Development of Kinetic Energy Storage Systems for Island Grids

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Abstract

Energy storage systems have the capability to provide viable reductions in the fuel consumption of diesel generators in islanded grids with medium to high penetration of renewable energy sources. Kinetic energy storages systems (KESS) can provide spinning reserve capacity (SRC) in such grids. This allows operating with a lower capacity of diesel generators to meet the same demand. This contribution utilizes the Specification, Design and Assessment Methodology (SDA) to develop a KESS and its operational strategy for the islanded grid of Nome, Alaska. The resulting reduction of the diesel consumption is determined through simulations. A possible secondary function of the KESS is to provide load smoothing which relieves the generators from high dynamic load changes.

1 Introduction

In isolated grids diesel generators have two functions: providing electric energy as well as grid stabilization. With the technical improvement and reduction in cost of renewable energy generators an increasing number of these systems are used in isolated grids to supplement diesel-generated electricity. Where implemented well, utilization of renewable energy leads to reduced costs for the energy supply as well as reduced CO_2 emissions.

Other than providing prime power, diesel generators also provide important services to grid stability, e.g., voltage and frequency stability and reactive power support. To compensate the fluctuations in renewable energy production as well as the stochastic components in the power demand a spinning reserve in form of running diesel generators is kept online, i.e., added capacity is always available to provide for sudden reductions of renewable energy production or sudden increases in demand. Providing spinning reserve capacity (SRC) with diesel generators leads to their operation at reduced load factors, and subsequently to reduced efficiency of the diesel plant. This diminishes the ability of the renewable energy systems to realize fuel savings. This also limits the maximum penetration of renewable energy on the grid, as online diesel generators require being loaded to a minimum operating level (MOL). This is generally determined by the engine manufacturer and can vary from 15% to 60% of nameplate capacity.

An alternative way to stabilize these grids and thus allow for a higher share of renewable energy is the use of electric energy storage systems (EESS). The basic function of the EESS is to store energy when there is too much energy available and to release energy when there is too little. From this task a multivariable problem results with the objective to find an efficient, minimal-cost system without compromising grid stability.

One application for EESS in islanded grids is to provide the spinning reserve instead of the online diesel generators. The complete coverage of the spinning reserve with EESS requires a large capacity of the storage system, leading to high installation costs. A more cost effective way to reduce the diesel consumption in existing islanded grids is the integration of short term, high power energy storage. Such EESS can provide spinning reserve long enough to bring available diesel generators online. For a generator kept in hot standby, the energy storage system must provide SRC for about 2 min to 10 min, depending on specific generator properties. High power density and a practically unlimited cycle-life make kinetic energy storage systems (KESS) well suited for this application.

In order to optimize grid stability and to reduce actual energy costs the soft facts of the EESS are important. Both sizing and operational strategy of the EESS have to be carefully considered. The properties of the specific islanded grid have to be taken into account, and the operational strategy must be deeply integrated into the energy management of the grid since it influences the scheduling of the diesel generators.

To solve this problem a holistic development approach must be chosen, taking the specification of the EESS, the resulting real world system properties and operational strategy into account. This paper utilizes the 'Specification, Design and Assessment Methodology' [1] to size a KESS for the islanded grid of Nome, Alaska, which provides a good example of a medium sized islanded microgrid with medium to potentially (if a suitable EESS was available) high wind penetration.

Based on a data-driven time-series energy balance model, developed by the Alaska Center for Energy and Power [2], technology neutral requirements are derived in the 'Specification' step. In the 'Design' phase a KESS is designed that meets the requirements of the previous step. Before the system can be simulated a suitable operational strategy must be determined. In the 'Assessment' step the KESS is simulated and analyzed within the time domain to ensure its functionality and economic feasibility. The amount of diesel fuel saved compared to the scenario without KESS is the main considered performance figure.

2 Description of the Exemplary Island Grid

Nome, population 3600, is located about 200 km south of the Arctic Circle at 64°30′14″N 165°23′58″W. The community grid exhibits an average load of 4 MW and is supplied by 5.2 MW to 1.9 MW diesel generators and 2.7 MW wind power capacity. Table 1 states the properties of all available diesel generators in the grid. During the analyzed time period only the first two generators are in operation. To cover stochastic components in the load a SRC of 250 kW is kept online. Due to the volatile characteristic of the wind generation the complete wind production is also covered by the SRC. Thus, the minimum online capacity of the diesel generators is 250 kW above the load, regardless of the amount of wind power.

