Computation of Hysteresis Torque and losses in a Bearingless Synchronous Reluctance Machine

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This paper presents the methodology and computation results for the torque and iron losses in a bearingless synchronous reluctance machine. The aim of the paper is to compute the hysteresis torque related to the asynchronous operation of the machine under the effect of the levitation field rotating at twice the synchronous speed. For this purpose, and because the hysteresis torque is not possible to compute with a single valued BH-characteristic, a magneto dynamic vector hysteresis model is used. The computations show that the hysteresis torque-related shaft power is considerable under no-load operation of the machine.

***Index Terms*— Electrical machine, finite element analysis, magnetic hysteresis, magnetic levitation, magnetic losses.**

I. INTRODUCTION

SYNCHRONOUS RELUCTANCE MACHINES are nowadays very popular for their robust construction, efficient operation, and inexpensive materials used for their manufacturing [1]. A novel use of these machines has been expanding lately, which consists of making them bearingless. These machines integrate the torque production and the magnetic levitation in the core of the machine and remove the need for additional mechanical or magnetic bearings [2]. The operation of a bearingless machine is based on the use of p-pole pairs rotating field for the torque production and p±1-pole pairs for the levitation of the rotor of the machine [3]. Bearingless machines can be of different types, but in this paper we focus on the synchronous reluctance machine. The aim of the paper is to investigate the effect of the levitating field on the torque production of the machine. Indeed, the bearingless machine can be illustrated as shown in Fig. 1, where it is separated into a fundamental synchronous machine with respect to the torque producing field and an asynchronous hysteresis machine with respect to the levitation field. Further the field harmonics can produce synchronous or asynchronous torque. Since the levitation field is rotating at twice the rotor speed (in this particular case), the slip related to this field is very high and equal to 50%. Altogether with the hysteretic behavior of the rotor material, such a field makes the machine operates as an asynchronous hysteresis machine. The computation of the torque and power related to this operation mode requires a special attention.

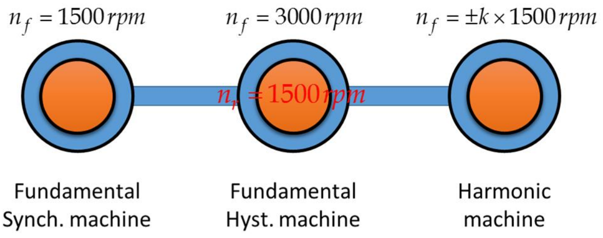

Fig. 1. Illustration of the operation of the bearingless synchronous machine operation from the point of view of the rotating fields. The speed of the rotor of the 3 machines is the same.

In this paper we propose the usage of a previously developed and validated magneto dynamic vector hysteresis model (MDVHM) [4], [5] to estimate the hysteresis torque and power transferred by the asynchronous field to the rotor when it is under self-levitation mode. Besides these parameters, the model is used to accurately estimate the different components of iron losses in both the stator and the rotor of the machine.

In this digest we use a hypothetical machine design, but in the extended version we will present the results for another design, which is being prototyped as well as for a permanent magnet machine [6].

II. THE HYSTERESIS MODEL

The MDVHM used in this work has been presented earlier in [4], [5]. It consists of a Preisach-based rate-independent hysteresis model augmented with eddy current and excess fields' contributions. The whole model is vectorized in eight (8) directions according to the Mayergoyz methodology [7], which makes it possible to account for the rotational hysteresis behavior. The model is further incorporated into an in-house 2D time stepping finite element software for the simulation of rotating electrical machines.

III. SIMULATION MODEL

The machine under investigation is a hypothetical bearingless synchronous reluctance machine with a four-pole main winding and a two-pole levitation winding. The geometry of the machine is shown in Fig. 2 together with the computed magnetic flux density difference as will be explained in the results section. The above mentioned simulation software is designed to account for the coupling between the windings' circuit equations and the field equations, which makes it possible to simulate the machine under voltage supply. The software has also options to model the magnetic material with a single-valued BH-curve or with the above described MDVHM. Contrary to the current supply methodology, the voltage supply ensures that the flux density in the machine airgap is almost the same for both models provided that the same voltage and load angle are used in the simulations. The difference between the simulations results is then seen in the computed input power and power factor.

