Multicriteria Design Process for Outer-Rotor Kinetic Energy Storage Systems

Maximilian Schneider[a], Hendrik Schaede[a], Stephan Rinderknecht[a]

[a] Institute for Mechatronic Systems in Mechanical Engineering, Otto-Berndt-Straße 2, 64287 Darmstadt, Germany,
schneider@ims.tu-darmstadt.de

***Abstract*—Due to the global energy transition, energy storage capacities are necessary. Kinetic energy storage systems can be used to provide valuable grid services but have to be redesigned to fulfill this task. A structured process is necessary in order to cope with the complexity of those systems and to maximize performance and profitability. This multicriteria design process is described in detail for an outer-rotor kinetic energy storage system. The approach is based on a detailed system model consisting of the several sub-models. It incorporates the design of the drive system, the magnetic bearing system, as well as the composite rotor. This approach enables the use of optimization algorithms in order to find systems matching the application specific objectives such as minimal operational losses or a maximal energy density. The multicriteria design process is then applied to an exemplary application.**

I. INTRODUCTION

In many countries, the government has initiated a transition of the energy system. Conventional power sources such as coal or nuclear power are being replaced by renewable energies such as wind and solar in order to provide a more sustainable energy supply. Most renewables, however, come with a main disadvantage. Their power output is volatile and uncertain resulting in high prognosis errors. In combination with the stochastic demand of electricity a stable and secure energy supply can only be efficiently achieved by installing a certain amount of storage capacity.

When analyzing the characteristics of this storage demand it becomes clear that different storage characteristics are needed. This is especially true for grid stabilization services, where systems with a moderate storage capacity, high electrical power, and a high cycle life are necessary. At first glance, conventional kinetic energy storage systems, which are already commercially available for uninterruptable power supply applications, seem to be able to fulfill those requirements. In-depth analyses show, however, the need for a redesign of the basic technology in order to be competitive with chemical batteries and capacitors within this field of application. Moreover a customization of the storage technology to the final application is crucial to its performance and thus its profitability.

This contribution introduces a detailed technical design process for kinetic energy storage systems in outer-rotor design. Firstly, different topologies are compared by analyzing their energy density and degree of integration. Secondly, the technical development process is put into perspective to the overall development process (SDA methodology). Thirdly, the optimization process is described in detail and advantages as well as challenges are discussed. The last chapter applies the process to a real application.

II. ANALYSIS OF KINETIC ENERGY STORAGE SYSTEM DESIGNS

Before the development process can be analyzed in detail, some considerations about the technology itself and different designs are necessary.

A. *Overview of Possible System Designs*

A kinetic energy storage system (KESS) stores energy in the rotation of a mass with certain inertia. The stored kinetic energy E_{kin} is given by equation (1):

$$E_{kin} = \frac{1}{2}\,\theta\omega^2\,. \tag{1}$$

It is square-depended of the rotating frequency ω and linear-depended from the inertia θ. While the inertia for a cylindrical tube depends linearly on the mass of the rotor m and squarely on the inner and outer radii:

$$\theta = \frac{1}{2}\,m(r_{outer}^2 + r_{inner}^2)\,. \tag{2}$$

A maximum energy density is achieved by high rotating frequencies as well as large radii, requiring high strength materials, such as carbon fibers, in order to be able to reach high tangential velocities [1]. All types of kinetic energy storage systems have certain main parts in common. A schematic drawing is shown in Fig. 1.

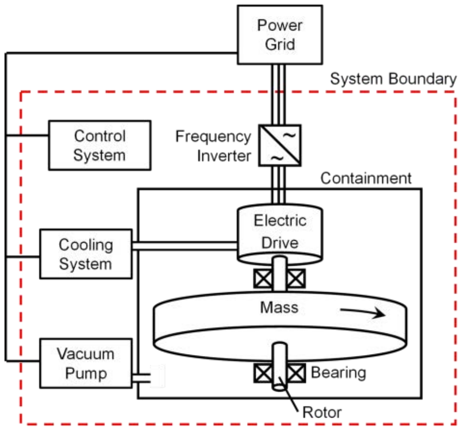

Figure 1. Components of a typical kinetic energy storage system

Via an electric drive the rotor is accelerated and hence its energy content varied. The rotor can be supported by different kinds of bearings. All kinds of magnetic bearings are in discussion; roller bearings can also be found in commercial systems. Depending on the design and the components used, different peripheral subsystems, such as a vacuum pump, a cooling as well as a control system, are needed to efficiently operate the kinetic energy storage system.

