Dimensioning the Internal Components of a Hydrogen Storage Power Plant

Martin Töpfer, Nayeemuddin Ahmed, Harald Weber
Institute for Electrical Power Engineering
University of Rostock
Rostock, Germany
{martin.toepfer, nayeemuddin.ahmed, harald.weber}@uni-rostock.de

***Abstract*—Electrical power networks today are undergoing a transition towards integrating an ever increasing proportion of renewable energy sources. However, reducing the number of conventional fossil fuel based power plants introduces additional challenges in terms of grid stability. One of the solutions to this is to implement large-scale electrical energy storages in the grid, which not only provides the required ancillary services to ensure stability, but also compensates for the intermittent behaviour of renewable sources. Such a system is called the Hydrogen Storage Power Plant. In this paper, a futuristic scenario is highlighted, where a 500 MW coal power plant in the eastern German grid is replaced with a Hydrogen Storage Power Plant. The necessary storage elements inside it are dimensioned to provide the required frequency regulating. Next, for two study cases, the response of both types of power plants to disturbances in the network are compared. The results show that the storage power plants can ensure operation of the grid with the same reliability as coal power plants.**

***Index Terms*—ancillary services, frequency regulation, intermittent, storage power plant, reliability.**

I. Introduction

In the present European interconnected transmission grid (ENTSO-E), conventional thermal power plants with synchronous generators are the backbone of a reliable and safe supply of electrical energy. Due to their ability to provide inertial response, primary and secondary control power, it is possible to maintain the equilibrium of active power generation and consumption at any time.

Presently, an increasing number of conventional power plants are being replaced by generation units based on renewable energy sources (RES). Such RES are not able to entirely provide all forms of ancillary services as mentioned previously. Additionally, these sources are often not installed close to load centres, but in areas with the highest exploitable potential of the primary energy. This leads to increasing active power transit in the ENTSO-E and has already caused critical situations in network operation in the past [1]. With increasing extension of RES in the ENTSO-E, this problem is expected to become more evident in the future [2].

Due to these issues, caused by a high infeed of RES in the future power system, it will become significantly important to ensure large-scaled storage of electrical energy. Different storage systems have been categorised by various authors according to their energy density, response time and economic factors [3]. Also their gird integration is widely researched at the moment [4]. To entirely replace conventional power plants in terms of ancillary services, it is necessary to absorb and inject active power to the grid instantaneously and over a long period. Only when these requirements are fulfilled, a safe and reliable supply of electrical energy can be ensured in a network with increasing penetration of RES.

A possible solution to achieve this is the so-called Hydrogen Storage Power Plants (SPP) [5]. The SPP has been observed to function coherently with conventional power plants in the electrical grid [6]. In addition, it has been proved that such a power plant is able to independently improve grid stability and security by providing frequency regulation [7]. This makes SPPs particularly desirable in networks with a high penetration of RES.

This paper investigates the possible replacement of a 500 MW coal power plant in eastern Germany with a SPP and shows how the latter can provide the required ancillary services. Therefore, in the first step, the working principle of a SPP is explained. Next, the internal storage devices are dimensioned to provide frequency regulating services equivalent to the 500 MW coal power plant. These results are implemented in a dynamic network model of the ENTSO-E grid, with a detailed representation of the east German section, to verify the concept.

II. The Hydrogen Storage Power Plant

The idea and working principle of the SPP has already been investigated and discussed in detail [8]. In this section the most important features are summarised.

The idea of a SPP is to replace the mechanical and chemical storages of a conventional power plant by electrical and electro-chemical storages, as indicated in Fig. 1.

