

Sizing Optimization of Inserted Permanent Magnet Synchronous Generator for Large Wind Turbine

Amina Bensalah, Georges Barakat, Mohammed Ali Benhamida, and Yacine Amara

Université Le Havre Normandie, GREAH, Le Havre 76600, France.
amina.bensalah@univ-lehavre.fr

Abstract— This paper presents an optimal design of 15 MW inserted permanent magnet synchronous generator IPMSG dedicated to a direct drive large-power wind turbine. Multi-objectives optimization using genetic algorithm coupled with both the analytical and reluctance network model is applied to minimize the permanent magnet and machine masses with respect to the required power and thermal capabilities. Then, obtained Pareto front in the analytical model case is compared to the same Pareto front obtained with a meshed reluctance network model. Further, the performances of the optimal machines are checked with finite element method. The present comparison is to demonstrate that the analytical approach, with a swift exploration of the solution space and less complex Pareto tradeoff curve compared to reluctance network model, allows the designer to make appropriate decisions in some formulation choices before using more complex and exact models (Finite Elements Method FEM); thus it could be used as preliminary mean in the pre-design optimization process.

Index Terms—Permanent Magnet Synchronous Generator, Direct-Drive, Parametric Optimization.

I. INTRODUCTION

Direct-drive systems offer better performances compared to indirect ones, such as low maintenance cost, higher reliability, reduced noise and higher efficiency. Furthermore, with their important torque to weight ratio, PMSG could be an attractive solution for direct-drive wind turbine. In addition, PMSGs with interior magnets have been designed to counter many shortcomings of surface mounted PMSG by offering a protection to the PMs (some degree of shielding) and producing reluctance torque, which improve the performance of the machine [1].

This paper presents a multi-objective optimization of IPMSG. The proposed approach intends to address the multi-physical nature of electrical machines, in the early stage design process, by combining electromagnetic and thermal analyses. For the electromagnetic analysis, a 2D analytical field solution based on the formal solution of Maxwell's equation is proposed, in low permeability regions. The solution involves the separation of variables method along with the Fourier series. It provides the direct solution for the Maxwell equation by solving the Laplace equation in the source free regions and the Poisson equation in the with assuming the linearity of the material proprieties. Further,

combining both the advantages of numerical and analytical model, the reluctance network could be an alternative solution. A 2D mesh-based reluctance network is used to describe the machine's magnetic circuit. The electromagnetic device is divided into regions with refined mesh (e.g. in the air gap), and others with rough one. Each elementary block is represented with unidirectional elements, allowing the flux to flow tangentially and radially. The magnetic saturation is considered by solving the non-linear equation obtained from the mesh-base reluctance model with an iterative way in the ferromagnetic regions. the thermal behavior of the proposed machine is performed with lumped model. However, the lamped parameters depend on the geometrical division of the machine, the nature of materials and the transfer mode. In steady-state, the thermal behavior is represented by heat sources(due to the losses) and thermal resistance connecting the nodes of each mesh element.

The aim of this paper is to find an optimal design of low-speed and high-torque 15 MW Inserted Permanent Magnets Synchronous Generator, for the early stage designing. Frist, an analytical and semi-analytical (RN) magnetic model will be presented. Then in the second section, the thermal lamped model is developed. Further, both the magnetic models and thermal model are combined with genetic algorithm in order to optimize the performances of the machine, by downsizing the mass of the rare-earth magnets within the generator. Finally, the paper concludes with a discussion spotlighting the influence of modeling method on the complexity of the Pareto's trade-off surface. By using the proposed models, the computing time has considerably been reduced comparing to the finite element analysis.

II. MAGNETIC ANALYTICAL MODEL

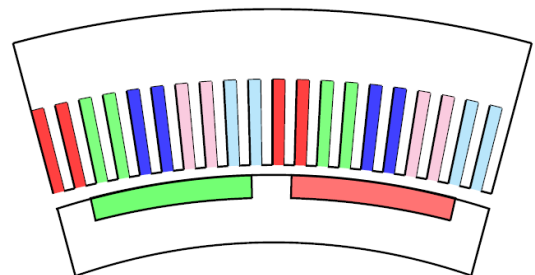


Fig. 1. View of the IPMSG (Pole pair)

The analytical model is obtained by solving the Maxwell equations in low permeability regions of the machine, thanks to the separation of variables technique [2]. This method presents a low time process; thus, it could be used in high iterative pre-design optimization. The governing differential equation of the 2D magnetic field can be written in cylindrical coordinates system as:

$$\frac{\partial^2 A_z}{\partial r^2} + \frac{1}{r} \frac{\partial A_z}{\partial r} + \frac{1}{r^2} \frac{\partial^2 A_z}{\partial \varphi^2} = -\mu_0 J - \frac{1}{r} \left(\frac{\partial(rB_{R\varphi})}{\partial r} - \frac{\partial B_{Rr}}{\partial \varphi} \right) \quad (1)$$

Where A_z is the magnetic vector potential, J is the current density in the slots and B_{Rr} and $B_{R\varphi}$ are respectively the radial and circumferential components of the PM remanence.