As already mentioned before, kinetic energy storage systems have been investigated for a long time, explaining the different topologies available today. Four main types can be distinguished [2], see Fig. 2.

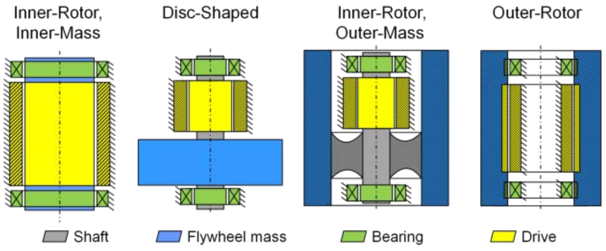

Figure 2. Overview of different flywheel types [3]

B. *Degree of Integration*

A suitable characteristic to compare different kinetic energy storage system designs is their degree of integration (DoI). A high DoI is necessary to maximize the energy density of a kinetic energy storage system and to minimize the production cost. It can be defined as the extent to which different system components are used to generate a high inertia. The disc-shaped flywheel type can be found in commercially available systems and has the lowest DoI. Only the actual flywheel mass is used to store the energy. The inner–rotor/outer-mass concept has a higher DoI because the flywheel mass rotates around the drive and bearings, leading to a higher inertia. A high DoI can be observed for the inner-rotor/inner-mass concept, because the rotor parts of the electric drive and the bearings largely contribute to the moment of inertia. Since the electric drive and the bearings have to have the diameter of the mass, the overall system size is limited. The highest DoI is reached with the outer-rotor concept because all components of the rotor are placed at the largest possible radius leading to a high inertia of the rotor with respect to the rotors mass. The outer-rotor concept is the only topology that is not commercially available today. One reason for this may be the high development effort that is still necessary for such systems. Only little knowledge is present on outer-rotor magnetic bearings as well as outer-rotor high-speed electric drives. In spite of the straight forward overall system structure, interdependencies between the different components of these highly integrated systems lead to a complex overall system. The remainderof this contribution will focus on the outer-rotor topology because it has the highest potential in terms of energy density and DoI but is not sufficiently developed yet.

III. THE OVERALL DEVELOPMENT PROCESS

In [3] a general methodology for the development of energy storage systems is described as the so-called Specification, Design and Assessment Methodology (SDA-Methodology). It enables the efficient and reproducible development of energy storage systems for a specific field of application. Based on this method, requirements for the design process of a certain storage technology can be derived.

A. *The SDA Methodology*

The methodology consists of the three meta-steps: ‘Specification’, ‘Design’ and ‘Assessment’. Every meta-step can be divided into several sections. The exact process is displayed in Fig. 3. The specification process starts with the load profile synthesis. Here the necessary storage power profile is derived from the application load profile. Based on this, the energy storage system can be dimensioned. The storage dimensions are forwarded to the design process that starts with a decision for a certain storage technology. Within the block ‘Energy Storage’ the system is designed and optimized. In order to ensure a correct and efficient operation of the system, a suitable operational strategy has to be developed. The designed storage technology is then forwarded to the step ‘Assessment’. Here the technology can be tested and evaluated based on simulations. Necessary iterations and optimization steps can then be initiated.

