Axial-Flux Generator Robust Design Aided by Numerical Electromagnetic Field Computation

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Abstract — **A robust design methodology of an 10kW axial-flux permanent magnet synchronous generator (AFPMSG) for direct coupled wind turbines is described. Based on the TORUS topology, some of the generator parameters were optimized by a tailored NSGA-II regarding maximum efficiency, and minimum active material cost and weight. Since the electromagnetic and dimensional parameters are strongly correlated on the design procedure, field calculation errors and inaccurate construction tools become a source of uncertainty that depreciate the overall generator performance. These uncertainties were taken into account on the multiobjective optimization, where the search was guided considering the worst case scenario. The optimized results were post-processed and validated by 2D/3D electromagnetic simulations using finite-element-method (FEM) tools. Thus, the construction of a prototype became feasible due to the robustness consideration.**

Index Terms — **Design optimization, robustness, computational electromagnetics, generators.**

I. INTRODUCTION

The methodology for designing a robust and optimum 10kW axial-flux permanent magnet synchronous generator (AFPMSG) is described.

There are many types of AFPMSG designed for wind turbines applications. From all of them, the TORUS machine, which has a toroidal winding, introduced in [1] was chosen and considered the best topology for low power applications. The TORUS concept generator has larger power-to-weight ratio, more flexible field and winding design, better cooling, and the possibility of modular construction if compared with a radial machine [2]. The axial-flux generator is mounted with NdFeB permanent magnets with NN polarization.

Due the low speed operation of wind turbines and no gear connection between the turbine rotor and the machine rotor, the generator need a very large pole number, resulting in a design of substantially enlarged diameter and high cost. To be economically competitive, the design of a low-speed and large-diameter generators has to be optimized. Recent works have been made in such direction [2]-[3]. However, none of them considered robustness issues, which makes unpractical the optimum theoretical design.

II. MULTIOBJECTIVE ROBUST DESIGN OPTIMIZATION

Three objective functions were defined, aiming to maximize efficiency, and minimize active material cost and weight. Based on the conventional sizing equations [4], seven parameters were chosen to be optimized, as shown in Table I. These parameters were the current density on the stator conductor (Ja), linear current density (Am), peak value of the magnetic flux density on the air gap (Bmg), peak value of the magnetic flux density on the stator core (Bcs), peak value of the magnetic flux density on the rotor core (Bcr), inner and outer diameters ratio (Kd), and the air gap length (g).

TABLE I
BOUNDS OF THE OPTIMIZATION VARIABLES

Variables	Ja	Am	Bmg	Bcs	Bcr	Kd	g
Units	MA/m^2	KA/m	T	T	T	-	mm
Lower Bound	3	42	0.3	1.7	1.4	0.4	1
Upper Bound	9	98	0.9	1.9	1.6	0.8	3

Other design parameters were fixed according to a former study [5], e.g., the poles number (p = 20), the magnetic remanence of the permanent magnet (Br = 1.35 T), the number of parallel coils per phase (Ap = 20), and the nominal stator voltage (Vs = 150 V). In [5] the robustness issues were not addressed, with the drawback of practical implementation problems, resulting in unexpected performance.

Field calculation error and inaccurate construction tools were the two sources of uncertainties considered. The former is inherent of a simplified electromagnetic analytical model that must have low computational cost to be evaluated several times in the optimization process. The latter refers to constructive tools limitations, where cheaper ones lead to worse dimensions accuracy. Table II and Table III present the range of uncertainties for each parameter. Note that some parameters are decision variables.

TABLE II
UNCERTANTIES DUE TO MODEL ERROR

Parameters	Ja	Am	Bmg	Bcs	Bcr
Uncertainty	10%	10%	5%	5%	5%

TABLE III
UNCERTANTIES DUE TO PARAMETRIC DEVIATION

Parameters	Kd	g	Wcu	Lcs	Lcr	Lpm
Units	-	μm	mm	mm	mm	μm
Uncertainty	0.1%	±100	±1	±1	±1	±100

These uncertainties roughly represent the errors associated to the simplified model, and to the constructive limitations.

The optimization was conducted by a NSGA-II [6] tailored to conduct a robust optimum search concerning the worst case possibility for all combined uncertainties.

To reduce the computational effort, the worst case scenario was estimated for each candidate solution according to [7]. Whereas a worst case is found for one objective function, it might not be equally worst for the other objectives. So, a conservative procedure [8] was adopted to set the worst case to the fitness function.