To provide the frequency regulating ancillary services, i.e. instantaneous response, primary and secondary control, three different energy storages are accessed by a coal power plant-

- Rotating mass of the turbine-generator set to provide instantaneous response
- Live steam storage to supply primary control power

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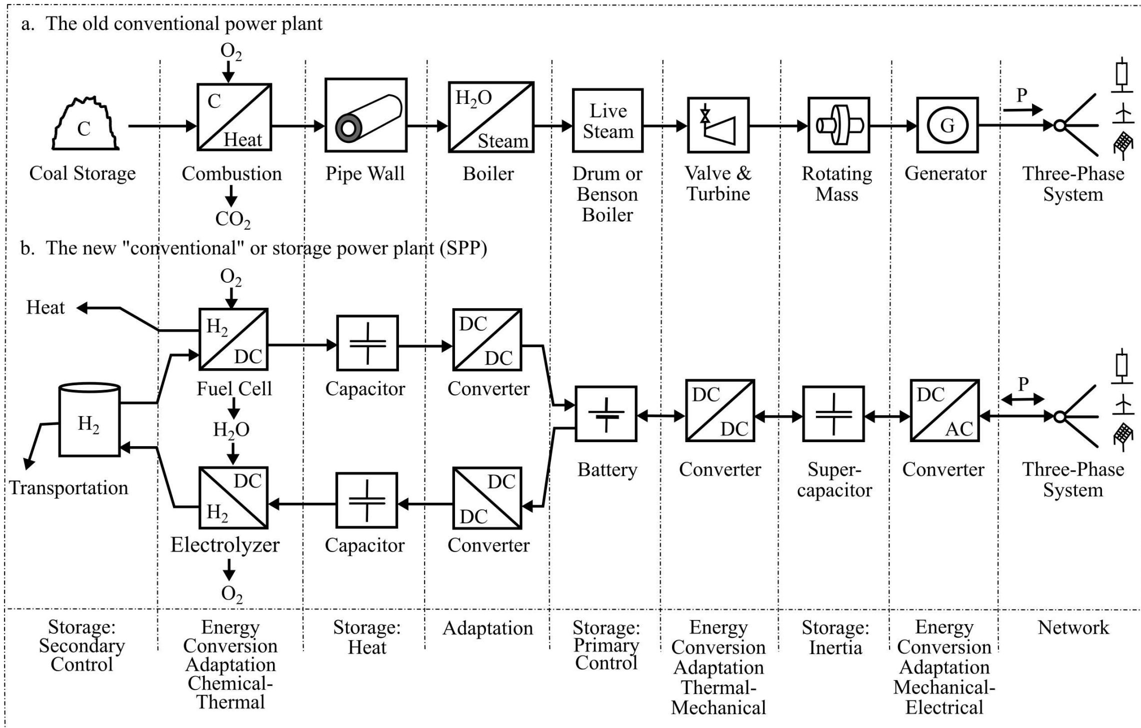

Fig. 1. Working principle of a Conventional and Storage Power Plant (SPP)

- Coal storage to generate secondary control power

As indicated in Fig. 1, these storages in the SPP are correspondingly a Supercapacitor, a Battery and a Hydrogen storage.

The SPP is connected to three phase system via a DC-AC converter which functions as a voltage source converter.

In case of a sudden increase of load or decrease of generation in the three-phase system, the initial response of a coal power plant is supplied from the kinetic energy of the rotating mass in the generator's rotor and connected turbine shaft. Consequently the rotor is decelerated which results in a decrease in frequency.

To provide primary control power, an adjustment of the power plant's steam valve position is implied by this decrease in frequency. Thus the valve is opened and the mass flow rate of steam is increased. As a result, the pressure in the steam storage is reduced. Depending on whether the plant is operated in fixed or flexible pressure mode, the steam pressure is either controlled back to its original setpoint by changing the fuel flow or is adjusted to a new value. So, the frequency is stabilised at a value within defined limits.

In case a power plant contributes to secondary control, the remaining frequency deviation causes an additional infeed of coal to the combustion chamber until the frequency is restored to its nominal value. At the same time, the storages for inertia and primary control are replenished. For power plants operating in interconnected systems with different control areas, not only the frequency deviation but also the area control error (ACE) has to be taken into account.

The operation of the SPP is similar. In case of a sudden load increase or decrease of generation the initial response is supplied by the supercapacitor. This causes it to discharge, resulting in a voltage drop over its terminals
This voltage drop is detected by the governor of the DC-DC converter between the battery and supercapacitor. After some delay, the battery current is increased. Then this DC-DC converter's controller is adjusted in such a way that the supercapacitor's voltage is restored to its initial value.
Consequently, the battery is discharged and its voltage is decreased. The battery's voltage signal is fed to the DC-DC converter between the battery and fuel cell.
This converter's governor has to keep the battery voltage constant between lower and upper threshold values of 0.99 pu and 1.01 pu. Therefore, the current flow from the fuel cell into the battery is increased.
As a result, the Hydrogen storage is accessed by the fuel cell and its storage level is reduced. In contrast to a conventional power plant, the Hydrogen storage can be replenished. Therefore an electrolyser is used to store excess energy from the grid to the SPP during excess generation from RES.

