Iron loss evaluation on a hybrid synchronous generator using FEM

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This paper presents a study of iron losses on a 1MVA synchronous hybrid generator. The machine operates as a classical salient pole with wound rotor generator, with permanent magnets on the rotor poles surface. A numerical model of this machine has been developed and used to analyze iron losses with the association of different *a posteriori* methods. The results are compared to measurements performed on the generator itself. Also, the influence of some geometrical details on the rotor poles has been considered.

***Index Terms*—Synchronous generator, magnetic losses, hybrid excitation, finite element analysis.**

I. Introduction

There is a growing need to improve efficiency in electrical machines, and then it is crucial to be able to estimate losses in the design phase. In fact, it is important to know where these losses are located in the device and how they may be reduced.

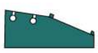
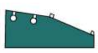
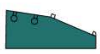
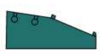
Hybrid excitation synchronous generators can be advantageously used for wind turbine applications. The modeled machine consists in a 1MVA, 8 pole hybrid excitation generator with salient poles, with double excitation in the rotor: classical windings and surface mounted permanent magnets [1], [2].

Three different calculation methods of iron losses will be compared. They will also be compared to those measured on the generator without magnets. Moreover, the influence, on the losses, of some geometrical details on the rotor poles, close to the air gap, will be investigated.

II. Numerical model

A 45° section of the machine has been modeled in 3D using the finite element method (FEM). The magnetic vector potential formulation was used for the calculations and the movement has been taken into account using the locked step method. First, the machine has been studied without permanent magnets. Since the same rotor is also used for the hybrid synchronous generator, it contains wedges on the pole ends, which are mechanical parts designed to ease the placement of permanent magnets. Their influence, as well as the one of the damping bars, is considered as shown on Table I, in a magnetostatic model.

TABLE I
Geometrical Details On Rotor Poles

	G1	G2	G3	G4
Damping bars	Air	Air	Iron	Iron
Wedges	Iron	Air	Air	Iron
				

Stator sheets have been characterized with an Epstein frame, and the identified magnetic permeability has been used for the calculations. The iron loss coefficients have also been determined from the experiment.

Three different iron loss models have been used, based on the classical decomposition in hysteresis, eddy current and excess losses [1]. In the first model, M1, hysteresis losses are calculated with the flux density peak $\hat{B}$, whereas eddy current and excess losses are calculated considering the flux density time derivative [4].

$$P = k_h f \hat{B}^{\alpha} + k_{ec}\frac{1}{T}\int_0^T \left(\frac{dB(t)}{dt}\right)^2 dt + k_{exc}\frac{1}{T}\int_0^T \left|\frac{dB(t)}{dt}\right|^{1.5} dt \quad (1)$$

The coefficients α, k_h, h_{ec} and k_{exc} are related to material characteristics and were determined experimentally. In the identification procedure, a sinusoidal flux density is imposed on a lamination stack, and the model with the flux density peak value is used to determine the coefficients, which remain the same for the different loss models M1, M2 and M3. The equivalent waveforms for frequencies between 300 Hz and 1200 Hz are shown on Fig. 1. The frequency of 1200 Hz corresponds to the stator slotting effect.

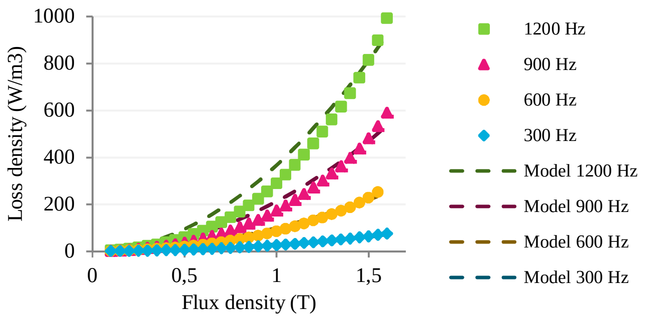


Fig. 1. Iron loss coefficients determination

The second model (M2) is similar to the first one, but a Fourier transform is used to evaluate hysteresis losses in each element *i*, for each harmonic *j* of the magnetic field, based on the stator slotting frequency [5]. This method has the advantage of taking minor loops into account, but in their absence it may overestimate losses [6].

$$P = k_h \sum_{i=0}^{m} \sum_{j=0}^{n} f_{i,j} \hat{B}_{i,j}^{\alpha} + k_{ec} \frac{1}{T} \int_0^T \left(\frac{dB(t)}{dt} \right)^2 dt + k_{exc} \frac{1}{T} \int_0^T \left| \frac{dB(t)}{dt} \right|^{1.5} dt \quad (2)$$

