Losses in an Outer-Rotor-Type Kinetic Energy Storage System in Active Magnetic Bearings

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***Abstract* - This paper starts with a general description of the losses and the classification of the loss components in kinetic energy storage systems. Based on the design of an outer-rotor-type kinetic energy storage system an analytical loss model is presented. It considers the conversion losses and the drag losses of the electric drive, the drag losses of the homopolar active magnetic bearings and the gas friction losses, as well as the constant losses such as caused by the bias magnetization of the active magnetic bearings. In detail a new approach for the analytical calculation of the drag losses of the homopolar active magnetic bearings is presented, taking the eddy current and hysteresis losses as well as the penetration depth of the magnetic field into the rotor in account. The paper ends with the presentation of a developed measurement method for the experimental determination of the loss map of kinetic energy storage systems. It enables for the isolation of the drag loss components of the drive system, the magnetic bearings and the gas friction losses.**

TABLE I. USED VARIABLES

Symbol	Name (all units SI)
P_{Iron}	Iron losses
m_{Iron}	Mass of magnetized iron
f	Frequency
B	Flux density
d	Penetration depth
μ	Permeability
κ	Electrical resistivity
ω	Angular frequency
Θ	Polar moment of inertia
E	Energy content
P	Power
Δt	Duration of measurement

I. INTORDUCTION

Losses in energy storage systems can be divided into power-dependent losses, state-of-charge-dependent losses and constant losses. In a kinetic energy storage system the power-dependent losses result from the energy transfer in the drive system. The state-of-charge-dependent losses are caused by drag losses on the rotor, which are mainly the drag losses in the bearings, the drag losses of the motor as well as the gas friction losses. Constant losses result from the control system, the vacuum-system and, in case of active magnetic bearings, from the bias magnetization. A visual representation of the overall loss structure gives the three dimensional loss-map. Figure 1 shows an analytically calculated loss map of a kinetic energy storage system. The loss power is plotted on the vertical axis over the systems state defined by the energy content and the power transfer on horizontal axes.

With a higher energy content, which is quadratic to the rotational speed, the drag losses arise. These loss components are mainly proportional to the quadratic rotational speed, hence the drag losses appear mainly linear with the energy content in the loss map (see Power = 0 kW). Caused by the ohmic losses in the electric drive system, the power-dependent conversion losses rise quadratic to the system power. With lower rotational speeds the efficiency of the electric drive decreases, resulting in a higher loss power when energy is transferred.

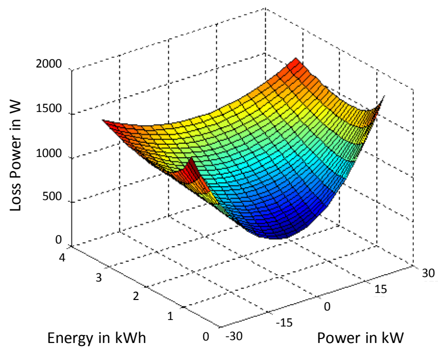

Figure 1. Analytically calculated lossmap of a Kinetic-Energy-Storage-System.

Figure 2 gives the basic structure of an outer-rotor-type kinetic energy storage system. The rotor in form of a hollow-cylinder made of fiber-reinforced-plastics (FRP) rotates around the stator, the rotor components of the magnetic bearings and the drive are integrated on its inner side.

Such systems have already been in discussion in the year 1980 [1]. This rotor geometry provides the maximum polar moment of inertia for the used rotor material, hence it promises the highest achievable energy density resulting in lower costs per capacity of the complete system. Yet no such systems are commercially available. In addition to the normal problems concerning inner-rotor kinetic energy storage systems, like highly gyroscopic effects, new problems arise with this topology. The comparable low stiffness of the rotor made of FRP and the centrifugal forces, caused by the rotation, result in a widening of the rotor of up to 1 % of its inner diameter. Depending on the properties of the overall system, the electric drive and the magnetic bearings must deal with an air-gap enlargement of approx. 0.5 mm to 1.5 mm. With the current state of development of FRP, electric machines and active magnetic bearings (AMB) currently new approaches to develop such outer-rotor-type kinetic energy storage systems are undertaken [2],[3].