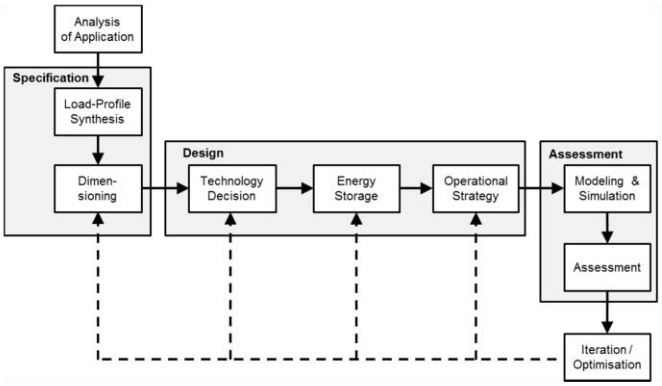

Figure 3. Specification, Design and Assessment methodology [3]

B. *Requirements Resulting from Specification*

Depending on the field of application of the kinetic energy storage system different requirements can result from the ‘Specification’. Indispensable for the design process, however, is the nominal electrical power and the usable storage capacity. Other requirements such as certain efficiencies, cycle life, safety, total costs or energy/power densities can be defined by the specification process and have to be fulfilled by the design process. In the following we assume that in the step ‘Technology Decision’ the outer-rotor concept has been selected.

IV. DESIGN PROCESS FOR THE OUTER-ROTOR CONEPT

This contribution proposes an integrated design approach for an outer-rotor KESS. The optimal design of KESS has been discussed in various publications. Most of the authors, however, focus only on the rotor design (e.g. [4], [5], [6]). The contributions considering the overall system design do not focus on the characteristics of the outer-rotor design (e.g. [7], [8]).

Before the actual design process can be initiated the interdependencies between the different system components must be determined. The insight into those relations leads to a better understanding of the system itself and the optimization problem. Afterwards an overall system model can be developed which is used to find an optimal solution to the specified requirements.

A. Identifying Important Interdependencies

According to Fig. 1, the important parts of every kinetic energy storage system are the bearings, the rotor and the electric drive. Additional properties can be identified that characterize the system such as vacuum quality and rotational speed. Table I gives the results of an analysis of interdependencies between components and properties.

TABLE I. INTERDEPENDENCIES BETWEEN IMPORTANT SYSTEM COMPONENTS AND PROPERTIES OF THE OUTER-ROTOR DESIGN

	Bearing type	**Rotor geometry**	**Electric drive**	**Rotor material**	**Vacuum quality**	**Rotational speed**
Bearing type	/	●	◐	◐	●	●
Rotor geometry		/	●	●	◐	●
Electric drive			/	○	○	●
Rotor material				/	◐	●
Vacuum quality					/	●
Rotational speed						/

●: high, ◐: medium, ○: low

As can be seen in Table I, especially the rotor geometry and the rotational speed have high interdependencies with all other components and properties. This means that a high change in rotational speed, for example, leads to a strong change in rotor material or electric drive. The connection between bearing type and electric drive, for instance, is low because the same electric drive can be operated with different bearing types.

B. Optimization Problem

In the previous chapters the complexity of the optimization problem has been described. It is obvious that with the high DoI of the outer-rotor concept and the resulting large number of interdependencies a sequential selection and design of the different components does not lead to an optimal system design. In addition to the interdependencies several non-linear constraints, such as the maximum stress in the material or the design of the magnetic bearings and the electric drive have to be considered. Depending on the exact field of application several objective functions need to be optimized at the same time. For most systems at least two of those objectives can be conflicting goals, for example the energy density and the operational losses. Combining the requirements imposed on the optimization process a non-linear, multicriteria optimization with a large number of input variables has to be carried out.

C. Developing a System Model

In order to be able to optimize the KESS a detailed system model is necessary. In the following a model for an outer-rotor kinetic energy storage system with active magnetic bearings (AMB) for the radial suspension, a rotor out of fibre-plastic composite material, and a permanent magnet excited synchronous motor is described, see Fig. 4. To reduce the large number of input variables only four important geometric variables (outer-rotor radius, inner-rotor radius, rotor height, radial length of fittings), the number of stator windings of the electric drive and one operational variable (rotational frequency) are used as input parameters.

The first step of the system model is to complete the system parameters so that the requirements (maximal power, storage capacity) are fulfilled using geometrical, material and electrical, operational assumptions. The geometrical assumptions consist of geometrical parameters that are kept constant or within a certain range, such as the air gap between rotor and stator, the balancing quality of the rotor or the number of pole pairs of the electrical drive. The material assumptions are densities, maximal stresses, electrical conductivities, temperatures and pressures. Electrical assumptions are defined as maximal currents and voltages for the electric drive and the AMB as well as maximal flux densities and loss factors. Operational assumptions are important for the next steps as they define operational situations that have to be fulfilled by the components, such as power and force requirements for the electric drive and AMBs.

