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Battery Energy Storage System for Grid Support and Charging of Electric Ships

Feasibility Study of Implementation in the ports in Gothenburg and Kiel

Master's thesis in Electric Power Engineering

Arvid Persson & Mohammad Sabbouh

MASTER'S THESIS 2021

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Cover: Battery power on the hybrid RoPax vessel Stena Jutlandica in the port in Gothenburg, taken from the Stena Mediabank.

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Abstract

The vast electrification of the transportation sector has many effects on the power system and can, in many cases, cause a shortage of power. Electrification of the maritime sector is growing and the power required to charge these ships could create a big strain on the electric grid. Therefore, a solution is needed in order to meet the power demands in the harbors.

In collaboration with DNV in the EU funded project called "Sea Li-ion" initiated by Stena, this master's thesis investigates the possibility of implementing a Battery Energy Storage System (BESS) in the ports in Gothenburg and Kiel to supply power to the ships when the power in the grid connection is limited. This is done by evaluating three different conceptual battery sizes on a ship: 20, 50, and 70 MWh. The shortage of power from the grid is evaluated which results in different capacities for the BESS. This is compared to the solution of expanding the capacity in the grid. The costs of the BESS and grid expansion are compared.

To evaluate the BESS grid impact and benefit, two models are implemented in DIgSILENT PowerFactory of the electrical network in the harbor and the BESS. The first model is used to simulate the BESS contribution in peak shifting, voltage support, and fault ride-through. The second model is used for dynamic simulations of system frequency stability with the BESS in Gothenburg and Kiel. The earnings from the energy arbitrage and the system frequency stability services are evaluated.

The simulations for system frequency stability show a small improvement in the system frequency. The earnings from the frequency stability services in Gothenburg resulted in a payback period longer than the BESS lifetime. In Kiel, the earnings from the frequency stability services showed a much shorter payback period. The simulation results for voltage support showed that the BESS is able to enhance the voltage profile at the PCC. The fault ride-through simulation showed good results in the BESS behavior during a three phase short circuit fault.

The results from the analysis showed that in Kiel it is more economical to implement a BESS since the payback period is short compared to the lifetime of the BESS. In Gothenburg, the BESS could be a better solution since Stena Line plans to move the terminal in the future, and the fact that grid expansion has a big social impact on the civilians. However, a more comprehensive economical analysis is required since there are many parameters that were not considered in this thesis.

Keywords: Battery Energy Storage System, BESS, Electrification, Peak shifting, System frequency stability, Voltage support, Fault ride-thorough

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A few words from Arvid Persson:
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Arvid Persson & Mohammad Sabbouh
Gothenburg, May 2021

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Introduction

Global warming is one of the biggest problems today and many sectors are therefore investigating how to reduce their carbon footprint. The International Maritime Organization estimates that the CO_2 emissions from the maritime sector in 2012 were 2.2 % from the total human-made emissions. This contribution is anticipated to rise with 50 % to 250 % by 2050 if nothing is done about it [1]. The maritime sector has a vital role in the worldwide trade flow, namely more than 90 % of the global trade is dependent on sea-based transportation [2]. Conventionally, most of the ships use cheap quality fossil fuel for propulsion and to generate electricity during traveling and when staying at the port. This releases a huge amount of CO_2 emissions during the ship voyage and when staying in the harbor [2].

To mitigate the environmental impact and minimize the CO_2 emissions in the harbor area, many harbors are limiting the operation of the onboard generators when the ship is berthed [2]. As an initial step to mitigate the environmental problem in the harbor area, a shore connection is provided from the harbor electrical network to supply the ship while at berth [2].

1.1 Background

To cut down CO_2 emissions furthermore, many shipowners are considering battery-powered electric propulsion. However, the availability of shore-side power, the speed of charging, and the capacity for charging are holding them back. Two solutions might solve this issue. The first is to reinforce the grid in the harbors, secondly, is to install a Battery Energy Storage System (BESS) in the ports. DNV is carrying out the EU-funded project "Sea Li-ion" together with the companies Battery Loop, Stena Recycling, Stena Rederi, Stena Line, and the ports in Gothenburg and Kiel [3].