Figure 1 gives 14 exemplary days of Nome's load profile with a high wind generation during the first week and low wind generation during the second. In total 15 weeks were during wintertime are analyzed. On the demand side there is a clear midday peak of about 4.5 MW, while the load drops to 3.1 MW during the night. The total power capacity of the online diesel generators is at least 250 kW above the load.

From 10/22 through 10/28 the demand is completely met by the diesel generators since there is no significant wind generation. On 10/21 the wind production is quite high. Since the wind production must be covered by online diesel generators two generators are running. During that day the wind generation still grows, requiring diverting the excess wind energy into a boiler, so the diesels do not drop below their minimum operating level.

Table 1: Available diesel generators

Max. Power	No. of Generators	Max. Efficiency	Min. Operating Level	Min. Run Time	Start-up time (warm state)
1.9 MW	1	34 %	30 %	90 min	2 min
3.7 MW	1	34 %	40 %	180 min	2 min
5.2 MW	2	42 %	60 %	180 min	10 min

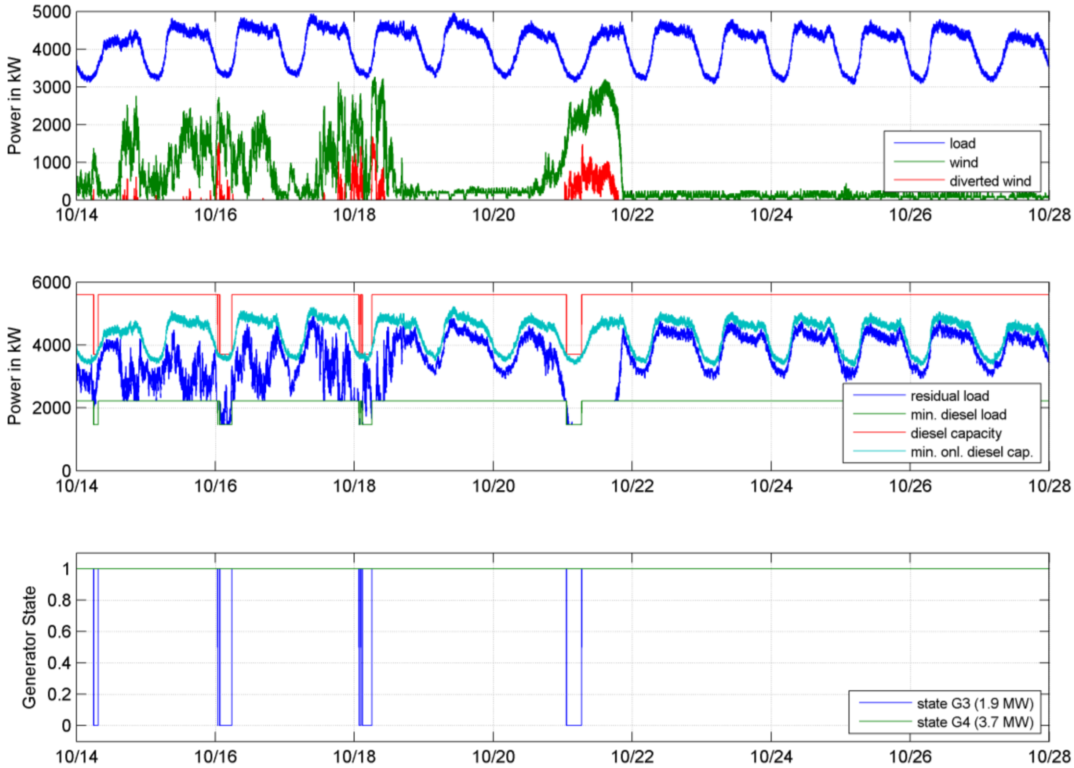

Figure 1: Load, wind generation and wind diversion (top); residual load, minimal load of diesels, maximum capacity of diesels and minimum online capacity due to SRC rules (middle); states of used diesels (bottom) for week 2 and 3

3 Kinetic Energy Storage Systems for the Application

For grid stabilization of island grids different storage technologies can be applied. Due to a high cycle-life and high charging and discharging power, relative to capacity, kinetic energy storage systems are well suited to provide ancillary services. Moreover many island grids are characterized by harsh environmental conditions such as extreme heat or cold leading to advantages for mechanical storage systems compared to electrochemical energy storage systems. The power electronics, however, have to cope with those conditions. In this chapter a classification of different flywheel topologies are discussed.

