3D Modeling and Optimization of a C-Shape Permanent Magnet Synchronous Generator for Wind Power Plants

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Abstract — In this paper, a 3D electromagnetic and thermal model is used to optimize a C shape wind generator by taking into account its long term performances. The optimization is done using a general index performance coupled with Weibull distribution of the wind velocity. The modeling and genetic algorithm optimization process is done in three levels to limit the number of iterations. The first level is an analytical approach to obtain a first set of parameters. The second level uses a magnetostatic nodal 3D h-φ formulation and the third level uses an A-V magnetodynamic edge formulation to take into account the harmonic fields and losses.

I. Introduction

To fulfill the objectives of the climate protocols, large investments in renewable energy are necessary. In this context, wind power is one of the most promising and economical technologies. In conventional wind turbines, the blades spin a shaft that is connected through a gearbox to the generator. The gearbox converts the turning speed of the blades, from 20 to 200 rpm into the faster speed according to the normal frequency of the network (50Hz to 60Hz). However, the multiple wheels and bearings in the gearbox suffer tremendous stress because of wind turbulence, and a small defect in any one component can bring the turbine to a halt. This makes the gearbox the most high-maintenance part of a turbine.

In order to overcome these difficulties, a growing interest has been paid to direct drive structures to eliminate the gearbox. These structures present also the advantage of the low noise emission which plays an important role when such systems are erected close to welling places.

Many studies have dealt with original direct drive structures with an objective to optimize weight/torque and cost/torque parameters [1]. However, these optimizations do not take into account the long term performance and extremely variable working conditions of the generator.

In this paper, a direct drive generator will be studied and optimized on the base of its long term energy production. A 3D finite element method coupled with genetic algorithm is used to calculate the optimized parameters of the generator.

II. Problem Description

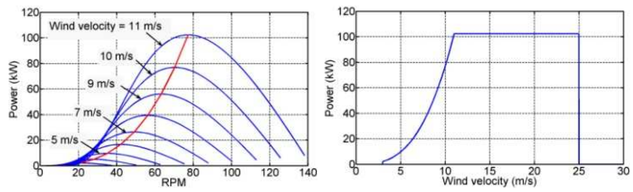
The power as a function of wind velocity V_w can be calculated from the equation of the wind turbine power [2]:

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\beta)\, \pi R^2 V_w{}^3 \qquad (1)$$

where, ρ_{air} is the mass density of air, R is the wind turbine rotor radius and $C_p(\lambda,\beta)$ is the power coefficient defining the aerodynamic efficiency of the wind turbine rotor. C_p is a function of the tip speed ratio λ and blade pitch adjustment β. The tip speed is defined as follows:

$$\lambda = \frac{R\Omega}{V_w} \qquad (2)$$

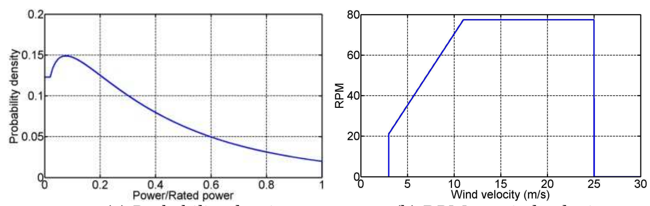
where, Ω is the rotational speed of the blades. For a given value of β, $C_p(\lambda,\beta)$ presents a maximum for a well-determined tip speed, denoted by λ_{opt}. In this case, the overall conversion of wind energy to electric power is described by turbine power curves, which show turbine electrical output as a function of the tip speed. These power curves have a maximum for each wind velocity. All these maxima determine a so-called '*Optimal Regimes Characteristic*' (ORC). In order to maximize the power extracted from the wind, the tip speed ratio should be kept around its optimal. Fig. 1-a shows the ORC for a typical 100 kW three blades wind turbine with R=9.5 m. The rating wind velocity V_r for this turbine is 11m/s, the rating rotational speed N is 80 rpm, the start wind velocity V_s is 3m/s and the cut-in wind velocity V_c is 25m/s. Fig. 1-b presents the power developed with this turbine for the wind velocities between V_s and V_c. The probability density of the power generation may be obtained from the Weibull law for the wind velocities. Fig. 2-a shows this probability for a site having a mean velocity of 5.4 m/s.



(a) *Optimal Regimes Characteristic* (b) *Optimal power vs wind velocity*

Fig. 1 : Optimal power

For the optimal regime, the rotational speed is proportional to V_w. But for the wind velocities from V_r to V_c, where the power is kept at its rated value, the tip speed ratio is lower than optimal value. The rotational speed is then kept constant by adjusting the blade pitch β as shown in Fig. 2-b.



(a) Probability density (b) RPM vs wind velocity

Fig. 2 : Operating mode of wind turbine

III. Optimization Criterium

As shown in Fig .2-a, the probability that the turbine works at its rated power is about 2%. In this case, it does not worth to maximize the performances of the generator (efficiency for example) near its rated power. Instead, we use a general performance index I_g defined by:

$$I_g = \int_{V_s}^{V_c} I(P,\Omega) \cdot p \cdot dv \qquad (3)$$

Where, I(P,Ω) is the performance index for a given couple of power P and rotational speed Ω and p is the wind velocity probability density. This index is weighted by the long term working conditions of the generator.