The "Sea Li-ion" project is the second step of the "Global project", where the first step is to install a 1 MWh battery on a ferry, this has already been completed [4]. The main objective in the second step of the "Global project" is to lay the ground for the investment of two BESSs in the ports in Gothenburg and Kiel to boost electrification of the maritime sector using lithium-ion batteries [3], [4]. This is required to increase the charging capacity in the harbors of Gothenburg and Kiel.

The third and last step of the "Global project" is to realize a fully electric ferry [4].

Providing shore connection combined with the fast-charging of electric ferries will put a big strain on the electric grid [5]. To achieve the final goal of the "Global project", which is to have a fully electrified ferry, a substantial amount of power from the electrical harbor network is needed. The geographical location of the harbors inside the city makes the vast grid reinforcements problematic and might take a couple of years to construct. Since Stena Line has plans to resettle the terminal in Gothenburg in the near future, a temporary solution is needed to provide power in order to deliver the required capacity in the harbor.

On-shore BESSs could be a suitable solution. This BESS should avoid overloading the network during the charging process and should have sufficient capacity to supply the power that is needed when the ship is berthed. The BESS will potentially be able to provide ancillary services to the grid, like peak shifting, voltage support as well as frequency regulation and balancing.

This master's thesis work will investigate the need of BESS solution, the ability to provide ancillary services, and the impact of the BESS on the grid.

1.2 Aim

The objective of the master's thesis project is to assess if a BESS should be implemented in the port in Gothenburg and the port in Kiel. Potential grid impact and grid benefit from ancillary services provided by the BESS are evaluated.

1.3 Problem specification

First, the BESS capacity needs to be assessed. In order to calculate this, the maximum available capacity in the electrical network needs to be mapped out. The capacity needs to be sufficient to charge the ship in the given time frame. The existing electrical facilities in the harbors need to be assessed, as well as the BESS port-to-grid setup. The extra equipment that is needed to implement the BESS solution must also be investigated. The economic figures of such electrical facilities and possible grid expansion need to be known.

It's also crucial to know the capacity of the battery on the ship, the ship battery depth of discharge during the trip, maximum charging time, the interval of the ships arriving at the berth, etcetera. The project should also consider the future requirements for the ship in order to realize the third step of the "Global Project" project, which is a fully electric ferry. This should be considered when locating the BESS to enable future expansions.

When the ship is not berthed in the harbor the BESS could be used for grid stabilizing ancillary services. This could expand the use-case of the BESS and improve the reliability of the local harbor grids in Gothenburg and Kiel. It's important to not compromise the charging solution of the BESS since it's the primary role. Other benefits of the BESS could also be assessed in order to improve the useability of the BESS.

In order to connect the BESS to the electric grid, there are specific requirements from both the distribution system operators (DSO) and the transmission system operator (TSO) that the BESS needs to meet. This needs to be investigated in the terms of frequency dynamics, voltage dynamics, and fault ride-through. The requirements should be followed for both operation modes, in the charging phase of the ship, and when providing ancillary services from the BESS.

This thesis work will consider the ethical aspects of the batteries, for example how the construction of the BESS affects the environment in different ways. Ethical aspects of this master thesis work will be taken into consideration. The main ethical aspects are the mining or rare-earth materials used in the cathode of the batteries. One more aspect that will be taken into consideration is the social aspects. While evaluating upgrading the already existing network, the social aspects of excavating the city streets in order to construct the extension from the 130 kV network need to be taken into consideration.

1.4 Scope

The scope of this study is limited to the port in Gothenburg and the port in Kiel. No consideration is taken towards the implementation of the BESS in other or similar harbors. Even though the work assessed in this report might be applicable to other scenarios, it's not something considered in the scope of this thesis work.

In order to maximize the profits from the ancillary services, an evaluation and possible sensitivity analyses need to be conducted. However, developing an optimal operating strategy that is most profitable and viable is not within the scope of this study. Different operational strategies are discussed, however, no comprehensive analysis is conducted.

This study will consider that the BESS implementation is tailored for the projected capacity required with ship battery sizes of 20, 50, and 70 MWh. The battery size of 20 MWh corresponds to a hybrid ship. While the 50 MWh and 70 MWh batteries are conceptual sizes for a fully electric ferry. It is assumed that there is only one ship requiring charging from the BESS at a time.

