

Brushless Doubly-Fed Reluctance Machine Optimization using Reluctance Networks

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Abstract—The Brushless Doubly-Fed Reluctance Machine (BDFRM) is being considered as a viable generator alternative to be used in wind turbines. However, a literature review shows that there is still a lack of researches to define a design procedure to make this machine commercial. This paper aims to address this issue by considering a new BDFRM design method using a reluctance network approach with focus on the machine electromagnetic structure optimization. The design example using the proposed methodology presents interesting results where the torque has increased significantly whereas the iron mass has been kept to a minimum.

Index Terms—Design optimization, Brushless machines, Finite element methods, Electromagnetic analysis, Wind energy

I. INTRODUCTION

This paper focuses in the modeling, design and optimization of the Brushless Doubly-Fed Reluctance Machine (BDFRM). This sort of machines (self-cascaded structures) have been investigated in the last years to be used in applications such as wind turbines [1], [2], [3]. The BDFRM is being particularly considered as a viable alternative to the Doubly-Fed Induction Machine (DFIG) in variable speed wind energy conversion systems (WECS). It keeps the cost advantages of the DFIG in terms of the possibility to process a fractional part (around 25%) of the total generated energy with the additional advantages of maintenance-free brushless operation [1]. Although a very promising solution, there is still a demand for new researches on the electromagnetic structure design so that this machine could be used in industrial scale [3].

One of the most used tool for electrical machine design is the Finite Element Analysis (FEA). Although very precise, this strategy is time consuming and because of that usually not very well adapted for optimization models. To address this issue, a new methodological approach on the modeling, design and optimization of the BDFRM is proposed by using Reluctance Networks (RN). This technique provides a model which is a compromise between precision and computational time. Similar strategy has already been used in the design of other kinds of machines such as Permanent Magnet Synchronous Machines [4] and it is now applied to the BDFRM. The importance of an alternative method to calculate initial design

parameters has also been shown in [5] for the Brushless Doubly-Fed Induction Machine (BDFIM) version.

The BDFRM stator is constructively similar to the induction machine, but it has two sets of three phase windings with different number of poles. Magnetic coupling between the two stator windings is achieved using a reluctance rotor with number of poles equal to the total number of pole pairs on the stator. The machine uses a reluctance rotor which can be salient, axially laminated or radially laminated with flux barriers (ducted) in the axial direction [2], [1]. The BDFRM basic analytical modeling can be found in [2] and its references.

II. MACHINE MODELING AND PRELIMINARY RESULTS

In earlier design stages, it is usually indicated utilize a more macroscopic approach which allows the consideration of several dimensioning parameters with many constraints such as the reluctance network approach. To illustrate the method capabilities, this paper proposes a network topology which includes saturation effects for a BDFRM with $p_r = 4$ salient pole reluctance rotor type. The considered machine has $p = 1$ and $q = 3$ pole pairs in the primary and secondary windings, respectively. This network is implemented in the software package Cades/Reluctool which generates and solves the design equations [6]. Fig. 1 shows a quarter of the reluctance network implemented for the optimization purpose.

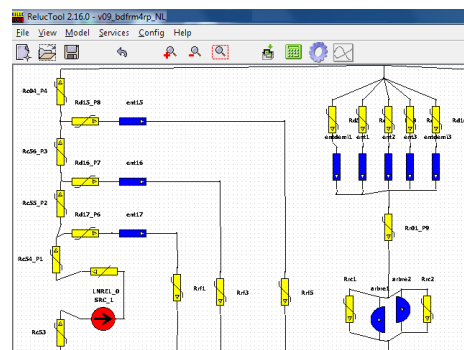


Fig. 1: BDFRM Reluctance Network model.

To develop this network, a first FEA has been performed in the machine considering a DC excitation in only phase A of the primary winding (i_A). This procedure allows to define the most significant flux paths where the reluctances should be located in the network and also to calculate λ_{AA} , the phase A flux linkage, to verify the initial model accuracy. Some idealized assumptions have been considered to find a simplified torque expression, that can be shown to be proportional to (1), which is of great interest for the proposed model.

$$T_e \propto \frac{n_2}{n_1} \frac{\lambda_{AA}}{i_A} \quad (1)$$

where n_1 and n_2 are the total number of turns per phase per pole pair divide by 2 in the primary and secondary respectively.

