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Multidisciplinary design optimization of direct-drive PMSG considering the site wind profile

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ABSTRACT

The paper proposes a multidisciplinary design optimization (MDO) of permanent magnet synchronous generators (PMSG) for wind energy conversion systems (WECS). Such a MDO seeks the best compromise between the PMSG cost and the lifetime energy production of the WECS. So far, most of the papers in this field presented design methods using quite a few optimization variables and requiring a lot of assumptions. In the proposed MDO the specifications consist of geometrical, economical, magnetic, electrical and thermal constraints. Several analytic and semi-analytic sub-models where used to deal with these constraints, resulting in a large non-linear optimization problem that uses a sequential quadratic programming optimization algorithm. The paper considers the annual wind profile to estimate the lifetime wind turbine energy production. Moreover, the best possible solutions are presented in a Pareto front showing the trade-off between the generator cost and the wind turbine energy production. Among them, one optimal solution machine was chosen to be further investigated and its results were verified by finite element analysis.

1. Introduction

Wind power generation has significantly increased in the last decade and it is still conquering more space in the global energy production scenario. To be competitive with other types of energy generation, not only the wind must be available, but the cost of the wind turbine ought to be attractive.

The electric drivetrain of wind turbines is based mainly on two types of electrical machines: doubly-fed induction generators (DFIG) and synchronous generators. There is a tendency of changing from drivetrains based on DFIG to those based on direct-drive technology [1], which has a better efficiency due to the nonexistence of a gearbox, among other reasons. The efficiency is even higher when the rotor is excited by permanent magnets, making the permanent magnet synchronous generator (PMSG) a good solution for wind power even facing the recent increase of NdFeB permanent magnets price.

There are two important characteristics that contribute to a cost-effective generator: low cost and high efficiency. These objectives are contradictory since an increase in efficiency is usually achieved by the use of high quality materials and by increasing the volumes of active materials, which increases the cost. The multidisciplinary design optimization (MDO) method proposed in the paper seeks the best compromise between the PMSG cost and the lifetime energy production of the WECS.

A design optimization only minimizing the cost of the active material was presented in Ref. [2] and the results were validated by a prototype. This paper is based on the optimization method of Ref. [2], but it was largely improved. Among other improvements, it takes into account the annual statistical distribution of the wind speed for a given site, to compute the energy yield.

Some papers also consider the statistical estimation of the wind profile of the wind turbine site in the optimization, like Refs. [3–5]. Grauers [3] computes the PMSG energy dissipated in losses and attributes a cost to them; the cost of losses is added to the PMSG cost and the total cost is minimized. Li and Chen [4] optimize several PMSG with different rated power and estimate the energy produced by each one to find the most suitable one for a given wind profile. Alshibani et al. [5] propose to add the cost of other components and subsystems (and their cost of losses) to the PMSG lifetime cost and compare the lifetime revenues of the resulting machines. These papers estimate the generator output power as a function of the wind speed, such an estimation being done by assuming that the PMSG efficiency is constant during all turbine rotational speed and power ranges. Differently, this paper proposes to compute the actual PMSG efficiencies and losses at all operating

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points to accurately calculate the energy produced by the wind turbine. Additionally, the MDO used in this paper includes hundreds of variables, that are the degrees of freedom of the optimization, whereas most of papers (including Refs. [3–5]) deal with fifteen or less optimization variables.

To deal with the numerous constraints related to the PMSG design, a set of sub-models was used: mechanical, geometrical, economical, thermal, magnetic and electrical. The main design model, containing the above-mentioned sub-models, is complex and uses a large number of input and output variables. Hence, a large non-linear optimization problem that includes hundreds of variables had to be solved. Such an optimization approach increases the system degrees of freedom, decreases the number of assumptions and the results are more realistic.

An optimization to minimize the PMSG cost, including the cost of losses, was presented in Ref. [6]; whereas in Ref. [7] an improved method was proposed, including the actual resistance value (as a function of the winding temperature), and maximizing the energy proceeds instead of minimizing the energy losses.

In this paper, the proposed optimum design strategy was used to generate a Pareto front giving a set of optimal solutions for the PMSG cost as a function of the annual estimated energy (AEE). One of those optimal solutions was further examined and its results were verified using Finite Elements Analysis (FEA) software.