This study assumed that the only load in the harbor is the power consumed by the ships electrical network and the power that is required to charge the battery on the ship. No consideration was taken for the power consumption of other loads in the harbor area. The study did also not consider that the loads of the ships could increase in the prospected future, only the present demand was accounted for.

2

Harbor background

In order to properly analyze the BESS integration in the ports, one must know the background parameters. In this section, the ports location and electrical network are presented, as well as the requirements from the DSO and the TSO.

2.1 Port location and orientation

The ports where Stena Line operates its ferries between Sweden and Germany are located in Gothenburg and Kiel. In Gothenburg, the port is called Majnabben which is located just inside of Älvsborgs Bridge. There are two ferries in use, Stena Germanica and Stena Scandinavica. The ferries were built between 2001 - 2011 and carry a maximum of 300 cars, 1300 passengers as well as coaches and trailers [6]. The ports are surrounded by an expansive area designated for the logistics of container transportation.

Figure 2.1: Birdseye view of the Stena Line terminal in Gothenburg. Map data is provided by Imagery ©2021 Google, Imagery ©2021 Aerodata International Surveys, CNES / Airbus, Lantmäteriet / Metria, Maxar Technologies.

Figure 2.2: Birdseye view of the Stena Line terminal in Kiel. Map data is provided by Imagery ©2021 Google, GeoBasis-DE/BKG (©2009).

The route between Kiel and Gothenburg currently has two ferries that leave the respective harbor at the same time each evening and arrives the next morning [6],

[7]. Because of this, there will never be two boats in one harbor at the same time. The trip between Gothenburg and Kiel takes roughly 14 hours, and since there is only one trip per day, the ships will stay at the quay for 10 hours [7].

2.2 Current electrical grid setup in the ports

The electrical grids in the ports are very similar in terms of topology and configuration. The main differentiating factor is the capacity ratings of the components used.

In Gothenburg, the terminal is supplied by two connections for the sake of redundancy. The High Voltage Shore Connection (HVSC) has a maximum contracted capacity of 3500 kW [6]. The HVSC is 10 kV and limited to a maximum technical capacity of 4000 kW, so there is a possibility of a 500 kW increase [8].

While in Kiel the technical capacity in the harbor is much larger, at 16 MW. However, there are other customers connected to the same substation, so the maximum available capacity in the HVSC is 5000 kW at 10 kV [9].

As already mentioned, the electrical grid setups in both harbors are very similar. Since the Stena Germanica and Stena Scandinavica utilize 60 Hz in the onship electrical networks, a frequency converter is needed onshore since the electrical grids in Sweden and Germany are 50 Hz. So the grid consists of a medium voltage connection and a frequency converter coupled with two transformers. In figure 2.3 a simplified model of the electrical setup for the high voltage connection in Gothenburg and Kiel is presented.

