation. This paper presents analytical models for optimizing doubly-fed induction generators, with the objective of reducing the costs of wind turbine drivetrains. The structural design for the doubly-fed induction generator includes the casing, stator, rotor, and high-speed shaft modeled using the National Renewable Energy Laboratory's systems engineering design tool, *GeneratorSE*. Stresses, structural deflections, and modal properties were analyzed to ensure structural integrity. The optimization results were then validated using finite element analysis. The results suggest that our analytical model correlates with the finite element analysis in some areas, such as radial deflection, which differ by less than 20%. But the analytical model requires further development for axial deflections, torsional deflections, and stress calculations.

Introduction

A system's approach to design is being widely adopted by turbine designers to reduce the levelized cost of energy. This approach involves trade-offs in component masses and materials to achieve an overall reduced weight and installed capital costs. High-speed drivetrains, employing doubly-fed induction generators (DFIGs), are considered to be the most competitive option for land-based wind turbines because of their lightweight construction requiring less capital costs. However, the scalability of their designs, reliability, and performance issues have not been identified for large-scale offshore wind turbines. Few studies have examined the optimization potential of high-speed drivetrains employing DFIGs [1].

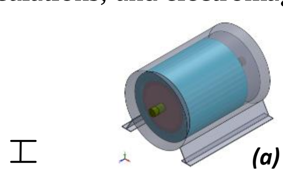
GeneratorSE is the National Renewable Energy Laboratory's new modeling tool specifically intended to optimize variable-speed wind turbine generators. The analytical models for the DFIG integrate electromagnetic and thermal models providing performance parameters with the main focus of optimizing the electromagnetic design [2]. This project expanded the DFIG module to include more detailed structural models. The model was developed in Python using a high-performance computing platform for systems analysis and multidisciplinary optimization, OpenMDAO. The model was validated against results from finite element analysis (FEA) using ANSYS. This approach will enable designers to consider a wider range of generator designs with the potential for cost savings for large offshore applications.

Methods

The generator structural design is identified by important variables that define its geometry. These variables (Table 1, Figures 1 and 2) describe the structural design of the generator including the casing, stator, rotor, and high-speed shaft (Figure 1). The limits of each design value are taken from *GeneratorSE* and from existing generators that range from 0.75 MW to 10 MW [2]. Constraints are imposed based on deflection limits, the yield strength of the material, and operating speeds. The output variables are dependent upon the design variables, structural calculations, and electromagnetic calculations.

Table 1: Design variables.

Symbol	Design Variable
r_s	Air-gap radius
l_s	Stator length
h_s	Stator-slot length
h_r	Rotor-slot length
h_{ys}	Stator-yoke height
h_{yr}	Rotor-yoke height
t_{sc}	Stator casing thickness
t_{sep}	Stator casing endplate thickness
R_o	Shaft radius



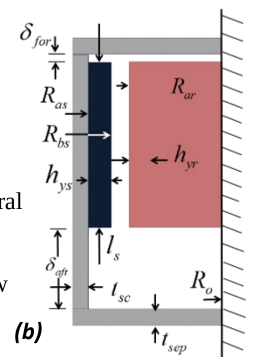


Figure 1. DFIG model with structural design variables: (a) isometric view with casing, stator, rotor, and high-speed shaft, and (b) the section view of the rotor, stator, and shaft.

The structural analytical model incorporated calculations of mass, moment of inertia, stress, structural deflections, and the first natural frequency of the rotor and shaft. Three worst-case scenarios were considered for the structural deflections of the components. The first case examines normal operation under the influence of the normal Maxwell forces of the coils. The second case represents transportation in which the generator could be oriented vertically with gravity acting along the shaft, creating stress on the bearings. The defection and stress calculations are derived from [3] and [4]. The third case occurs during operation when the machine is under high torque loads. The allowable deflections and stresses were determined for the loading cases based on engineering constraints (Table 2) [2]. A range for the first natural frequency of the rotor and shaft was found using an empirical formula for a simply supported uniform shaft [4]. The lower bound was considered with the distributed load of the total weight rotor and shaft but assuming the shaft diameter is constant. The upper bound was considered taken with the same load but the rotor diameter is constant. The design was optimized for lowest costs while constraining minimum efficiency at 93%.

Once optimization results were obtained, the structural dimensions from the optimizer were used to create a corresponding CAD model in ANSYS. Static structural simulations were performed on the rotor and stator for the loading cases. One case is the Maxwell loading and the second is the effect of gravity during transportation. A modal simulation was also run to find the first natural frequency of the structure. The FEA and the analytical model were compared quantitatively based on the maximum deflection results.

Results

The deflection results (Table 2) between the analytical model and the FEA differ by less than 20% for the normal component of Maxwell stress on the rotor and stator. However, the axial, torsional, and stress results differ by more than 20%, therefore the derivations in the analytical model require ongoing development. Despite the large difference between some of the analytical and FEA results, both are significantly below all the allowable margins.

Table 2: Deflection constraints and comparison between the optimization and the FEA.

	Analytical	**FEA**	***Δ*%****	**Allowable**
Radial Def Rotor	2.9E-04 mm	2.5E-04 mm	17	0.29 mm
Radial Def Stator	0.0027 mm	0.0033 mm	-19	0.29 mm
Axial Def Rotor*	0.0015 microns	1.9 microns	-100	2.4 mm
Axial Def Stator*	0.48 mm	0.89 mm	-46	3.4 mm
Torsional Def Rotor*	6.49E-4°	0.97E-4°	-93	0.05°
Torsional Def Stator*	1.56E-4°	0.34E-4°	-95	0.05°
Bending Stress Casing (Gravity)*	36.6E+6 Pa	106E+6 Pa	-65	136E+6 Pa
Shear Casing (Gravity)*	1.90E+6 Pa	4.36E+6 Pa	-57	136E+6 Pa

*Further development required $** \; \Delta\% = \frac{x_{analytical} - x_{FEA}}{x_{FEA}} * 100\%$

The operating speed of the high-speed shaft ranges between 600 and 1800 rpm, which translates to between 10 and 30 Hz. If the natural frequency of the structure was permitted to be near the operating speed, catastrophic failure could occur. Therefore, a constraint was imposed on the optimization for the natural frequency to be outside the operating frequency. The natural frequency from the FEA was found to be within the analytically computed range. The range predicted by the analytical model for the natural frequency was 36.1-680 Hz. The modal simulation found the natural frequency to be 90.78 Hz.

Conclusions

This paper presented an analytical structural model of a DFIG. The structure was introduced and optimized with the objective function of cost, a direct function of mass. Then, the structural dimensions were verified with FEA to ensure the deflections did not exceed the limits and to find a more accurate critical speed. 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 the squirrel-cage induction generator within *GeneratorSE*.

References

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