3.1 Classification of different flywheel topologies

Kinetic energy storage systems have been investigated for many years, explaining the different topologies available today. Four main types can be distinguished, see Figure 2.

A suitable characteristic to compare the different topologies is their degree of integration (DoI).

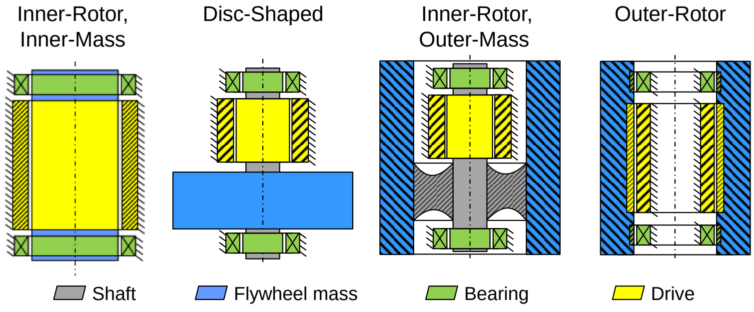

Figure 2: Overview of different flywheel topologies

It can be defined as the extent to which different system components are used to generate a high inertia leading to high stored energy. A high DoI is necessary to maximize the energy density of a kinetic energy storage system and to minimize its production cost.

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 energy. The inner–rotor/outer-mass concept has a higher DoI because the flywheel mass also rotates around the stator parts of electric 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 must at least have the diameter of the mass, the overall system size and thus the storable energy is drastically 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. In spite of the straight forward overall system structure, interdependencies between the all components of these highly integrated systems lead to a complex overall system.

3.2 The outer-rotor concept

The remainder of 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. At the beginning of 2014 the feasibility of the technology was proven with a first prototype at the laboratories of the IMS. Currently a second advanced version is set up. A picture of the first system is shown in Figure 3. Table 2 shows the technical data of both prototypes.

The developed concept enables the adaption of the systems properties in terms of power and capacity to the requirements of the application. In order to find the application specific system with the minimum losses two analytical models have been set up, which allow for fast parameter studies. The design model defines the general properties of the outer-rotor made of high strength fiber composite materials, the active and passive magnetic bearings which allow for the contact free levitation of the rotor in high vacuum environment as well as the permanent magnet synchronous motor-generator-unit.

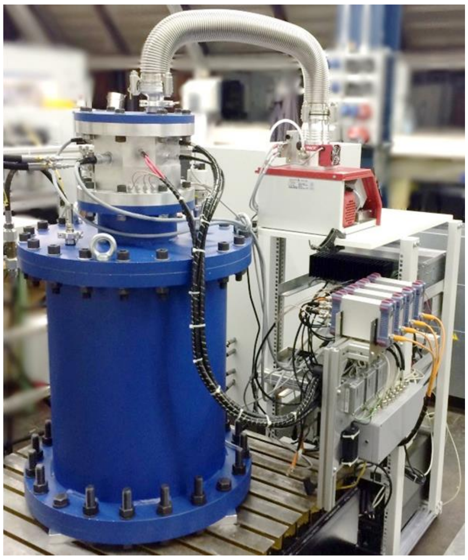

Figure 3: Photo of the outer-rotor prototype

Table 2: Properties of the prototypes

	1st prototype	2nd prototype
Power	36 kW peak	60 kW const.
Capacity	0.5 kWh	1.4 kWh
Flywheel mass	50 kg	150 kg
Outer rotor diameter	300 mm	450 mm
Inner rotor diameter	180 mm	290 mm
Height Rotor	500 mm	600 mm
Min. rotating frequency	10.500 rpm	7.000 rpm
Max. rotating frequency	21.000 rpm	14.000 rpm
Bearing type radial	Active magnetic bearings	
Bearing type axial	Passive magnetic bearings	

The second model is the loss model, which calculates the losses of the designed system for all operating points. It takes the losses of the systems main components as well as of the periphery components like the vacuum system, the cooling and the controls into account. The complex characteristics of the losses can be described by the loss map, as given in Figure 4. The loss power for each operating point defined by the systems energy content and its power is given.