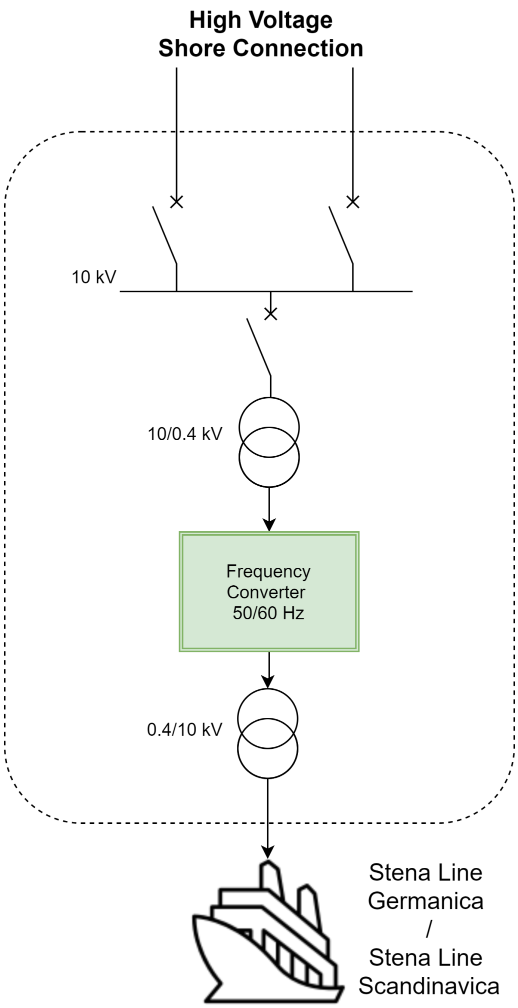

Figure 2.3: *A simplified model of the electrical setup in Gothenburg and Kiel.*

In order to properly calculate the BESS size required there are parameters that need to be known. These parameters are based on the schedules of the ships, the already existing electrical network, and information given by [6], [10]. In table 2.1 below these parameters are presented.

Table 2.1: *Parameters used for the BESS sizing analysis in the ports in Gothenburg and Kiel.*

Description	Parameter	Value		Unit
		Gothenburg	Kiel	
Charging efficiency	η	95	95	%
Time to initiate the charging process	$t_{connect}$	5	5	minutes
Charging time of ship	t_{ship}	10	10	hours
Charging time of BESS	t_{BESS}	14	14	hours
Maximum available power	P_{max}	4	5	MW
Maximum peak	P_{peak}	2.194	2.194	MW
DOD of battery on boat	DOD_{ship}	60	60	%
DOD of the BESS	DOD_{BESS}	80	80	%

The time that is needed to connect the ship to shore power $t_{connect}$ is assumed to be 5 min. The maximum power consumption for the ship when it's at berth P_{peak}, is considered to be 2.194 MW which correlates to the highest averaged hourly power drawn from the HVSC during 2019, the measurement data was provided by [6]. This consumption of the electrical network of the ship is called "hotel load".

Stena is the key-holder for the design of the ships, and they have decided that a DOD of 60 % will be used for the batteries on the ship. The batteries that will be used in the BESS are reused lithium-ion batteries that are provided by BatteryLoop. Since the battery in the BESS will be less stressed than the battery on the ship, an 80 % DOD_{BESS} for the BESS is considered to be used for the project calculations. So the BESS will operate between 10 % and 90 % State of Charge.

2.3 Distribution system operator requirements

In the port in Gothenburg, the local Distribution System Operator (DSO) is Göteborg Energi Nät AB (GENAB). In Kiel the local DSO is Stadtwerke Kiel Netz AG. They have specific requirements on the loads connected. The requirements from the DSO in Kiel are found in standards VDE-AR-N 4120 (high-voltage) and VDE-AR-N 4110 (medium-voltage). However, these were not available and therefore the DSO requirements provided by GENAB were used, these are specified in [11]. In this section, the requirements from the DSO will be presented.

2.3.1 Voltage quality

The most basic voltage requirement is the condition of slow voltage variation. This requirement specifies that during a week, all ten-minute voltage values must be within 90 % and 110 % of the nominal voltage according to [12]. The value of the voltage is measured at the PCC. In addition to this, the customer is allowed to have an additional 4 % voltage drop within the installation.

A short-term voltage anomaly is a voltage distortion lasting from 10 ms up to 60 s.

These variations can be both voltage drops and voltage swells. For a system up to 45 kV, the voltage drop may never drop to such a level where it would correlate to area C in table 2.2 below [12]. If the voltage drops to a level that would correlate to area B, then the DSO must make reasonable reinforcements so such a scenario would not happen again.

Table 2.2: *Requirements according to [12] for short term voltage drops.*

U [%]	**Duration of voltage drop [ms]**				
	$10 \leq t \leq 200$	$200 \leq t \leq 500$	$500 \leq t \leq 1000$	$1000 \leq t \leq 5000$	$5000 \leq t \leq 6000$
$90 > u \geq 80$					
$80 > u \geq 70$	A				
$70 > u \geq 40$			B		
$40 > u \geq 50$					C
$5 > u$					

Fast voltage variations is a voltage anomaly where the absolute value of the voltage changes faster than 0.5 %/s, and where the voltage value during and after the variation is within 90 % and 110 % of the nominal voltage. In the medium voltage grid operated by GENAB the maximum change of the fast voltage variation must be < 3 %/s [11]. If these variations exceeds the requirements, then the customer must make appropriate changes. The frequency of the variations is also limited to a maximum of 4 times/day. A higher voltage change for 3-5 %/s is acceptable as long as it only occurs 1 time/month.

