Robust Design of an Axial-Flux Permanent Magnet Synchronous Generator Based on Many-Objective Optimization Approach

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A new methodology is described for designing a robust optimum TORUS topology based 10kW axial-flux permanent magnet (NdFeB) synchronous generator (AFPMSG) for direct coupled wind turbines. A set of variables was optimized by the many-objective evolutionary algorithm, NSGA-III, regarding maximum efficiency; minimum active material cost, weight, and outer diameter. Since the design procedure is correlated with dimensional and electromagnetic parameters, uncertainties that depreciate the generator performance may be introduced due to inaccuracies in construction and in field calculation. These likely uncertainties were taken into account in optimization by an additional objective function, where the search was guided considering the minimization of the standard deviation of efficiency. The optimized design was post-processed and validated by 3D electromagnetic simulations using finite-element-method (FEM) tools. Thus, the novelty of this work is the design of a robust optimum axial flux generator based on the many-objective optimization approach coupled with FEM, which will support the construction of a robust prototype.

***Index Terms*—Computational electromagnetics, design optimization, generators, robustness.**

I. Introduction

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

The AFPMSG has a TORUS topology, which has a toroidal winding [1], and it is considered one of the best for low power applications. TORUS generator has larger power-to-weight ratio, more flexible field and winding design, better cooling and the possibility of modular construction if compared to a radial machine [2]. The axial-flux generator is mounted with NdFeB permanent magnets (PMs) with NN polarization.

Generally, AFPMSG needs a very large pole number, because of the low speed operation and gearless connection, resulting in a design of substantially enlarged diameter and high cost. Hence, to be economically competitive, the design has to be optimized, especially for the Brazilian market that has a latent demand for technology of small-sized wind power generators, mainly for isolated applications and grid connected countryside systems.

Recent works [2]-[6] have been made to search for optimum designs. However, none of them handled the robust design as a constrained many-objective problem.

II. AFPMSG Robust Design Optimization

The 10kW AFPMSG was set to work on 190 rpm with 150V nominal voltage and with PMs remanence of 1.35T.

Five objective functions were defined, aiming to maximize (i) efficiency, and to minimize (ii) active material cost, (iii) weight, (iv) outer diameter, and (v) efficiency standard deviation. The last objective makes the efficiency robust against design uncertainties, which are likely to happen due to field calculation errors and inaccurate manufacturing tools.

Table I presents the design variables (input for optimization process), the dimension parameters (output of the optimization process), and their respective range of values and uncertainties (error). Table I also presents the results for the robust and non-robust AFPMSG optimum design.

TABLE I
Optimization Variables, Uncertainties and Results for AFPMSG

Design Optimization Setup					Results	
Variables	Units	Variable Lower Bound	Variable Upper Bound	Error	Robust	Non-Robust
Ja	MA/m^2	3	9	-	5.47	5.57
Am	KA/m	42	98	-	54.4	52.5
Bmg	T	0.3	0.9	-	0.87	0.90
Bcs	T	1.7	1.9	±10%	1.74	1.75
Bcr	T	1.4	1.6	-	1.59	1.60
Kd	-	0.4	0.8	-	0.8	0.8
g	mm	1	2.5	±1mm	1.33	1.29
kdPM	-	1	3	-	1.0	1.3
p	-	6	16	-	16	16
ap	-	1	32	-	16	32
Dout	mm	-	-	±2mm	600	603
Din	mm	-	-	±2mm	479	482
Lcs	mm	-	-	±2mm	17	17
Lcr	mm	-	-	±2mm	21	23
Lpm	mm	-	-	±1mm	27	28
N1	-	-	-	-	236	229
sa	mm^2	-	-	-	0.53	0.26
Nw	-	-	-	-	118	229
Wcu	mm	-	-	-	9.8	9.3
dPM	mm	-	-	-	11.2	13.8
Inom	A	-	-	±10%	46.2	46.2
f	Hz	-	-	±10%	50.9	50.9
Kdisp	-	0.9	0.9	±10%	0.9	0.9

The following eight variables are continuous: 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-to-outer diameter ratio (Kd), air gap length (g), and permanent magnet adjacent distance multiplier (kdPM). The two discrete variables are: number of poles pair (p), and the number of parallel coils per phase (ap). The ap value is dependent on the p value, according to the relation established in [3].