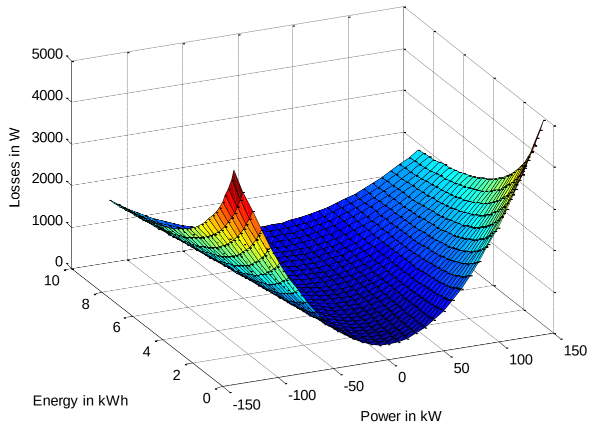

Figure 4: Loss map of the KESS

4 Specification, Design and Assessment Methodology

In [1] a methodology has been developed enabling for the technology-neutral specification, development and assessment of EESS. Figure 5 gives a graphical representation of the developed Specification-Design-and-Assessment Methodology (SDA). Based on the applications objectives generic load profiles of an ideal loss free EESS are synthesized. The analysis of these profiles enables the technology-neutral specification of the requirements on the EESS, such as the system's power and capacity, as well as the number and types of load cycles and the dynamic properties the EESS must provide. Based on these requirements the "Design" of the EESS takes place, starting with a decision for a storage technology and the layout of the EESS. The next step consists of the development of a proper operational strategy in order to control the EESS. The dynamic behavior and other properties of the investigated EESS can be assessed in the following steps. The assessment is based on the time domain simulations of the EESS. Based on the simulation results performance figures such as the efficiency in the field of application, the system's lifetime as well as the operational costs can be calculated and enable the assessment and the objective comparison of various types of EESS. These performance figures also enable the iterative optimization of the EESS.

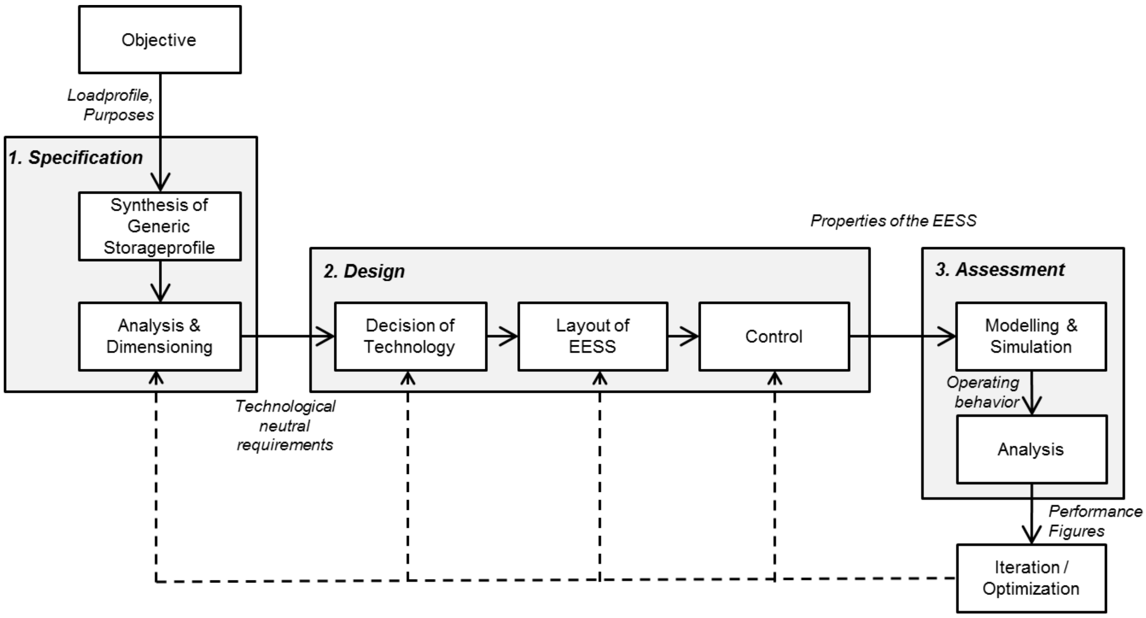

Figure 5: Specification, Design and Assessment Methodology [1]