The global wind turbine cost would include the costs to produce, transport and install all wind turbine components, like blades, tower, electric generator and power converter. Maintenance and operational costs should also be included to an accurate lifetime global wind turbine cost. However, these costs are not easy to estimate and they are often obtained thanks to numerous assumptions. Moreover, this optimization deals with the PMSG design and the costs not strictly related with the electrical machine are out of scope. Hence, this paper considers only the PMSG costs.

2. Methodology

The MDO is explained in two parts: presentation of the specifications and description of the sub-models.

2.1. Specifications

This section specifies the constraints that ought to be respected by the design. Firstly, the PMSG architecture and its dimensional parameters are presented. After that, the characteristics of the wind turbine are introduced; these characteristics define the PMSG shaft power and rotation speed over all wind speed range. Then, the wind profile (defined by a Weibull probability density function), which defines the number of hours of each operating wind speed, is presented. Finally, a list of other constraints imposed to the design and the objective function are presented.

2.1.1. PMSG architecture

The permanent magnets of the radial flux PMSG used in this design optimization are located on the rotor surface, as shown in Fig. 1. There is one slot per pole and per phase, meaning that the winding factor is unitary. This kind of machine is known by its high torque density and simple manufacturing. The stator is skewed by a slot pitch to reduce harmonics and the cogging torque.

Some geometrical dimensions showed in Fig. 1 are constrained. Whereas some others are limited by the application, such as the outside diameter (D_{es}) and the machine length (L_{stk}); others are constrained to ensure a safe operation of the machine, e. g. the air gap (ag). The following assumptions were considered in the PMSG design:

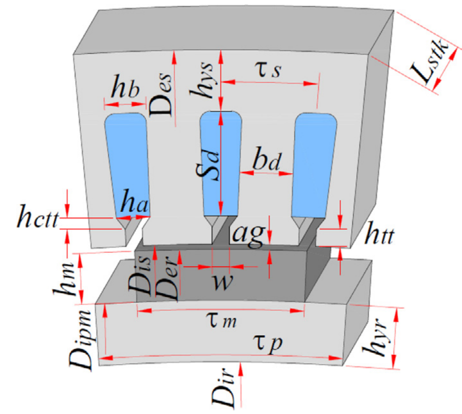

Fig. 1. One pole pitch section of the PMSG to be optimized.

- The air gap ag was considered as 0.1% of the outside diameter D_{es}. This constraints, suggested by Grauers [3], assures proper mechanical operation;
- The permanent magnet width τ_m was fixed to 2/3 of the pole pitch. Other values of τ_m, from 1/3 to 3/3 of the pole pitch, were tested. The tests showed that 2/3 is a good choice regarding the permanent magnet volume, the EMF harmonic content and the cogging torque;
- The slot filling factor was considered as 0.6 based on a previous prototype experience [8];
- The ratio between the slot depth and the slot width was constrained to be less than 8.5 in order to have a suitable slot shape;
- The tooth width should not be less than 10 mm to prevent mechanical stress;
- The NdFeB magnet remanent flux density was taken as 1.21 T based on the magnetization curve provided by the permanent magnet manufacturer.

2.1.2. Wind profile

The PMSG is supposed to operate in a site where the average wind speed is 7.5 m/s. To represent such a wind profile, a Weibull probability density function with a shape parameter (k) equal to 2.0 and a scale parameter (a) equal to 9.02 was used [9]:

$$W(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} \cdot e^{-\left(\frac{v}{a}\right)^k} \quad (1)$$

where v is the wind speed.

A discrete representation of this function (from 0 m/s to 25 m/s in intervals of 1 m/s) multiplied by the annual number of hours gives the period of time per year that each wind speed blows, as shown in Fig. 2.

2.1.3. Wind turbine characteristics

The design of the wind turbine rotor is out of scope; hence, typical characteristics of commercial wind turbines were imposed to the PMSG design. The wind turbine has horizontal axis and three blades, the chosen rotor diameter is 14.2 m and the wind turbine power coefficient is 0.33. The rated shaft power, which occurs for a 12 m/s wind speed, is 55 kW. The availability factor and the wind turbine lifetime, both used to compute the wind turbine energy yield, where chosen as 0.95 and 20 years, respectively.

Fig. 2 shows three zones with respect to the wind speed: zone A, under 3 m/s; zone B, from 3 m/s to 12 m/s; zone C, from 12 m/s to 25 m/s.

In zone A, the wind turbine does not generate any power because there is not enough wind to make it viable. The lower limit of zone B (3 m/s) is the cut-in wind speed, above the cut-in wind speed the wind turbine produces energy. In zone B, the wind turbine control