III. RESULTS

A. Non-Robust versus Robust Optimization

Two Pareto fronts are shown in Fig. 1, one despises the robustness issue while the other takes it into account.
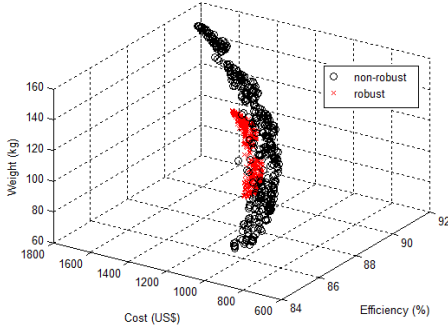

Fig. 1. Non-robust (black circles) and robust (red crosses) Pareto fronts.

The Pareto front for robust solutions is narrower than the Pareto front for non-robust solutions. The displacement between the fronts imposed by the uncertainties is remarkable.

B. Decision Making

The decision maker could choose the best solution according to its preference. To illustrate the methodology, the three objectives were considered equally important. The chosen solutions and their objective values are shown in Table IV and V, respectively, for one of the 20 runs processed.

TABLE IV
BEST SOLUTIONS FOR THE DECISION MAKING

Variables	Ja	Am	Bmg	Bcs	Bcr	Kd	g
Units	MA/m^2	KA/m	T	T	T	-	mm
Non-robust	7.1422	64.863	0.51	1.70	1.60	0.80	1.0
Robust	6.5187	64.741	0.50	1.75	1.55	0.80	1.1

TABLE V
OBJECTIVE VALUES FOR THE BEST SOLUTIONS

Objectives	Efficiency	Cost	Weight
Non-robust	87.26%	US$ 1017.33	91.511 kg
Robust	86.88%	US$ 1052.81	95.259 kg

The robust solution is worse than the non-robust one in all objectives. Actually, this is true for nominal values in the absence of uncertainties. Though, in real world problems, where uncertainties are unavoidable, robust solutions take an important role.

The boxplots in Figs. 2-3 show the efficiency, and the active material cost of the non-robust (left) and robust solutions (right) in uncertain environments. For each one of the 20 runs, 5000 random uncertain cases were simulated.
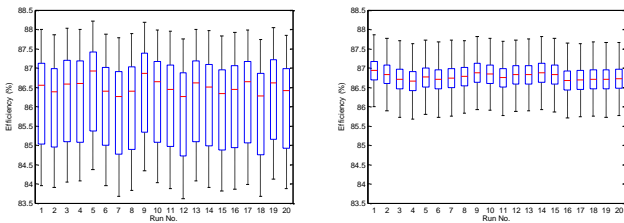

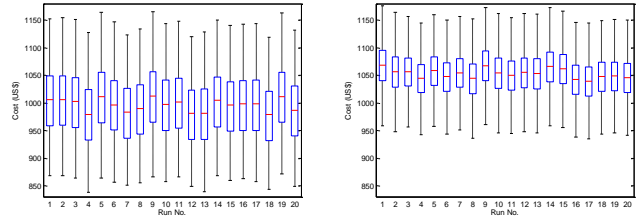Fig. 2. Efficiency boxplot of the non-robust (left) and robust solutions (right).

Fig. 3. Cost boxplot of the non-robust (left) and robust solutions (right).

The non-robust solutions provided an efficiency of (86.06±1.10)% and a cost of US$ (994.71±56.70) while the robust provided (86.77±0.34)% and US$ (1052.89±37.67). So, high efficiency and robustness are achieved at high costs.

C. Post-Processing

The generator final design was submitted to a finite element analysis (FEA), processed both in 2D and in 3D. Through the simulations, the values Bmg, Bcs, and Bcr were validated. It also served to feedback the sizing equations of [4], and to find saturation points on the structure.

The magnetic flux density on the air gap (Bmg) calculated by FEA 3D in Fig.4 matches the robust solution in Table IV.
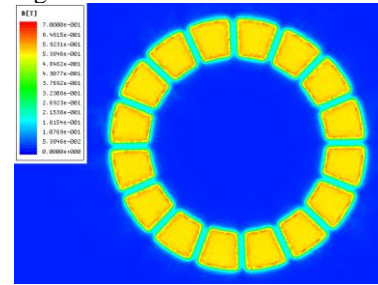

Fig. 4. Magnetic flux density on the air gap for Table IV robust solution.

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