5 Numerical analysis and results

5.1 Specification

The purpose of the energy storage system is to provide the SRC as long as the diesel generator needs to start up. To analyze the required power and capacity of the storage system a storage system with properties in a range that the systems boundaries in terms of maximum power and capacity are not exceeded during operation is integrated into the simulation model. After the simulation the resulting power and capacity profiles of the storage system is analyzed to determine the required properties of the KESS. Figure 6 shows the frequency distributions of the power and the energy content of a simulated very large ideal storage system without losses. The zero classes (times where the system is at stand-by) have been excluded from the distribution because they would dominate the results. With a system power of 959 kW, 99 % of all discharging power cases can be met, a capacity of 58 kWh covers 95 % of all energy states.

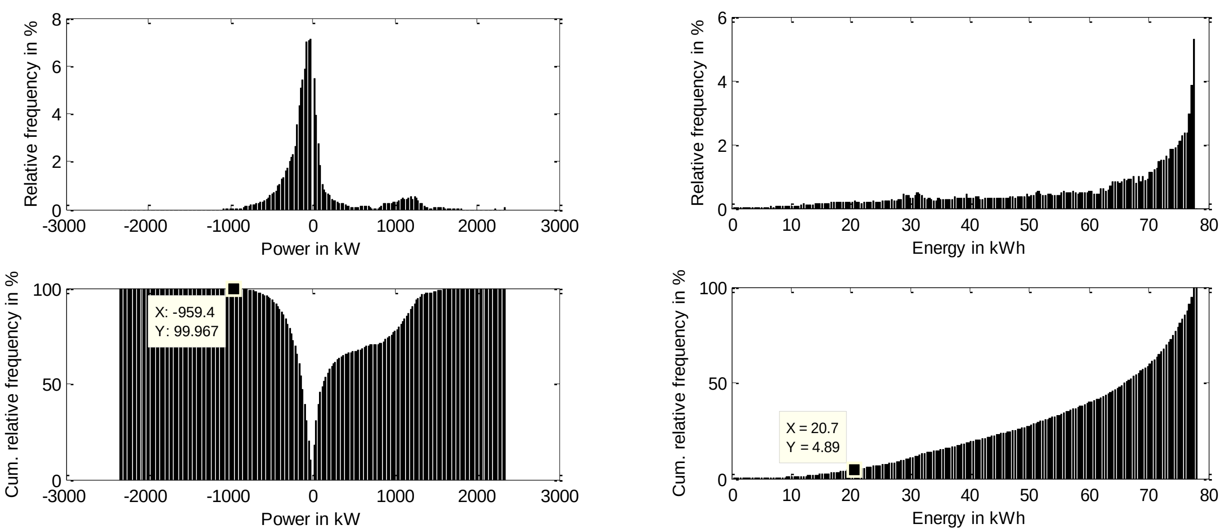

Figure 6: Frequency distribution of power (left) and energy classes (right) without zero classes

5.2 Design

Via parameter studies with the design and the loss model the flywheel design with the lowest operational losses is found following the methodology given in [1]. The required power and capacity for the application will be provided by seven similar flywheels. The properties of the resulting flywheel is given in Table 3, the loss map of the system is shown in Figure 4.

Table 3: Properties of the Kinetic Energy Storage System

Power	140 kW const.
Capacity	8.3 kWh
Flywheel mass	665 kg
Outer rotor diameter	800 mm
Inner rotor diameter	360 mm
Height Rotor	900 mm
Min. rotating frequency	6000 rpm
Max. rotating frequency	12.000 rpm

To control the KESS the diesel scheduling of the diesel generators is supplemented by the operational strategy of the storage system. This operational strategy manages the state of energy (SoE) of the KESS and the total SRC to be supplied. Based on the current condition of the grid in terms of running diesel generators and provided power as well as wind production the scheduling determines whether the KESS charges, discharges or idles. The KESS is dispatched according to the conditions outlined in Table 4. When a condition is met, the KESS will respond with an action, which is limited by control parameters and availability of power and energy capacity.