IV. Generator Studied

Because of the necessity to run the generator at unusually low rpm, direct coupling results in a large diameter and huge number of poles. Permanent Magnet generators are well suited for this kind of structure. They are highly efficient, robust and reliable. The availability of high-energy density magnets such as Neodymium-Iron-Boron (NdFeB) allows the design of a generator required by direct coupled. In reference [3][4], a new topology of direct-drive generator, called C shape is developed. The main benefits of this generator are reduced overall system mass (until 55%) and ease of manufacturing, due to the use of an air-cored winding, but with a modular PM rotor consisting of C-core modules. Fig. 3 shows the outline of a two poles segment of this generator.

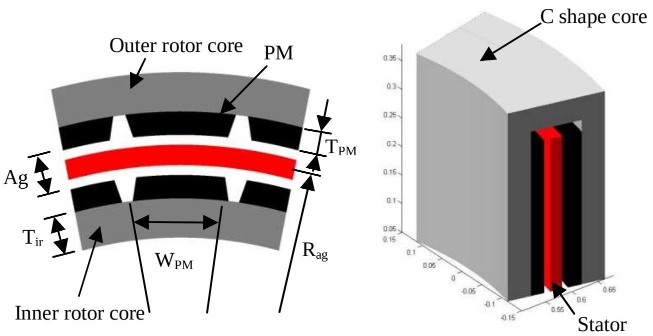


Fig. 3 : C shape machine outline

V. Electromagnetic Formulations

The generator modeling and optimization are done in three steps in order to save calculation time.

- In the first step, an analytical analyze is used to obtain a first set of optimized parameters.

- In the second step a 3D h-φ nodal formulation in magnetostatic case is developed and given by :

$$\int \mathbf{grad}w \cdot \mathbf{grad}\varphi \cdot dD = \int \mathbf{grad}w \cdot \mathbf{B_0} \cdot dD \qquad (4)$$

Where, $\mathbf{B_0}$ is the magnetic induction generated by the permanent magnets and the stator winding, D is the studied domain.The harmonic fields and losses are not considered in this case. The optimized parameters of analytical formulation are then used to initialize the optimization algorithm.

- In the third step, an edge A-V magnetodynamic formulation is used to take into accounts the harmonic fields and losses.

$$\int \left[\mathbf{CurlW_e} \cdot \frac{1}{\mu} \cdot \mathbf{CurlA} + j\omega\sigma \cdot \mathbf{W_e} \cdot (\mathbf{A} + \mathbf{grad}V)\right] \cdot dD = \int \mathbf{CurlW_e} \cdot \mathbf{B_0} \cdot dD \qquad (5)$$

$$\int j\omega\sigma \cdot [\mathbf{grad}W_n \cdot (\mathbf{A} + \mathbf{grad}V)] \cdot dD = 0 \qquad (6)$$

The optimized sets of parameters obtained in step two are again used to initialize the optimization algorithm. In each step, the electromagnetic and optimization calculations will be coupled with suited thermal formulations.

The electromagnetic and thermal problems are solved in a two poles segment of the machine using periodic conditions. In order to conserve the symmetry of the matrix, the procedure developed in [5] is applied.

VI. Results

The table 1 gives the main dimensions and characteristics obtained using 3D h-φ formulation. Fig. 4-a shows the flux density in different parts of the machine and Fig. 4-b presents the no load flux distribution in an electrical full period of one stator winding.

TABLE I
MAIN DIMENSIONS AND CHARACTERISTICS OF THE MACHINE

Air gap radius (Rag), m	0.6	Air gap (Ag) , m	0.04
Stator thickness, m	0.03	PM thickness (T_{PM}), m	0.022
Magnet width (W_{PM}), m	0.1	Rotor core thickness (T_{ir}), m	0.04
Outer radius of inner rotor, m	0.58	Outer radius of outer rotor, m	0.682
Inner radius of inner rotor, m	0.518	Inner radius of outer rotor, m	0.62
Magnet length, m	0.25	Power, kVA	124
Current, A	310	Number of poles	30
Voltage, V	400	Axial active Length, m	0.25
Rotational speed, RPM	80	PM induction, T	1.3

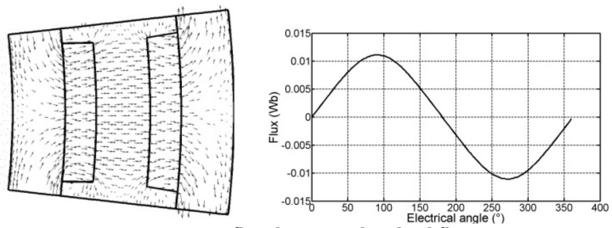


Fig. 4 : 3D flux density and no load flux

In the full paper, optimization results will be presented and the performance of the machine will be analysed.

VII. References

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