In the third model (M3), a Fourier transform is used to evaluate all the iron loss components.

$$P = k_h \sum_{i=0}^{m} \sum_{j=0}^{n} f_i \hat{B}_i^{\alpha} + k_{ec} \sum_{i=0}^{m} \sum_{j=0}^{n} f_i^{\,2} B_{m,i}^2 + k_{exc} \sum_{i=0}^{m} \sum_{j=0}^{n} f_i^{1.5} B_{m,i}^{1.5} \quad (3)$$

III. Results

The results obtained with the synchronous generator numerical model presented on this paper have been analyzed and compared with the measurements.

Figure 2 presents the magnetic flux density chart, as well as the iron loss density. One observes that losses are mostly located on the stator teeth and on the rotor pole extremities, but also on the wedges placed on rotor poles. This may lead to local overheating, which can be prejudicial, particularly when they are in contact to permanent magnets, in case of hybrid excitation.

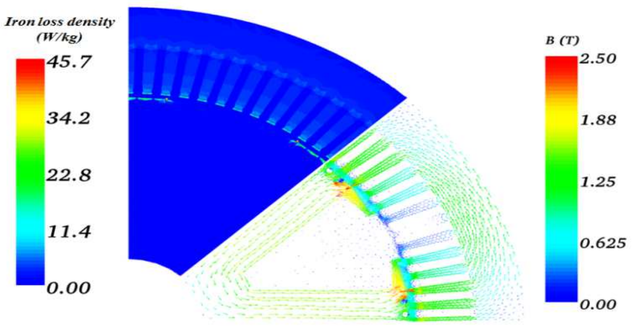


Fig. 2. Flux density (on the right hand side) and iron loss density (on the left hand side) charts of the numerical model.

On Fig. 3, losses obtained with the presented methods are compared to those obtained experimentally. For low values of excitation the FE model provides good agreement with the experiment. On the other hand, when excitation becomes more important, the gap between calculation and experiment becomes more important. This may be due to the choice of the loss calculation coefficients. Indeed, as shown on Fig. 1, they tend to underestimate losses for flux density values above 1.5T. Nevertheless, for lower values they should overestimate losses, what does not occur. Further magnetodynamic calculations will be carried out to take account of eddy current losses.

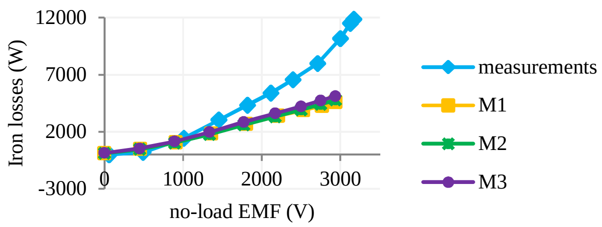


Fig. 3. Comparison between iron loss models and experiment

On Fig. 4, losses obtained with the different geometrical details on the rotor poles have been compared. For 50 A of field current, an increase of 30% has been observed when both the damping bar and the rotor pole wedges are considered as iron (G4), comparing to the case where they are both considered as air (G2). This reflects the importance of taking geometrical details near the air gap into account.

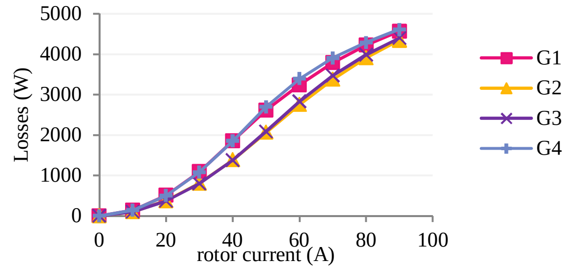


Fig. 4. Comparison between geometrical models using M1

IV. Conclusion

A finite element model of a synchronous generator has been developed. Different iron loss calculation methods have been compared, with close results among one another. However, when compared to experimental results, the difference becomes more important, especially for high excitation values. This may be due to an imprecision on the geometry or to the choice of loss calculation coefficients. The importance of a precise geometry around the air gap region has been demonstrated.

The extended version of this paper will include a more precise numerical model, with coefficients that represent more precisely the measurement values. The effect of permanent magnets will be taken into account as well. A magnetodynamic analysis will also be presented, where the influence of eddy current in the damping bars, permanent magnets and in the solid parts of the rotor will be considered.

V. Acknowledgment

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VI. References

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