Table 4: Rules of the KESS scheduling

Condition	Action	Limits
▪ Diesel generators are unable to meet SRC	▪ Supply required SRC ▪ Initiate the process of bringing a larger power capacity combination of diesel generators online.	▪ Max. discharge power ▪ SoE of the KESS must be able to sustain a discharge equal to the SRC long enough to bring the next largest combination of diesel generators online plus a 25% safety margin.
▪ Diesel generators are operating at full power capacity	▪ Discharge to prevent over loading of diesel generators ▪ Initiate the process of bringing a larger capacity combination of diesel generators online.	▪ Max. discharge power
▪ KESS not fully charged ▪ Renewable energy is being diverted	▪ Charge KESS with diverted renewable energy	▪ Max. charge power
▪ KESS not charged to SoE setpoint ▪ KESS is not being charged with renewable energy	▪ Charge with diesel generators	▪ Max. charge power. ▪ SoE setpoint depends on online power capacity of diesel generators (A lower power capacity has a higher SoE setpoint, since the KESS must supply more SRC). ▪ Charging rate is a function of SoE. Rate decreases with increasing SoE.

5.3 Assessment

A simulation was developed to determine the impact of integrating a KESS into the islanded grid of Nome. Fifteen weeks were simulated at 1 second intervals. The key results of the assessment are the average diesel consumption per week. Several iterations of the simulation were run to optimize the KESS control parameters and to maximize the efficiency and effectiveness of the energy storage system and minimize diesel fuel consumption. Figure 7 shows the exemplary two weeks with the operating KESS and Figure 8 shows power and capacity profiles of the storage system.