III. Dimensioning the Storage Devices

In this chapter, the calculation for the dimensioning of the storage devices of the SPP is carried out. The required parameters and their values are listed in Table I. The internal losses of the storage devices are not considered under the scope of this paper.

TABLE I
PARAMETER VALUES OF THE SPP COMPONENTS

Quantity		Values
Nominal active power ($P_{n_{SPP}}$)		500 MW
Nominal frequency (f_n)		50 Hz
Efficiency	DC-AC Converter (η_{DC-AC})	0.97
	DC-DC Converter (η_{DC-DC})	0.97
	Fuel Cell (η_{FC})	0.54
	Transformer (η_{tra})	0.98
Primary control droop (σ)		10%
Maximum frequency deviation (Δf_{max})		200 mHz

A. The Supercapacitor

The supercapacitor supplies the initial response power of the SPP. Therefore in the first step, the maximum power that has to be provided for instantaneous response is calculated, using the rate of change of frequency (RoCoF) method [9], [10]-

$$RoCoF = \frac{df}{dt} = \frac{1}{T_{acc}} \cdot (p_g - p_l) \tag{1}$$

where:

$\frac{df}{dt}$	Maximum first order time derivative of frequency in per unit (pu)
T_{acc}	Acceleration time constant in seconds
p_g	Generated power in pu
p_t	Load power consumption in pu

The term ($p_g -\ p_l$) represents the disturbance power in per unit that has to be compensated by the supercapacitor. The designated values for the maximum RoCoF and acceleration time constant differ for every network. In this example, they are designated to be 2 Hz/s (0.04 per unit) and 10 s accordingly. With these values, the maximum disturbance power amounts to 0.4 pu. As a result, the maximum initial power output of the supercapacitor (P_{max_SC}), i.e the instantaneous response of the SPP, can be computed using (2)

$$P_{max\_SC} = (p_g - p_l) \cdot P_{n_{SPP}} \tag{2}$$

Consequently, the maximum power output of the supercapacitor is 200 MW.

According to [11], all generation units are allowed to disconnect from the grid at a frequency of 47.5 Hz. With the assumed maximum RoCoF of 2 Hz/s, this value is reached after 1.25s. Thus, 200 MW of active power have to be supplied by the supercapacitor for 1.25s.
The energy stored in the capacitor (E_{SC}) can be computed using (3). The resultant energy amounts to 263 MWs (0.07 MWh). This is exactly equivalent to the amount of energy which would be released if a synchronous generator with an acceleration time constant (T_{acc}) of 10s would be decelerated by 2.5 Hz.

$$E_{SC} = \frac{\int_0^{1.25s} P_{max\_SC}\ dt}{\eta_{DC-AC} \cdot \eta_{tra}} \tag{3}$$

This result represents the amount of energy which is needed for the instantaneous response of the SPP. This is the minimum energy that must be available with the given parameters. In case the supercapacitor operates between some defined voltage thresholds or fulfills other operational requirements, the energy capacity has to be increased.

B. The Battery

In this subsection, the required battery energy content is determined. For reasons of clarity and comprehensibility it is assumed that only the battery provides primary control power. The following boundary conditions are designated for the investigations in this paper-

- A primary control droop (σ) of 10 % is selected
- According to the network operator's requirement, primary control has to be fully activated within 30 s at a maximum frequency deviation (Δf_{max}) of ± 200 mHz [11]
- The generation unit has to able to supply the maximum primary control power for at least 15 minutes [11]

The first step of the calculation is the computation of the generation unit's power frequency characteristic (K)-

$$K = \frac{1}{\sigma} \cdot \frac{P_{n_{SPP}}}{f_n} \tag{4}$$

With the designated values, K is 100 MW/Hz. Now the maximum primary control power (P_{prim_max}) can be calculated-

$$P_{prim\_max} = -\Delta f_{max} \cdot K \tag{5}$$

With the values assumed in this example, the maximum value for P_{prim_max} would not exceed 20 MW.