The next step within the system model is the design of the fiber-composite rotor, the active magnetic bearings and the electric drive. The rotor stresses are calculated using the analytical approach described in [9] for a one-layer, elastic and anisotropic composite rotor using the Euler–Cauchy governing equation. The AMB is designed such that it can provide the maximal forces occurring when exciting the nutation eigenfrequency of the rotor superimposed by the maximal radial coupling force of the permanent magnet axial bearing. The electric drive has to be designed for the maximal torque occurring when the maximal power is demanded at minimal rotational speed.

In the next step the constraints gate has to be passed. Here properties of the system that were calculated before are evaluated. Basic geometrical constraints such as a larger outer than inner diameter and a smaller total height of the fittings than the total rotor height have to be fulfilled. Also the maximum rotor strain at maximum rotational frequency has to be smaller than the critical strain defined by the material. Dynamic constraints that are verified are the eigenfrequencies of the stator or the controllability measured by the inertia ratio. Electrical constraints that are checked are the maximal current and voltage of the electric drive and the AMBs. The KESS is only forwarded to the loss model if all constraints are fulfilled by the system configuration. Otherwise the system configuration is discarded.

D. Optimization Objectives: Loss and Energy Density Model

Up to this point the model is independent from the optimization objectives. The Results are alternative designs fulfilling the constraints. In the following, the properties of each design concerning the optimization objectives are determined. Here, these objectives are minimal operational losses and a maximum energy density. Within the loss model three major loss components of the kinetic energy storage configuration are calculated. The operational losses are caused by air friction losses, losses of the electric drive (conversion losses and drag losses) and drag losses of the AMB as well as its Ohmic losses. The calculation is carried out using stationary analytical loss models. The loss estimations of the electric drive and the AMBs are based on material specific loss parameters that consider frequency dependent hysteresis and eddy current losses as well as Ohmic losses. The energy density of the configuration regarding the rotor is also calculated.

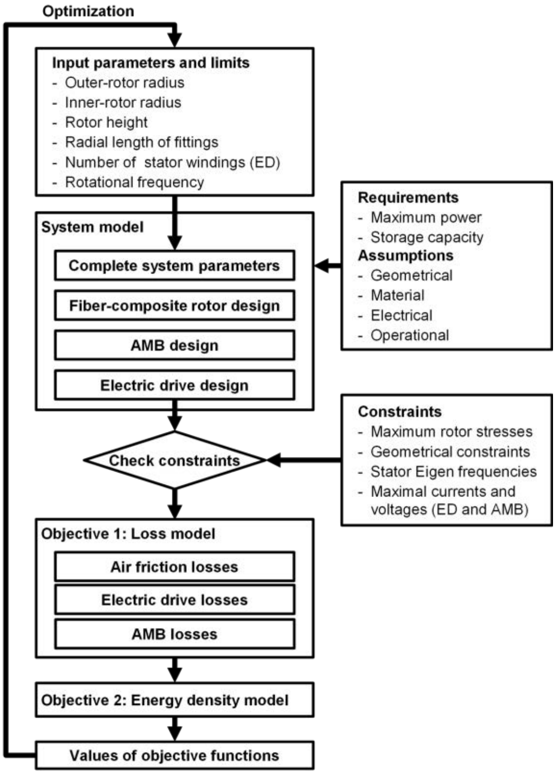

Figure 4. System model for the optimization

V. EXAMPLARY APPLICATION: FACTORY GRID

Kinetic energy storage systems can be used for different applications. Applications with a high number of cycles at high electrical powers compared to the total transferred energy are especially suitable for a KESS. As an example a small factory grid is analyzed in the following and a KESS shall be designed for this application.

A. *Specification*

According to the SDA methodology the dimensions of the energy storage system (power, energy capacity) have to be specified before it can be designed. Therefore the load profile is analyzed and the storage dimensions are derived in the following paragraphs.