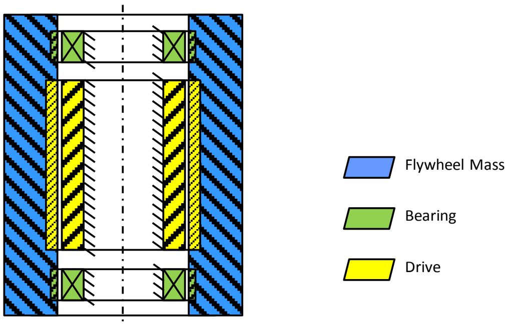

Figure 2. Structure of an outer-rotor-type kinetic energy storage system

Also at the IMS such systems are under theoretical and practical investigation. Figure 3 shows a photo of the set up prototype during the assembly. The rotor inner diameter is 180 mm, its outer diameter 300 mm and the rotor height 500 mm. Resulting in an inertia of the complete rotor of 0.7 kgm². In axial direction a passiv magnetic bearing (PMB) compensates the weight of the vertical rotor of 50 kg. The radial forces are compensated by active magnetic bearings of homopolar topology with active bias magnetization. The system is accelerated up to 20,000 rpm in a high vacuum environment, resulting in an energy content of approx. 0.4 kWh. A synchronous electric drive with Halbacharry-Rotor acts as motor and generator, providing 36 kW at 20.000 rpm. Figure 4 shows a photo of the complete test-rig.

Figure 3. Picture of the rotor on the stator during system assembly

Figure 4. Picture of the test-rig

II. Analytical Loss-Model

With the aim to find an optimal kinetic energy storage system for a given application an analytical model of the complete system is set up, allowing for fast studies over a wide range of parameters. For different parameters like inner-diameter, outer-diameter, height and maximum rotational speed as well as required capacity and power the model calculates the properties of the FRP-rotor, the AMB-system, as well as the drive. For the assessment of the resulting system its operational losses over the applications load profile are calculated via an analytical loss model. This loss model considers the conversion losses, the drag losses as well as the constant losses. While the constant- and the power-dependent losses can be calculated relatively easily, the drag losses of the rotor are more complex.

For most rotor geometries and rotating speeds the gas friction losses in high vacuum result from molecular flow. Because of the little number of left molecules under the low pressure environment, the gas molecules do not interact with each other like in fluids. Interaction takes place between the molecules and surfaces of the rotor, the stator and the containment. The resulting drag is calculated based on the momentum transferred between the molecules and the rotor.

The drag losses of the motor-generator result from the iron losses caused by the rotating rotor field. They can be calculated based on the approach of Steinmetz [4] or the more evolved approach of Bertotti [5]. In both cases the equations consider the mass of the magnetized material (m_{iron}), the magnetization frequency (f) and the magnetic flux density (B). Both approaches consider the hysteresis effects (k_h) and the eddy current effects (k_e) in the iron, the approach of Bertotti additionally considers the influence of abnormal eddy currents in the magnetic domains (k_a).

$$P_{iron} = m_{iron}(k_h \cdot f B^2 + k_e \cdot f^2 B^2 + k_a \cdot f^{1,5} B^{1,5}) \qquad (1)$$

These approaches take sinusoidal fields into account as they mainly appear in synchronous drives. Figure 5 compares the flux density in the air-gap of heteropolar and homopolar magnetic bearings. In both cases the magnetic field is approximated by a rectangular waveform. Fringing effects and leakage flux smoothen the waveform, so the approach of

Bertotti is often adopted to heteropolar bearings, as for example suggested in [6]. The analytical calculation of the drag losses in homopolar magnetic bearings is more complex. [7] proposes the Fourier transformation of the air-gap field to calculate the drag loss for each harmonic frequency of the signal. The set up model considers leakage flux and fringing effects via a cosine function, see Figure 5. The width of the cosine is estimated as 1.9 times the air-gap, following [9].