2.3.2 Harmonics

Harmonics are most common in the low voltage network, however, they can occur in the medium voltage network as well. Especially when there is a high penetration of converters [11]. Harmonics are important to minimize, especially the 3rd harmonic since it can, based on the principle of superposition, sum up creating a significant stray current in the neutral [11]. Harmonics propagates down into the low voltage network, therefore higher voltage means stricter harmonic requirements [11]. In the medium voltage network, the Total Harmonic Distortion (THD) needs to follow the limit $U_{THD} < 3$ %. For other harmonic orders, the maximum relatives are presented in table 2.3 below.

Table 2.3: *Requirements according to [11] for harmonic distortion of the voltage.*

Odd harmonics				**Even harmonics**	
Not multiples of 3		Multiples of 3			
Harmonic order (n)	U_n (%)	Harmonic order (n)	U_n (%)	Harmonic order (n)	U_n (%)
5	2.5	3	2.5	2	1.5
7	2.5	9	0.5	4	0.5
11	1.5	15	0.3	6	0.2
13	1.5	21	0.3	8	0.2
17	1.0			...	0.2
19	0.5			...	0.2
23	0.5			22	0.2
25	0.5			24	0.2

For current, there is a different set of rules according to [11]. The current is divided into two different categories which depend on the ratio between the maximum short circuit current and the maximum contracted current I_{sc}/I_{max}. For a ratio that is less than 50, a more strict set of rules are applied. These rules are presented in table 2.4 below. In both cases, however, the current THD needs to be lower than 8 % of the maximum contracted current.

Table 2.4: *Requirements according to [11] for harmonic distortion of the current.*

Harmonic order (h)	$I_{sc}/I_{max} > 50$		$I_{sc}/I_{max} < 50$	
	Odd I_h (%)	Even I_h (%)	Odd I_h (%)	Even I_h (%)
h < 11	6.0	1.5	4.0	1.5
11 ≤ h < 17	3.5	1.5	2.0	1.5
17 ≤ h < 22	2.0	0.5	1.5	0.5
22 ≤ h < 34	0.5	0.125	0.5	0.125
34 ≤ h	0.3	0.075	0.3	0.075

2.4 Fault ride-through requirements

The European Network of Transmission System Operators for Electricity (ENTSO-E) and the TSOs have requirements for small and medium-size grid-connected generation units, where the BESS is required to stay connected to the grid and ride through low voltage faults during a specified time period [13]. In figure 2.4, the generic profile of the fault ride-through (FRT) is presented according to ENTSO-E [14].