The necessary energy content of the battery (E_{prim_Bat}) can then be calculated using (6). This results in a value of 5.5 MWh.

$$E_{prim\_Bat} = \frac{\frac{1}{2} \cdot P_{prim\_max} \cdot 30s + P_{prim\_max} \cdot 900s}{\eta_{DC-AC} \cdot \eta_{tra} \cdot \eta_{DC-DC}} \tag{6}$$

C. The Hydrogen storage

The boundary condition for dimensioning the hydrogen storage should not only include the ability to provide secondary control power but also to compensate for periods of lacking infeed from renewable energies. The authors have no information regarding a precise value of the necessary strategic storage demand in the investigated region. Therefore, it has been designated that the SPP shall be able to supply nominal power for two weeks, without the need for recharging during that time [12]. The amount of energy (E_{hyd}) can be calculated using (7). For this example, the resultant energy amounts to 347.8 GWh.

$$E_{hyd} = \frac{P_{n\_SPP} \cdot t}{\eta_{DC-AC} \cdot \eta_{tra} \cdot \eta_{DC-DC}^2 \cdot \eta_{FC}} \tag{7}$$

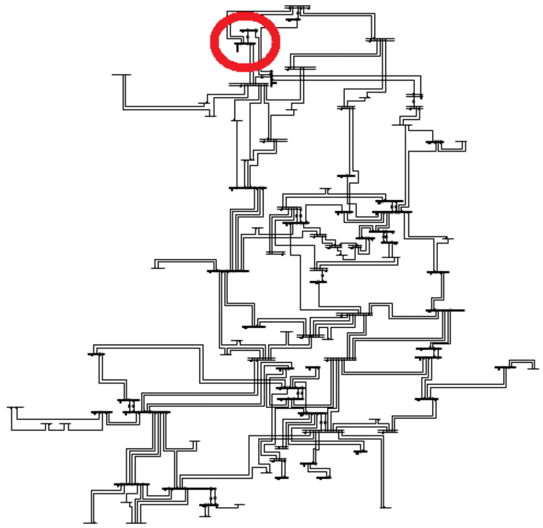

Fig. 2. Network model of 50Hertz control area

IV. Simulation and Observation

In this section, the performance of a conventional coal-fired power plant and a SPP is compared. The focus is on the SPP's ability to provide the frequency regulating ancillary services. The following investigations have been carried out using a dynamic network model of the ENTSO-E grid. The load flow data used for generation and consumption are according to Germany's network development plan 2025. In this paper, the focus is on the transmission grid of eastern Germany.

The single line diagram of the network is shown in Fig. 2. It is operated by the 50Hertz Transmission GmbH, referred to as 50Hertz control area. The generation data for this area have been modified to a scenario of 100% wind infeed, except for one coal power plant in the northern part of the control area. This is the coal power plant in Rostock (CPP Rostock) and has a rated active power of 500 MW. Its location is indicated by the red circle in Fig. 2. To cover some worst case scenarios, the wind turbines perform as PQ nodes.

In this network model, additionally a model of a SPP has been implemented. The storage devices have been dimensioned according to the calculations in the previous section. For reasons of clarity and comprehensibility, it is located at the same node as the coal power plant. The node is called $Bentwisch$ and in the following is referred to as $BW380kV$.

Both the SPP and CPP are connected to the network via individual identical transformers. This allows better comparison between the performance of the two power plant types. In the following steps, the SPPs ability to provide inertial response, primary and secondary control power is highlighted.

A. Inertia

To display the ability of both plant types (SPP and CPP) in providing instantaneous reserve power, the sudden disconnection of a 700 MW wind park is simulated.

