Magnetic Power Loss Estimation in Coaxial Magnetic Gears

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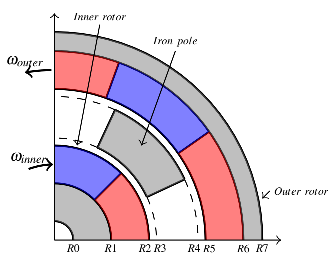
This paper proposes a procedure for computing magnetic loss in the iron regions of coaxial magnetic gears. These magnetic structures are made of permanent magnets and ferromagnetic poles in relative motion transferring torque between two shafts in a contactless way. Balance of energy conversion must take into account all phenomena and computation of losses in magnetic materials is crucial to define system performance. Flux distribution inside ferromagnetic parts is computed by means of a semi-analytical procedure and then a model of iron losses taking into account the rotational nature of the flux loci is applied. The procedure will become part of an electro-mechanical model for the evaluation of the whole chain of power conversion both in static and in dynamic conditions.

***Index Terms*—Electromechanics, Magnetic gears, Magnetic loss, Rotational flux.**



Parameter	Value
Inner poles	4
Outer poles	22
Iron poles	13
Gear ratio	5.5

Fig. 1. Magnetic gear structure and list of parameters adopted.

I. Introduction

Magnetic gears are promising devices because of the maintenance-free operation and no needing of lubrication [1]. These devices can also operate with a continuously variable gear ratio similarly to planetary gear sets. Optimal magnetic gears could be considered for substituting mechanical gearboxes when reliability and maintenance are key factors for a power train.

In order to assess the torque transfer in steady state conditions and to evaluate the dynamic behaviour in transient settings it is extremely important to model all the aspects of the energy conversion chain. The aspect of magnetic losses evaluation is particularly difficult because the magnetic locus has a rotational shape in most of the iron regions. In this work magnetic losses are computed as a post-processing of a magnetic analysis carried out considering a magnetic linear behaviour. This hypothesis is particularly efficient and allows to use the analysis model within an optimisation loop [2].

II. Magnetic gear model

Magnetic gears working principle is based on the modulating effect of the iron poles. The magnetic structure of coaxial magnetic gears is outlined in Fig. 1: two ferromagnetic yokes close the flux created by two arrays of permanent magnets on the inner and outer rotor. The main flux is modulated by iron poles. All magnetic parts are laminated. If Pi is the number of poles of the inner rotor, Q is the number of iron poles and Po is the number of poles of the outer rotor, the magnetic gear resulting in the maximum performances has to satisfy $Po = Q - Pi$. The outer rotor speed ω_{out} is:

$$\omega_{out} = \frac{Pi}{Pi - Q}\omega_{in} - \frac{Q}{Pi - Q}\omega_s \quad (1)$$

where ω_{in} is the inner rotor speed and ω_s is the iron poles rotational speed. If the iron poles are kept fixed, the gear ratio is $G = -\frac{Pi}{Po}$.

The analytical model introduced by [3] is adopted in this work for the computation of the magnetic vector potential. In this simplified model the iron regions are considered to have infinite permeability and the eddy currents are neglected. FEM simulations are performed in order to assess the validity of the method against non-linearities of the magnetic materials. The saturation level is in fact the main factor that infringes the infinite permeability hypothesis: in optimal gears the magnetic flux density levels in all the ferromagnetic parts can reach high values, especially in the iron poles. Nevertheless the hypothesis is able to catch the main features of the field even in in deep saturation conditions and the analytical method still fits the FEM results. Since the optimal devices are far from being completely saturated, the analytical method provides good results.

III. 2-Dimensional Loss Model

The formulation of a comprehensive two-dimensional magnetic hysteresis model of magnetic sheets by which the loss might be calculated under whatever polarization loci (alternating, circular, elliptical, etc.) and time behaviour has been accomplished to little extent so far. However, a rational approach to the 2D magnetic losses and their frequency dependence can be pursued in NO sheets following the method proposed in [4], [5]. This method is based on the concept of loss separation, by

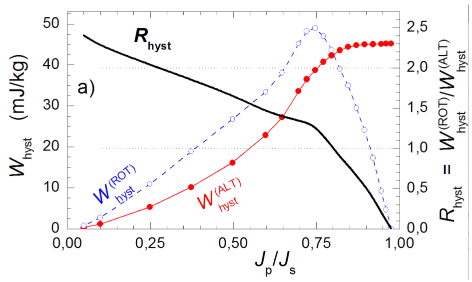


Fig. 2. Alternating and rotational hysteresis loss components and their ratio R_{hyst} as a function of the reduced polarization J_p/J_s for the the NO 0.356mm thick Fe-Si sheet (experimental data retrieved from [6]).