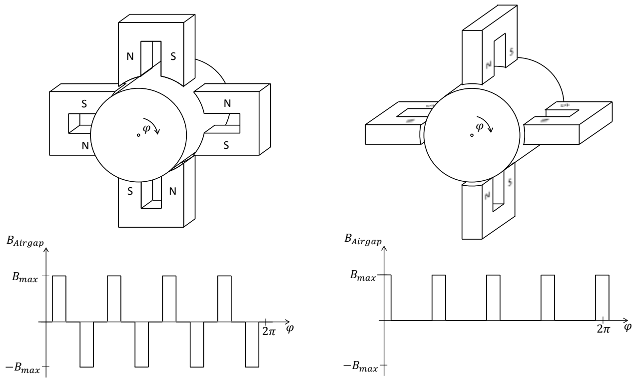

Figure 5. Comparison of the air-gap flux density of heteropolar (left) and homopolar (right) active magnetic bearings

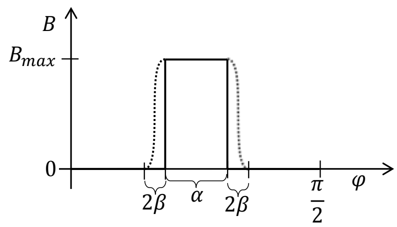

Figure 6. Approximation of the fluxdensity on the rotor surface under one pole of the homopolar bearing

With these assumptions the Fourier coefficients for the field of the homopolar bearing result as:

$$F(\omega) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n cos\,(4n\varphi) \tag{2}$$

With:

$$a_0 = 1 + \frac{4}{\pi}(\beta - \alpha)$$

$$a_n = a_1(n) + a_2(n) + a_3(n)$$

$$a_1(n) = \frac{1}{n\pi}(\sin(4n\alpha) - \sin(4n(\alpha - 2\beta)))$$

$$a_2(n) = -\frac{2}{\pi}\left(\frac{\sin(\pi - 4n\alpha) + \sin\big(4n(\alpha - 2\beta)\big)}{\left(\frac{\pi}{2\beta} - 4n\right)} + \frac{\sin(\pi + 4n\alpha) - \sin\big(4n(\alpha - 2\beta)\big)}{\left(\frac{\pi}{2\beta} + 4n\right)}\right)$$

$$a_3(n) = -\frac{2}{n\pi}\sin(4n\alpha).$$

The total drag losses of the homopolar bearing result by summing up the losses of the harmonic components. Especially for high magnetization frequencies, as they occur in this application, eddy currents reduce the depth the magnetic field penetrates the rotor. Hence the magnetized mass m_{iron} is reduced. For a two dimensional field the penetration depth results dependent on the materials electrical resistivity κ and permeability μ and the angular magnetization frequency ω as:

$$\mathrm{d} = \sqrt{\frac{2}{\mu\kappa\omega}} \tag{3}$$

In the rotor of the homopolar magnetic bearing a three dimensional field is present which cannot be calculated analytically. Figure 6 shows the geometric approximation enabling the calculation.

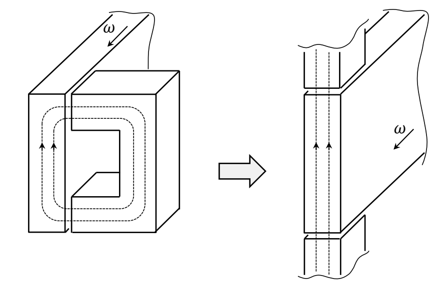

Figure 7. Approximation of the bearing structure for the calculation of the eddy current dept

For each harmonic frequency of the Fourier transformation the magnetized mass is calculated based on the penetration depth (3). With the flux density of the harmonics (2), the drag of each harmonic is calculated via equation (1). Figure 7 gives an example of the calculated losses over the rotation frequency. The consideration of the penetration depth leads to discontinuities in the calculated losses. These occur when the penetration depth of one Fourier coefficient is smaller than the needed depth to penetrate the rotor in total. Such discontinuities do not exist in a real system, the resulting error is considered to fall within the general accuracy of the model.

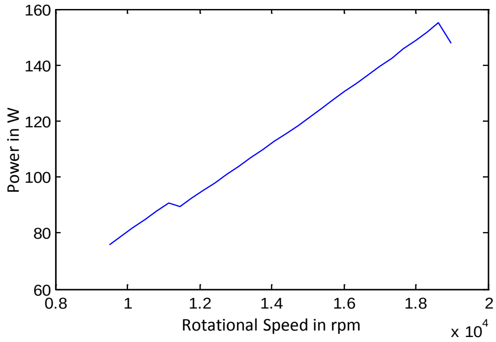

Figure 8. Calculated drag losses of both bearing planes of the homopolar active magnetic bearing

Figure 9 compares the gas friction losses, the drag losses of the AMB as well as the motor-generator unit and the summed up total losses over the rotational frequency. A detailed description of the underlying models is given in [10].