Figure 6 (top) shows the load profile of the factory grid for about 5.5 hours. The resolution of the signal is 1 second resulting in very high power peaks up to 150 kW. The aim of the KESS is to smooth the load profile and at the same time limit the maximum power to 100 kW. The resulting reduced volatility of the profile generates a value for the storage operator because electricity costs depend on the maximum power at the grid connection point of the factory. Moreover it helps to relieve the load of the distribution grid leading to a higher capacity to integrate renewable energies.

In order to generate the desired load profile, the original load profile is filtered. An analogue low-pass filter could be used but would lead to a phase delay of the filtered signal. The field of digital signal processing provides methods to overcome this drawback. One possibility is to use a zero-phase digital filter to generate the generic load profile. Such filters process the input data in both the forward and reverse direction [10]. Since the full load profile has to be known at the time of filtering this method cannot be used for real time applications. For the suggested procedure no online capabilities are necessary because the ‘Specification’ process is only performed offline and before installing the KESS. The filtered load curve was generated using a corner frequency of 0.0105 Hz.

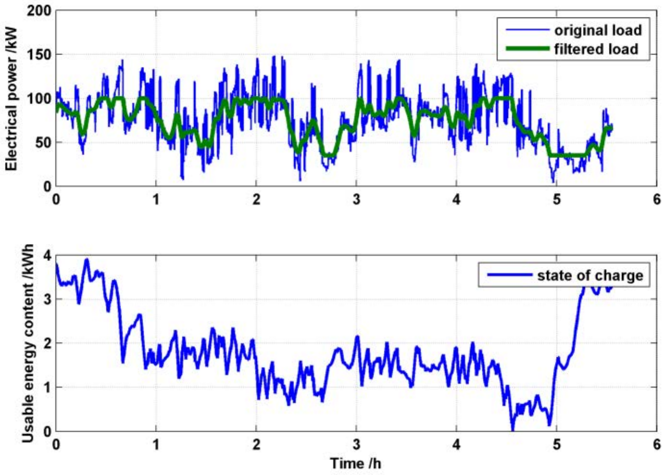

Figure 5. Load curve of the industrial plant (top) and the resulting energy curve of the KESS (bottom)

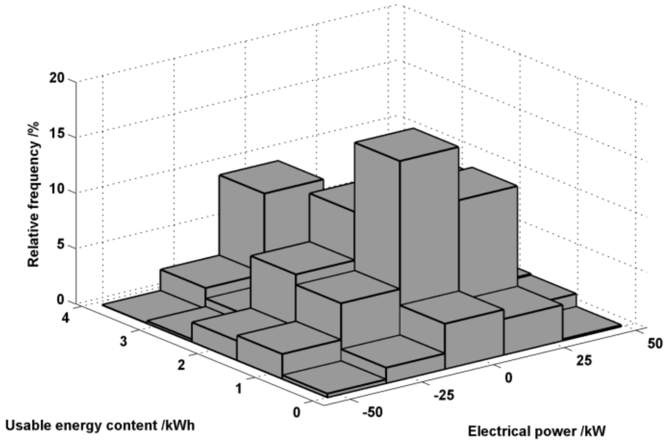

Figure 6. Relative frequencies of operating points

The KESS has to provide the difference between the filtered and the original load profile. A positive power difference equals charging and a negative difference discharging of the KESS. Fig. 6 (bottom) shows the resulting energy curve of the KESS during operation.

In order to analyze the operating points of the KESS, defined by power and energy content, the relative frequencies are determined. As can be seen in Fig. 6, the KESS mostly operates at medium to high energy levels and small powers. The maximum power is only needed a few times. From this analysis it becomes clear that a maximal electrical power of 54.3 kW and a usable energy capacity of 3.9 kWh are necessary to fulfill the task.

B. *Design*

For the design phase an optimization algorithm is needed. The problem is a non-linear multicriteria optimization problem with non-linear constraints and limited input variables. For such complex problems evolutionary algorithms deliver satisfying results (see e.g. [11]). Thus a genetic algorithm is applied here. In order to thoroughly search the design space the population size is set to 4000 and the number of generations is set to 500.