IV. RESULTS

The machine under investigations has been simulated with the above-mentioned software under voltage supply for both the main and the levitation windings. The load angle of the machine was set to zero, so that nearly zero shaft power was produced. The main voltage was 500 V at 50 Hz frequency and the levitation winding voltage was varied from 1 to 100 V with the same frequency. First order triangular elements were used to mesh the machine cross-section. The simulations were conducted under the same input conditions with the magnetic material modeled with single-valued BH curve or MDVHM.

The analysis of the results is carried out by comparing the two models outputs. Fig. 2 shows the difference in the computed magnetic flux density distribution in the cross-section of the machine, at the last time step, when it was working under a levitation voltage of 40 V corresponding to a computed levitation current of 5.98 A.

The difference in the shaft power, when it was computed with single-valued model and the MDVHM is shown in Fig. 3 together with the total shaft power computed with the MDVHM to appreciate the relative impact of the hysteresis power. This comparison is however far from being straight forward as in both simulations the computed shaft power was almost the same, which hindered the understanding of the simulations. However, this is not the actual shaft power.

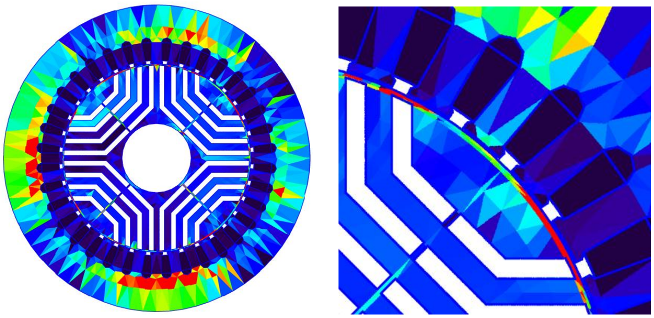
Fig. 2. The computed difference in the magnetic flux density distribution between single-valued model and MDHM. The whole machine (left) and a zoom around the airgap (right). The maximum difference (red color) is 0.2 T.

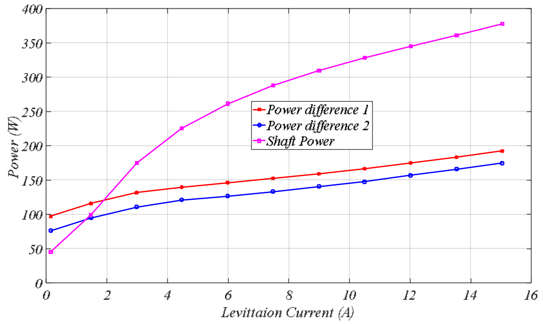

Fig. 3. The computed shaft power with the MDRHM and the differences from the one computed with single-valued model. *Difference 1* is calculated by subtracting single-valued iron losses whereas for *difference 2* MDVHM iron losses are subtracted.

Indeed, in the single-valued simulations the iron losses are not accounted for and thus they show as extra shaft power, when it is computed from the torque and the speed. Whereas in the case of MDVHM computations the iron losses are accounted for in the power balance of the whole machine. The copper losses in both cases are accounted for thanks to the field-circuit coupling. To have a better appreciation of the hysteresis torque related shaft power we needed to subtract the iron losses from the computed shaft power in the case of single-valued simulations and then compute the difference between this shaft power and the one computed with the MDVHM. However, the iron losses were different depending on the way the computations were made (about 20 W difference). This behavior, due to the difference in the flux density distribution as shown in Fig. 2, is illustrated with two different results shown in Fig. 3, where the terminology "*difference 1*" is for the iron losses computed with single-valued model and "*difference 2*" is for the iron losses computed with the MDVHM as follows:

$$P_{diff\,1} = P_{sh-MDRHM} - \left(P_{sh-SV} - P_{fe-SV}\right) \tag{1}$$

$$P_{diff\,2} = P_{sh-MDRHM} - \left(P_{sh-SV} - P_{fe-MDRHM}\right) \tag{2}$$

where P stands for power and the subscripts sh for shaft, SV for single-valued, fe for iron, and $MDVHM$ is self-explanatory.

In both cases, the shaft power computed with the MDVHM is much higher than the one computed with the single-valued model. This behavior is attributed to the power produced by the hysteresis machine as illustrated in Fig. 1 and could not be decided on without the use of the MDVHM. An approximation from the operation of the asynchronous machine theory, which consists of equating the shaft power to the product of the airgap power by (1-slip) could be utilized however. In the full paper we will discuss the accuracy of this methodology as well as present the separation of different loss components. Simulations with different rotor materials will be presented too.

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