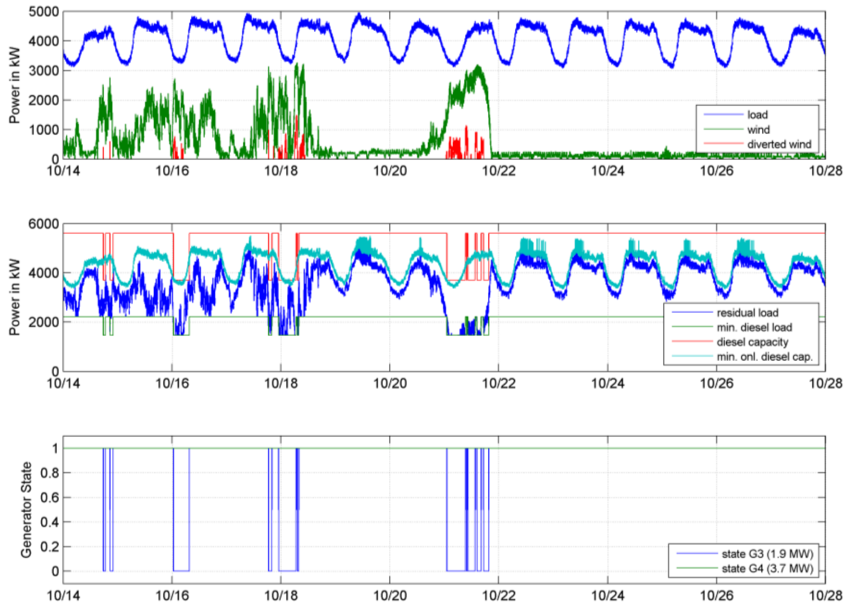

Figure 7: Load profiles and diesel scheduling with KESS for week 2 and 3

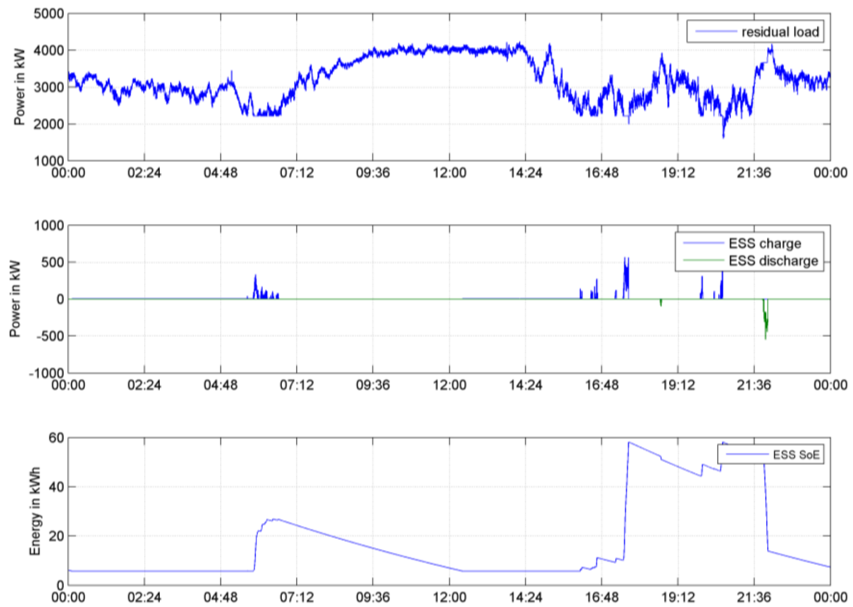

Figure 8: Simulated power and capacity profile of the KESS in operation (day 10/14)

Figure 9 gives the amount of diesel fuel saved with a loss-free (ideal) EESS and with the KESS designed for the application for the investigated 15 weeks in the dataset.

High savings are observed when there is a medium to high penetration of wind. In weeks with only little or no wind the KESS does not affect the diesel consumption significantly; in some of these weeks the losses of the KESS slightly increase the diesel consumption.

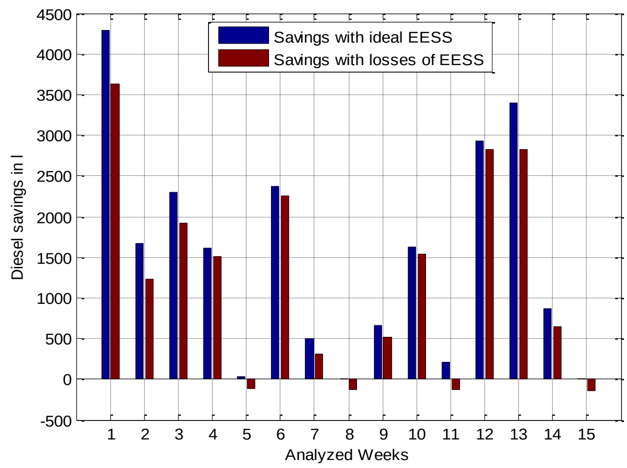

Figure 9: Calculated diesel savings with a lossfree (ideal) EESS and with the losses of the designed KESS

6 Combined function of the EESS

A secondary function is implemented providing load smoothing with the KESS. This function cuts the high dynamic components from the power profile the diesel generators have to provide and hence enables them to run more smoothly. It is expected this smoothing leads to a significant reduction in wear as well as in fuel consumption of the diesel generators. Table 5 gives the properties of the additional rule implemented into the operational strategy. Figure 10 gives the resulting storage profile for the first day of the second week. The power and capacity of the KESS required to provide the smoothing is small compared to the total properties of the KESS, so despite the lower priority, the system is capable to provide this function most of the time without an increase in dimensions. Due to the increase in the amount of energy transferred by the KESS the energetic losses increase by approx. 150 kWh per week. Currently no models describing the influence of the high dynamic components on the diesel generators are available for the used generators, so the benefits of this function cannot be quantified yet.

Table 5: Rules for the secondary load smoothing function

▪ Continually	▪ Charge/discharge to smooth diesel power output (implemented via lowpass FIR filter with a corner frequency of 1/15 min and 200 taps)	▪ Charge and discharge with consideration of power limits of the KESS