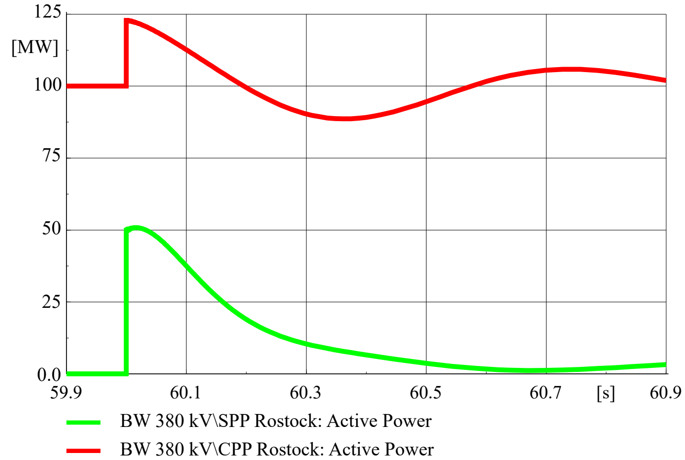

Fig. 3. Initial response of a coal power plant and a storage power plant

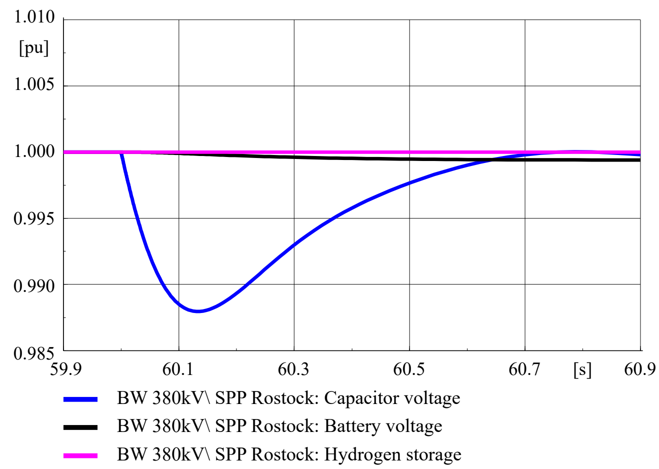

Fig. 4. Filling level of storage devices for initial response

It is commonly known that coal power plants have to operate at their minimum power output. The authors do not have any information about the real minimum power of the coal power plant in Rostock. Therefore, it has been assumed to be 100 MW. However, the results shown here are equivalently valid for any other initial working point.

In Fig. 3 the initial response of both plant types due to the disturbance are shown. Firstly, it can be observed that both plants react immediately. The instantaneous reserve power of the SPP amounts to 50 MW, whereas 25 MW is provided by the coal power plant. The reason for this difference is the additional transient reactance of the synchronous generator. Thus, it can be stated that both power plants inject instantaneous reserve power and thus contribute to limiting the initial frequency gradient.

In Fig. 4 the states of charge of the storage devices are shown. To represent the values in the same scale, they are displayed in per unit. The diagram indicates how these devices interact with each other.

The initial active power demand during the first two seconds

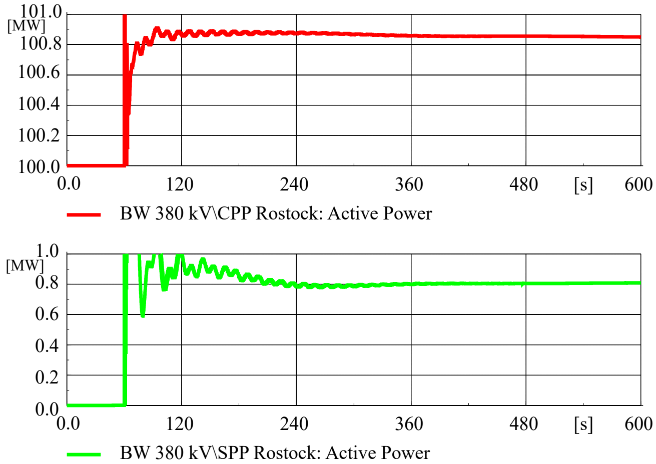

Fig. 5. Active power output of a conventional coal power plant and a Hydrogen storage power plant for primary control