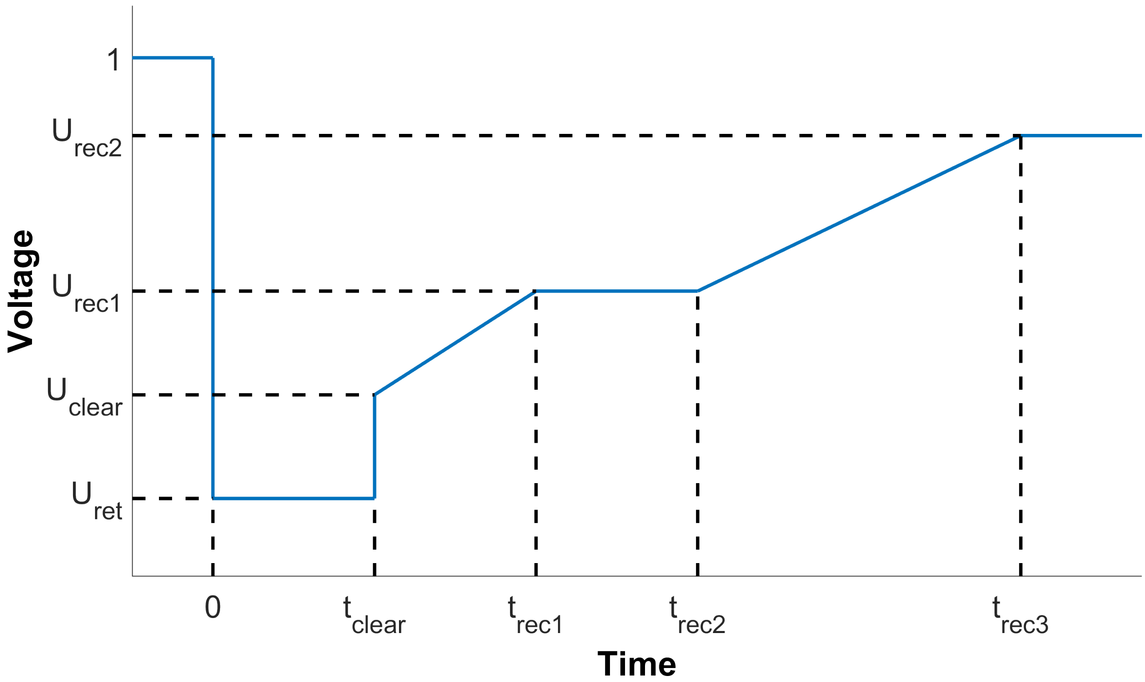

Figure 2.4: *Generic fault ride-through requirements according to [14].*

If the voltage at the PCC passes below the curve in figure 2.4 then the generation unit has the right to disconnect from the grid. The value of the time and voltage parameters that formulates the profile for the FRT requirements are presented in table 2.5.

Table 2.5: *Time and voltage parameters for the FRT profile for the BESS according to [14].*

Voltage Parameter	Value (pu)	Time Parameter	Value (s)
U_{ret}	0.05 to 0.15	t_{clear}	0.14 to 0.25
U_{clear}	U_{ret} to 0.15	t_{rec1}	t_{clear}
U_{rec1}	U_{rec1}	t_{rec2}	t_{rec1}
U_{rec}	0.85	t_{rec}	1.5 to 3.0

By studying table 2.5, the worst voltage profile during the fault can be realised, where the voltage drops to 0.05 pu for 0.25 seconds and then recovers to 0.85 pu after 3 seconds. This profile is presented in figure 2.4. Therefore, the generation unit has to stay connected to the grid if the voltage at the PCC is above or following the curve in figure 2.4.