The information generated during the specification phase is also implemented. The maximal electrical power and the usable energy capacity are given to the storage model as requirements. The relative frequencies are used to calculate combined total losses for different operating points. During the optimization process the total losses, consisting of air friction, electric drive and active magnetic bearing losses, are calculated for every operating point. The optimization algorithm, however, can only process a single value for every optimization criterion. Therefore the different losses are weighted with the relative frequency of their operation point. The combined total losses are then calculated by summing up the weighted losses. In addition the energy density is calculated using the rotor weight and the usable energy content.

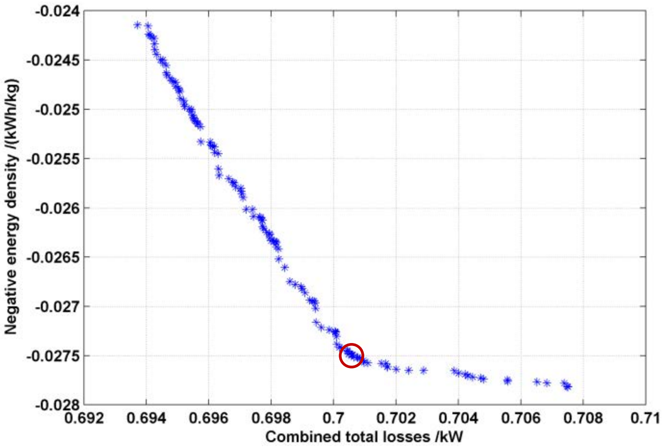

Figure 7. Pareto frontier of the optimization process

The optimization results can be displayed in form of a Pareto frontier of the two optimization criteria, see Fig. 7. Since the energy density is a criterion that is to be maximized, the sign has to be switched in order to get a minimization problem.

The total number of individuals on the Pareto frontier is 135. The optimization was terminated because the maximum number of generations was exceeded after about 22 minutes.

The Pareto frontier can be interpreted as follows. For a given value of combined total losses, there is no individual with a higher energy density than the one on the frontier. As can be seen from its form, there is one group of solutions that is likely to be chosen by a designer with balanced preferences (red circle). From there a further decrease of the losses would mean that a lot of energy density has to be sacrificed (left side of the circle). In order to increase the energy density even further, the losses increase significantly (right side of the circle).

In the following, the KESS in the middle of the red circle is analyzed in detail. The combined total losses of this system lie at 0.705 kW and the energy density at 0.0275 kWh/kg.

Table II shows the input parameters that are necessary to gain the selected KESS.

TABLE II. INPUT PARAMETERS OF THE SELECTED KESS

Parameter	Value
Outer-rotor diameter	234 mm
Inner-rotor diameter	115 mm
Total height	612 mm
Number of stator windings of electric drive	14
Radial length of fittings	8 mm
Scaling factor of rotational frequency	1.5 %

Together with the requirements, assumptions and the storage model, these parameters lead to the complete KESS. The geometrical dimensions of the system are displayed in Fig. 8.

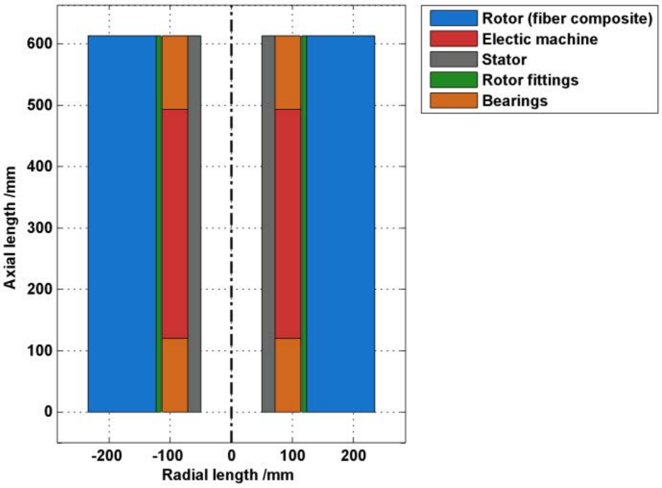

Figure 8. Geometrical dimensions of the selected KESS

TABLE III. OPERATION PARAMETERS OF THE SELECTED KESS

Parameter	Value
Minimal rotational speed	15,666 1/min
Maximal rotational speed	28,830 1/min
Moment of inertia	4.37 $kg \cdot m^2$
Minimal physical energy content	1.63 kWh
Maximal physical energy content	5.53 kWh

In addition to the geometrical dimensions the operation parameters result from the same model. As can be seen in

Table III the KESS is operated between 15,666 and 28,830 1/min.