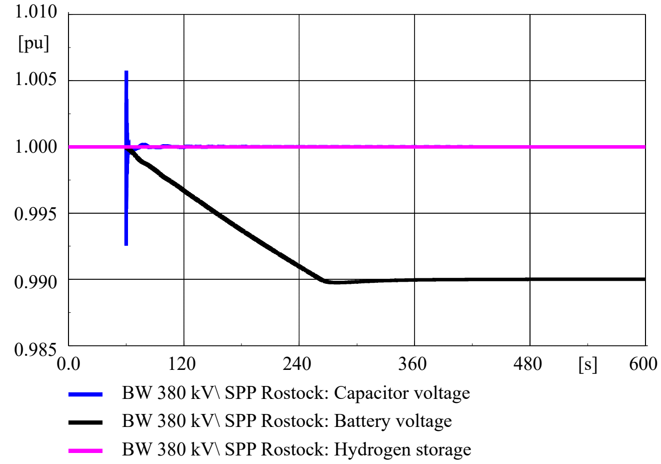

Fig. 6. Filling level of storage devices for primary control

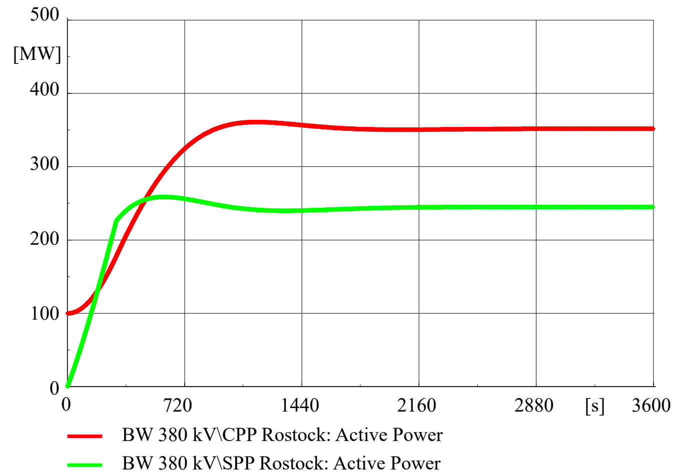

Fig. 7. Active power output of a conventional coal power plant and a Hydrogen storage power plant for secondary control

is compensated by the supercapacitor. As a consequence, it is discharged and its voltage declines. To prevent adversely affecting the battery's lifetime, its power output is ramped up more slowly. So after about 0.7 seconds the power demand is compensated by the battery only. Within this time, the supercapacitor is recharged, allowing its voltage to return to the initial setpoint.

The increase in the power output of the battery leads to a drop of the battery voltage. Due to the long response time of the hydrogen storage its state of charge does not change significantly in the depicted time frame.

B. Primary Control

To compare the performance of both plant types in terms of primary control, their response to the sudden disconnection of a 700 MW wind park has been viewed over a longer time scale, in Fig. 5. The primary control droop (σ) for each plant equals 10%.

The scaling of the figure has been magnified compared to that in Fig. 3. The power output of the SPP is more susceptible to oscillations compared to the coal plant. The reason is once again the higher transient reactance in case of the synchronous generator. However, the oscillations are damped in both cases and a new stable working point with providing 0.8 MW of primary control power each, is reached by both plants.

The state of charge of the storage elements can be analyzed in Fig. 6. The first reaction is supplied by the supercapacitor. Due to the decrease of its voltage, the battery's power output is increased after some delay. The effect is a drop of the battery's voltage with its lower threshold of 0.99 pu being reached at 240 s.

With the voltage of the battery decreasing below 0.99 pu, the DC-DC converter between the battery and fuel cell to increases the fuel cell's power output until it fully compensates the power demand. At the same time the battery is recharged. The level of the hydrogen storage does not change significantly in the depicted time frame, because of its large dimension. Further, it can be seen, that the oscillations are mostly compensated by the supercapacitor, allowing the battery to exhibit a relatively smooth operation.

C. Secondary Control

To demonstrate the performance of SPPs for secondary control, the scenario is changed. This time a decreasing wind front shall be compensated. It is arranged in such a way that the wind power in the control area decreases by 500 MW within five minutes.

Both, the coal-fired power plant and the SPP are supposed to provide the same magnitude of secondary control power. The active power injection of both plants for this scenario is shown in Fig. 7. With decreasing wind power, additional active power is injected to the network by both plants. It can be observed that the SPP reacts with a high power output gradient. However, after a while a stable working point with injecting a surplus of 250 MW of secondary control power each, is reached.