The machine global quantities are then derived from the magnetic field distribution, deduced from the potential vector. Meanwhile, the torque was evaluating by using the Maxwell stress tensor. Furthermore, this model is used to evaluate the maximum produced torque.

III. MAGNETIC MESHED RELUCTANCE NETWORK MODEL

Unlike analytical model where the magnetic flux is formulated in terms of magnetic vector potential, in reluctance network model the magnetic flux is written in function of the magnetic scalar potential. In addition, the nonlinear relationship B-H is integrated in this model, by using iterative algorithm to set the current operating point.

After development, the governing equation conducted as into matricial system and can be written as [3], [4]:

$$[P][U] = [\Phi] \quad (2)$$

Where $[P]$ is the permeances matrix; $[U]$ is the magnetic scalar potentials and $[\Phi]$ is the source vector. The saturation is considered, by solved in an iterative way using fixed point iteration method. A part of this, the electromagnetic torque is computed at the sliding surface and using maximum torque angle and Maxwell's stress tensor.

IV. LAMPED THERMAL MODEL

The lamped thermal model is one of the most common methods used in the estimation of the temperature distribution in each node. Only iron losses are considered in presented model. After development, the temperature estimation problem is set and could be reduce it to a system of matricial equation [5]:

$$[P][T] - [\phi_{th}] = -[\rho C] \frac{\partial [T]}{\partial t} \quad (3)$$

Where $[P]$ is the thermal permeances matrix; $[T]$ is the temperature at each node; $[\phi_{th}]$ is the source vector and $[\rho C]$ is a diagonal matrix containing the heat capacities of the different volumes.

V. DESIGN OPTIMIZATION APPROACH

It will be a question of studying the influence of the geometrical parameters of a 15 MW IPMSG generator in its performances. At the preliminary design stage an air-gap width of 20 mm has been chosen, while 42 pole machine

structure has been adopted. A multi-physic sizing model of IPMSG is coupled with Matlab multi-objective genetic algorithm in order to evaluate the maximum torque delivered and the hottest slot's spot, in order to provide the required power and prevent the overheating, respectively. A design optimization is described in which reduction in the PM mass and machine's active part is achieved by varying: Magnets height and opening, mean radius of the air gap, slot depth and opening, yoke thickness machine's active length and slot's current density. Preliminary results are presented in the Fig.2

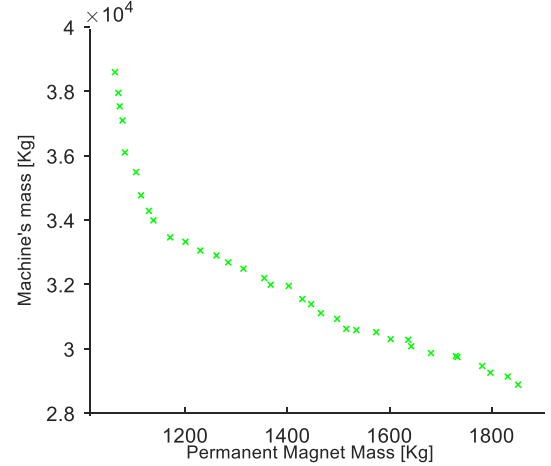


Fig. 2. Pareto optimality using analytical model

VI. CONCLUSION

In this paper, a comparative study was performed between the results of the analytical model and the one devolved with reluctance network. The choice of analytical model conducted us to a Pareto with lower masses, this is due to the linearization and the simplification assumptions, such as the non-consideration of both the iron saturation and the maximum allowed temperature in the slots. Consequently, the choice of solving analytically Maxwell's equation for the magnetic part could be of interest for the predesign step of concentrated flux PMSG, since offers reduced computation time in terms of model simulation and optimization.

REFERENCES

- [1] M. Barcaro and N. Bianchi, "Interior PM Machines Using Ferrite to Replace Rare-Earth Surface PM Machines," in *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 979-985, March-April 2014.
- [2] A. Bellara, H. Tiegna, Y. Amara and G. Barakat, "On Load Analytical Modelling of the Magnetic Field for Axial Flux Surface-Inset Permanent Magnet Machines with Semi-Closed Slots", 20th International Conference on Electrical Machines, ICEM 2012. 2852-2858.
- [3] C. B. Rasmussen and E. Ritchie, "A magnetic equivalent circuit approach for predicting PM motor performance," IAS '97. Conference Record of the 1997 IEEE Industry Applications Conference Thirty-Second IAS Annual Meeting, New Orleans, LA, USA, 1997, pp. 10-17 vol.1.
- [4] M. A. Benhamida, H. Ennassiri, Y. Amara and G. Barakat, "Reluctance network — Lumped mechanical & thermal models for the modeling of concentrated flux synchronous machine," 2017 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF) Book of Abstracts, Lodz, 2017, pp. 1-2.
- [5] D. Gerling and G. Dajaku, "Novel lumped-parameter thermal model for electrical systems," 2005 European Conference on Power Electronics and Applications, Dresden, 2005, pp. 10 pp.-P.10.