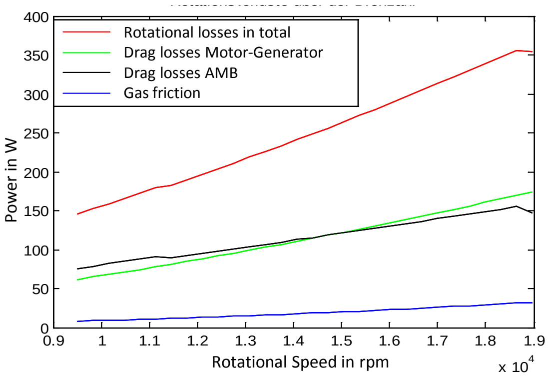

Figure 9. Rotational losses over rotation frequency

III. Intended Procedure for the Experimental Determination of the Losses

The losses for each operational point $P_{loss}(E,P)$ of the loss map can be calculated as the difference between the power transferred to the system and the resulting change in its energy content divided by the duration of the measurement. The energy transferred to the system is measured exactly with a wattmeter based on the drive currents and voltages. With the measured rotational speed and the known inertia θ of the rotor also its current state of energy can be calculated exactly.

$$P_{loss}(E,P) = P_{Drive} - \frac{\frac{1}{2}\theta({\omega_2}^2 - {\omega_1}^2)}{\Delta t} \qquad (4)$$

For the measurement two possibilities arise, conducting the measurement for a constant time period or a constant change of the rotational speed. To achieve a high accuracy the measurement should be conducted for a relevant change in the systems energy content. For operating points with a high system power the conversional losses dominate the drag losses. Also the change of the energy content is linear dependent on the power and the duration of the power transfer. Hence for these operating points the measurement should be conducted for a constant time period dependent on the systems power.

For little or no power transfers the drag losses dominate. Caused by the quadratic dependency between rotational speed and energy content, as well as rotational speed and the drag losses, the measurement should be conducted for a constant change in the rotational speed dependent on the system energy content.

A special case of the loss measurements is the coast down, when no energy is transferred to the rotor ($P_{Drive} = 0$). During this measurement only drag losses slow down the rotor, so it is an adequate measurement to determine the drag losses. Since the different loss components (gas friction, drag of the bearings and drag of the drive) occur simultaneously, they cannot be determined separately. In order to isolate the three different components two system parameters must be varied. The set up prototype allows for the variation of the gas pressure inside the containment and the variation of the bias magnetization, so the two needed parameters are present. An appropriate influence on the system's drag losses is expected for doubling the gas pressure from 0.03 Pa to 0.06 Pa, leading to approx. twice the gas friction losses. The reduction of the bias magnetization will reduce its drag losses, but also the maximum rotational speed of the system, since it reduces the force slew rate of the magnetic bearings. Since the bearings drag losses are proportional to the quadratic flux density, a reduction of the bias magnetization by 25 % will lead to a significant influence on the drag losses.

To speed up the coast down measurements, the measurements will be conducted at different operating points which are approached through a directed charge or discharge of the system.

IV. Discussion and Conclusion

An outer-rotor-type kinetic energy storage system in active magnetic bearings has been developed and setup. The system's current maximal rotating speed is 20,000 rpm, resulting in an energy content of 0.4 kWh. For further developments an analytical loss model is set up. It considers the conversion and the drag losses of the electric drive, the drag losses of the homopolar active magnetic bearings and the gas friction losses as well as the constant losses. For the calculation of the drag losses of the homopolar magnetic bearings a new approach combining different models given in the literature was developed. It enhances the approach of Bertotti for the magnetization waveform of the homopolar magnetic bearing and the field's penetration depth. The model shows small discontinuities over the rotational speed, which are expected to be within the models general uncertainty.

Our next step is the model update via the experimental determination of the losses on the set up prototype system. In order to achieve a high accuracy the presented measurement method takes the system's operating point into account. Special effort is needed for the isolation of the drag loss components of the permanent magnetic synchronous drive, the drag losses of the homopolar magnetic bearings and the gas friction losses.

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