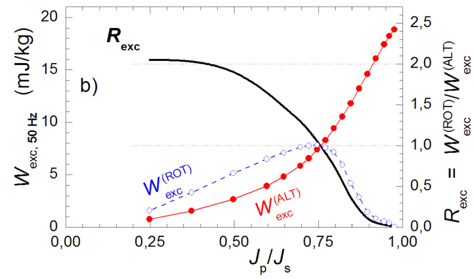


Fig. 3. Same material described in [6]: behaviour of the excess alternating and rotational losses versus J_p/J_s at 50 Hz and their ratio.

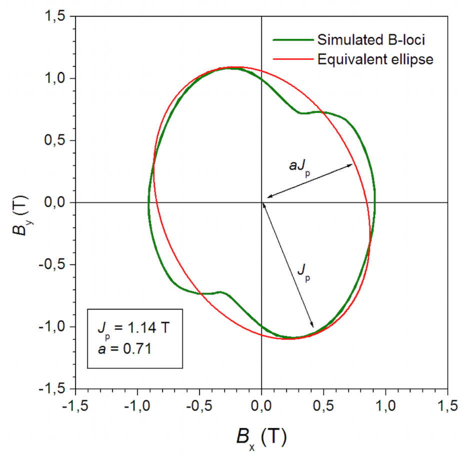


Fig. 4. B-loci at a given point within the iron pole: computed cycle and equivalent ellipsoidal one.

which the total loss W is expressed as $W = W_{hyst} + W_{exc} + W_{class}$, the sum of the hysteresis, excess, and classical components, and the connection with their unidirectional (scalar) counterpart. Following this approach, the hysteresis loss for a given elliptical flux loci is expressed as:

$$W_{hyst}(J_p, a) \simeq W_{hyst}^{(ALT)}(J_p) + W_{hyst}^{(ALT)}(aJ_p)\left(R_{hyst}(J_p) - 1\right) \quad (2)$$

where $R_{hyst} = W_{hyst}^{(ROT)}/W_{hyst}^{(ALT)}$ is the experimental ratio between the hysteresis losses obtained under circular and alternating polarization, J_p is the peak induction measured along the major axis of the ellipse, and a is the ratio between minor to major axis lengths ($a = 0$, alternating loss; $a = 1$, rotating loss). Fig. 2 shows for a non-oriented *Fe-(3.2 wt%)Si* sheet, thickness $d = 0.356\ mm$, electrical conductivity $\sigma = 2.04\ MS/m$, density $\delta = 7650\ kg/m^3$, and saturation polarization $J_s = 2.01\ T$, the experimental behavior of $W_{hyst}^{(ROT)}$, $W_{hyst}^{(ALT)}$ and the ensuing ratio $R_{hyst}(J_p)$, vs. J_p/J_s (experimental data retrieved from [6]). It is worth noting that the ratio $R_{hyst}(J_p)$ is little dependent on lamination type [7].

The excess loss is expressed as:

$$\begin{aligned} W_{exc}(J_p, a, f) &\simeq g(a)\frac{\sqrt{f}}{\sqrt{f_0}}\cdot \\ &\cdot\left\{W_{exc}^{(ALT)}(J_p, f_0) + W_{exc}^{(ALT)}(aJ_p, f_0)\left[\frac{R_{exc}(J_p)}{g(1)} - 1\right]\right\} \end{aligned} \quad (3)$$

where $W_{exc}^{(ALT)}(J_p, f_0)$ is the excess loss obtained under alternating conditions at peak induction J_p and at the reference frequency $f_0 = 50\ Hz$, $R_{exc}(J_p)$ is the experimental ratio, at a given frequency, between the excess losses obtained under circular and alternating polarization and the function:

$$g(a) = \frac{\sqrt{2\pi}}{8.76}\int_0^{2\pi}\left(\sin^2(\varphi) + a^2\cos^2(\varphi)\right)^{3/4} d\varphi \quad (4)$$

$g(1) = 1.8$ is the function $g(a)$ calculated for circular polarization ($a = 1$). Fig. 3 shows for the same material [6] the experimental behaviour of $W_{exc}^{(ROT)}$, $W_{exc}^{(ALT)}$ and their ratio $R_{exc}(J_p)$ vs. Jp/Js. It is worth noting that the ratio $R_{exc}(J_p)$ is to a good extent independent on frequency.

The classical loss, under negligible skin effect, at frequency f is obtained as:

$$W_{class} = \frac{\sigma d^2}{12}\int_0^{1/f}\left[\left(\frac{dB_x}{dt}\right)^2 + \left(\frac{dB_y}{dt}\right)^2\right] dt \quad (5)$$

where $B_x(t)$ and $B_y(t)$ are the induction components.

Starting from the induction distribution computed by the semi-analytical procedure, the magnetic power loss is computed by application of the 2-dimensional loss model. Distorted rotational loci are approximated by equivalent elliptic loci having the same peak induction and the same area of the simulated ones, as shown in Fig. 4. Results on specific magnetic structures will be presented at the Conference.

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