The output parameters are: outer diameter (Dout), inner diameter (Din), stator core length (Lcs), rotor core length (Lcr), permanent magnet length (Lpm), number of series winding per phase (N1), conductor section (sa), winding turns (Nw), winding width (Wcu), permanent magnet width (dPM), nominal phase current (Inom), nominal stator frequency (f). Although the dispersion factor (Kdisp) had a fixed value, it was submitted to perturbation. Three constraints were imposed to the model: Dout<700mm, Efficiency>80%, Weight<150kg, in order to force a compact design with high efficiency.

Details about the AFPMSG design and limitations are found in [2]-[3]. The set of dimensioning equations used to design the AFPMSG in this work is the same used in [5].

The optimization was conducted by a NSGA-III [7] tailored to conduct a robust optimum search concerning the minimization of efficiency standard deviation, with continuous and discrete variables [8]. This algorithm is based on dominance and reference points to make the selection procedure in the many-objective problem.

The set of the normalized robust Pareto optimum front is presented in Fig. 1. The highlighted blue line is the chosen robust optimum solution when decision maker chooses the following objectives weights ***w****=(3; 1; 1; 1; 3)/9*. The results of this solution are presented in Table II, jointly with the results of the non-robust design for a benchmark comparison.

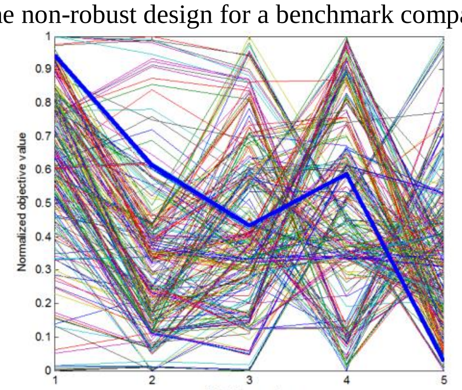

Fig. 1. Set of normalized robust optimum solutions for AFPMSG.

TABLE II
ROBUST OPTIMUM DESIGN FOR AFPMSG

Type	Efficiency	Cost	Weight	Dout
Robust	91.0%	US$1747	93.7kg	600mm
Non-Robust	91.2%	US$1696	95.7kg	603mm

Robust solution has lower efficiency deviation than the non-robust solution in Fig. 2, despite its lower mean efficiency.

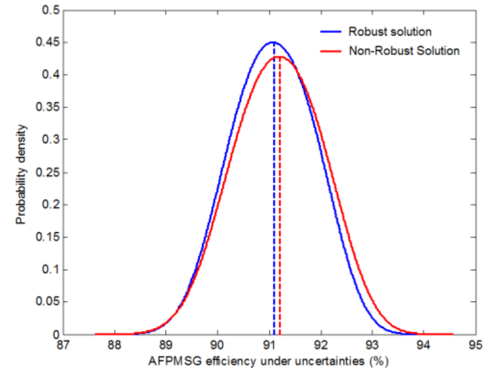

Fig. 2. AFPMSG efficiency deviation when submitted to uncertainties.

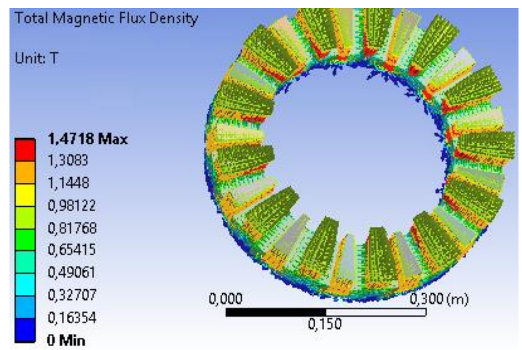

Fig. 3. Magnetic flux density on the air gap for the chosen robust design.

Fig. 3 shows the validation procedure with 3D finite element method (FEM). Simulations indicated that the optimized variables, such as Bmg, Bcs, and Bcr, were correctly calculated by the design model.

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