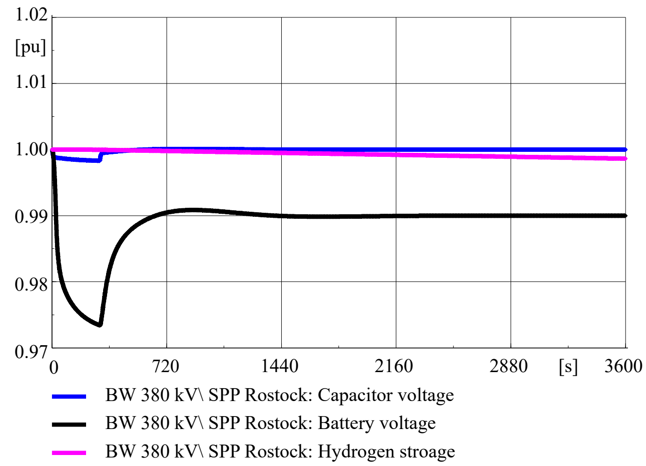

Fig. 8. Filling level of storage devices for secondary control

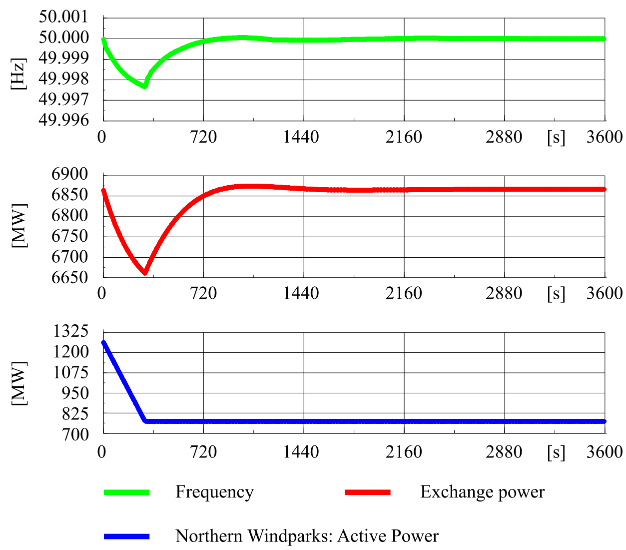

Fig. 9. Network frequency and exchange power of 50Hertz control area

The performance of the SPP storages is depicted in Fig. 8. It can be observed that the supercapacitor and battery are continuously discharged during the first few minutes and are then recharged to their corresponding setpoints as the wind front reaches a continuous level, Fig. 9. Over this long period of time a slight decrease in the hydrogen storage level can be seen, due to its large size.

To prove that the disturbance caused by the wind has been compensated in the control area, the frequency and exchange power are shown in Fig. 9. After the activation of secondary control, both parameters are returned to their initial values. So even with the changing power infeed from RES, it is possible to keep the scheduled exchange power and fulfil power trading contracts.

V. Conclusion

In this paper, the potential of a SPP to ensure a safe and reliable supply of electrical energy in networks with a high proportion of RES has been shown. Two scenarios, representing a sudden outage of generation and fluctuation in wind power have been implemented. It has been demonstrated that the difference between active power generation and load demand can be balanced by the SPP at all times. The drawbacks of reduced inertia associated in a grid with a high penetration of RES are overcome and requirements to supply the required frequency regulation are met.

The minimum dimensions of the storage devices in a SPP to replace a 500 MW coal power plant have been estimated. This has been done taking into account that upon replacement, the SPP must ensure the same reliability in electrical energy supply as is observed today. Since storages cannot generate energy on their own, a SPP of such a large size would need adequate infeed from RES. Part of this energy would be utilized to store hydrogen and have it readily available for producing electrical energy when required.

Further studies are required to investigate the necessary additional installed capacity of RES to fully replace all coal-fired and nuclear power plants in accordance to Germany's 2050 Energy Target. The overall efficiency of a SPP, about 30%, is relatively low and large-scale version of such a power plant would incur high initial costs. Hence, additional studies relating the economic viability of the SPP in electricity markets are required. However, such a plant is imperative for the future since the electrical energy supply system cannot be solely based on intermittent RES.

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