With the moment of inertia of 4.37 kg·m^2 this can be converted to a minimal physical energy content of 1.63 kWh where the KESS is considered empty because it cannot provide the full electrical power anymore. The maximal physical energy content lies at 5.53 kWh. Here the stresses within the rotor reach their fatigue limits. The stresses of the fiber-composite rotor at maximal rotational frequency are shown in Table IV.

TABLE IV. MATERIAL PARAMETERS (FIBER-COMPOSITE) OF THE SELECTED KESS

Parameter	Value	Limit
Maximal tangential stress	738.2 N/mm^2	740 N/mm^2
Minimal radial stress	-66.1 N/mm^2	-120 N/mm^2
Maximal radial stress	34.9 N/mm^2	35 N/mm^2

Since the losses of the system are fundamental to the optimization, they are analyzed in depth. Figure 9 shows a loss map of the KESS for different operational points. The losses for electrical power equal to zero are caused by the AMB losses, the air friction losses and the drag losses of the electric drive. All of them increase with increasing rotational speed resulting in an angled map. For positive or negative electric powers the conversion losses of the electric drive occur and contribute to the total losses. This leads to a bent loss map in the direction of electric power.

The total losses reach a maximum of 935 W for maximal rotational speed (28,830 1/min) and maximal negative electrical power (-54.3 kW). The loss minimum lies at 518 W for minimal rotational speed (15,666 1/min) and no electrical power.

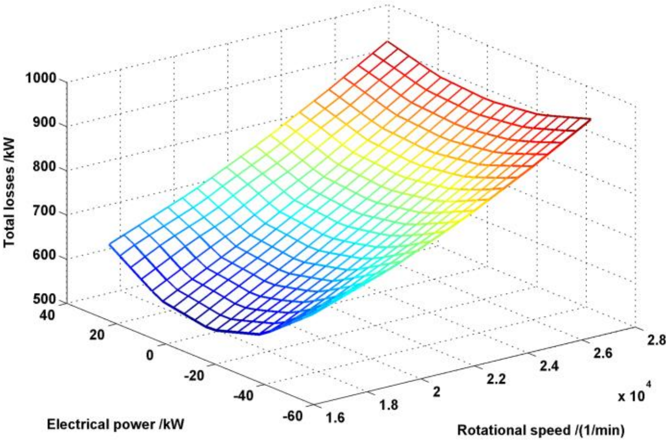

Figure 9. Loss map of the selected KESS

In order to get an idea of the order of magnitude of the different loss components, Table V shows their mean values of all operating points.

The electric drive losses have the highest contribution to the total losses, but also the AMB losses play an important role. The air friction losses are low because vacuum quality is very high (0.005 Pa).

TABLE V. AVERAGE LOSS PARAMETERS OF THE SELECTED KESS

Parameter	Value
Mean AMB losses	119.35 W
Mean electric drive losses	500.04 W
Mean air friction losses	2.43 W

VI. CONCLUSION AND OUTLOOK

Driven by the transition of the energy supply, new and efficient energy storage technologies are necessary. Outer-rotor kinetic energy storage systems have the capability to contribute to a sustainable energy supply. Their design process, however, is complex due to a high degree of integration leading to a large number of interdependencies between system components. A special optimization procedure based on a detailed system model is necessary to generate results suiting the detailed requirements of the application.

In this contribution a multicriteria optimization regarding the total system losses and the energy density is carried out. In order to perform such an optimization not only a detailed system model is needed but also a loss and energy density model. Since the optimization is based on those models the model accuracy directly contributes to the results. Very detailed and thus very exact models, however, dramatically increase the computation time. In order to make decisions concerning the right degree of abstraction, experimental validations of the system and loss models are essential and should be carried out in the next step.

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