The Cades software allows the integration of semi-analytical models (RN) which considers magnetic material saturation through non linear reluctances with analytical equations describing other system parameters such as sizing (number of turns, physical dimensions *etc.*) and performance (torque, inductions *etc.*) parameters. It also computes the partial derivatives between output and input parameters which gives a global analysis of the model sensitivity. The model is then compiled and coupled to a Sequential Quadratic Programming (SQP) optimization algorithm for system equations solution.

It is important to notice that the FEA in this strategy is also very important, because the optimization results are verified using FEA. The advantage of aforementioned procedure is to reduce the number FEA calculations (saving time) to obtain an optimized design.

To verify the methodology, two optimization analysis have been performed for a salient rotor type machine considering the operating point $I_1 = I_2 = 7.5$ A: “*Max T*” aims to maximize the torque and “*Min M*” to minimize the mass while keeping the mean torque maximum found in “*Max T*”. In both calculations the input physical parameters have been constrained in specific ranges, but left free to vary within the range. The minimum air gap length constraint has been set to the value considered in the initial machine and the external diameter and the stack length have been kept constant to match a specific machine frame. The thermal constraints are indirectly taken into consideration by limiting the current density in the windings at 5 A/mm² maximum.

The estimated iron mass for the initial design was 51.7 kg. The mass decreased to 42.0 kg in the first calculation to maximize the torque and it was minimized to 41.6 kg whereas keeping the torque to a maximum in the final optimization step. The resulting machines are verified using multi-static non linear FEA for different levels of current I_2 . Current $I_1 = 5$ A and angular mechanical speed $\omega_{rm} = 750$ rpm are kept constants. The mean torque curves of the optimized machines “*Max T*” and “*Min M*” are shown in Fig. 2. It can be seen that the torque has increased from 19.0% ($I_2 = 20$ A) up to 104.5% ($I_2 = 5$ A) whereas the mass has decreased 19.5% compared to the initial design. The different designs can be seen in Fig. 3.

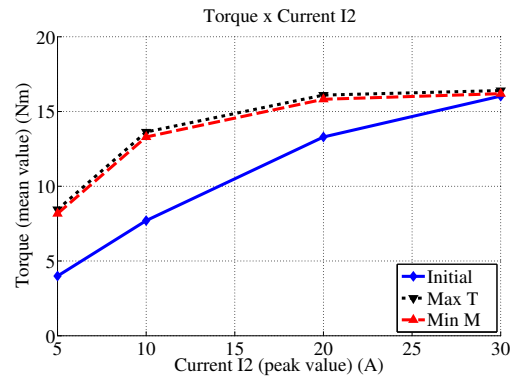


Fig. 2: Torque comparison between different designs.

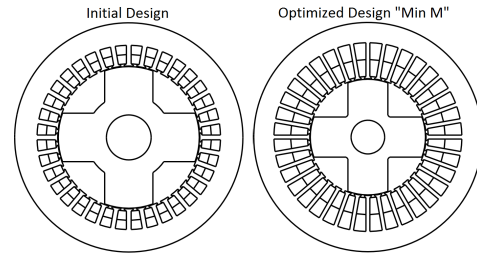


Fig. 3: Machine initial and optimized designs.

III. CONCLUSIONS

As stated by many authors, there is still much work to be done to make the BDFRM a commercial machine. This paper addresses a new BDFRM design method focusing on its electromagnetic structure optimization using the Reluctance Network approach. The described model is still not complete to define a design procedure, however the results show that it can be used to help reaching this objective. The provided example which maximizes the torque whereas keeping the mass to a minimum shows the interesting possibilities on using this procedure. Further refinements in the model to increase its robustness and the consideration of different reluctance rotors structures are ongoing and will be subject of future papers.

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