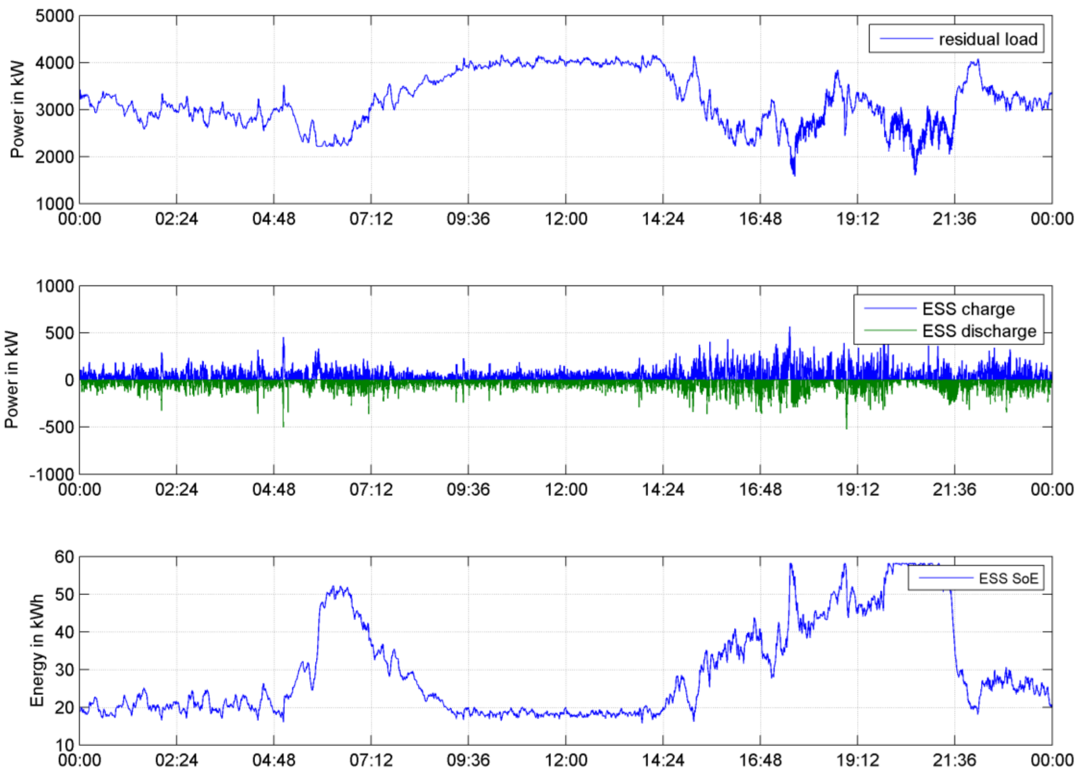

Figure 10: Storage profile for the first day of the second week with combined application load smoothing and providing SRC (day 10/14), compare Figure 8

7 Discussion and Conclusion

The Specification, Design and Assessment Methodology (SDA-Methodology) was utilized to find a suitable kinetic energy storage system (flywheel) for the islanded grid of Nome, Alaska. Results of the SDA-Methodology were confirmed and refined utilizing a time-series energy balance simulations and statistical analyses.

The application of the flywheel is to reduce the number of diesel generators providing the spinning reserve required to keep the islanded grid stable in case of wind fluctuations and stochastic demands on the load side. To keep the installation costs low the flywheel provides the required power as long as the diesel generator requires to ramp up to full power from warm stand-by.

The outer-rotor-flywheel developed at TU Darmstadt allows for the adaption of power and capacity to the requirements of the application. Through iterations following the SDA-Methodology the properties of the KESS are optimized. The resulting storage system consists of seven KESS and provides in total 959 kW of power and has a combined capacity of 58 kWh. A central part of the storage system is its integration into the application via the operational strategy which controls the storage system. This is done by an expansion of the diesel-scheduling module to accommodate the current condition of the grid and the storage system.

The simulations show that the storage system is an efficient way to provide the SRC in high wind periods. The storage system reduces the diesel consumption in during those periods by 2800 l to 3600 l per week. In lower wind periods the diesel savings are 1200 l to 2200 l per weeks. The implemented operational strategy of the storage system does not influence the scheduling of the diesel generators in very low wind periods. Consequently it does not lead to a reduction of the diesel consumption during these weeks, in some cases the energy demand of the storage system leads to a slight increase of the diesel consumption.

Load smoothing is implemented as secondary combined function into the operational strategy of the storage system, which reliefs the diesel generators from the high dynamic components of the load profile. Due to the low power and capacity required for the secondary function the primary function it is not in conflict with it. The storage system is capable of providing this function efficiently, despite increasing energy losses of the storage system. Since currently no models exist that describe the influence of the high dynamic loads on the diesel consumption and the generators wear, the benefits of the secondary function cannot be quantified yet.

The authors see high potential to further increase the amount of saved diesel by designing a specialized operational strategy which leads to a higher utilization of the storage system. Following the definition given in [3] this strategy must take internal information such as the state of the storage system and its properties as well as external information like weather forecasts into account.

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