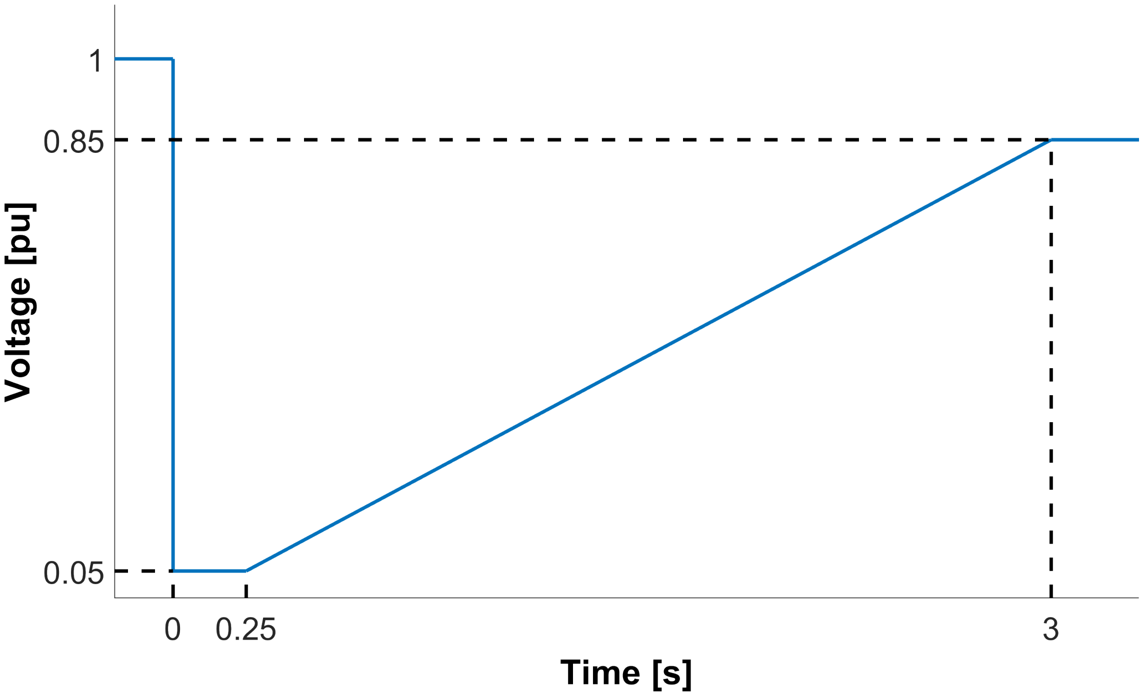

Figure 2.5: *The worst case scenario of a fault ride-through according to [14].*

It is also required that the generation unit should contribute to the short circuit current during the fault, which will help the protection system in the network to detect the fault [13]. For generation units that are connected to the grid through PWM inverters, the maximum short circuit current is usually 1 pu of the rated current [13].

3

Battery Energy Storage Systems

Electricity providers must always have sufficient installed power in order to match the generators with the real-time supply loads, even during peak powers. Battery Energy Store System (BESS) is a concept of stationary energy storage which could be utilized in order to store the energy closer to the loads in advance of the peak consumption period. This, and a multitude of other advantages are available by utilizing BESSs [15].

A BESS is a quite complex system, the first part of a BESS is battery cells which are connected in packs, these packs are individually monitored by a Battery Management System [15]. This supplies electricity through a power inverter controlled by a real-time computer control system [15]. A simplified model of a BESS is presented in figure 3.1.

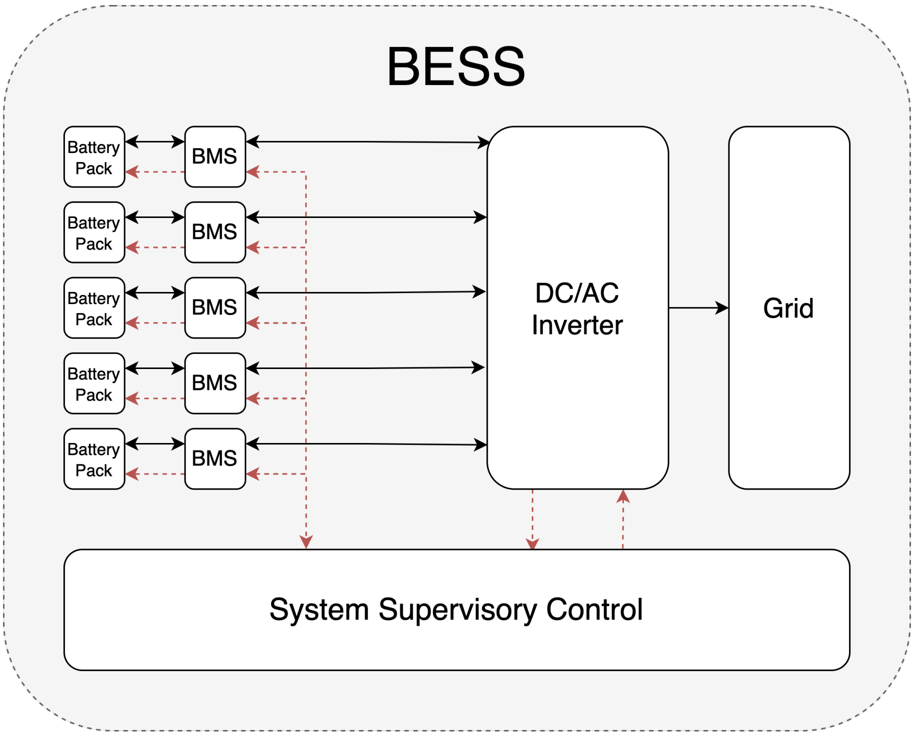

Figure 3.1: *General overview of a BESS according to [15]. Black lines are current carrying lines and red lines are communication signals.*

The battery cells in the battery packs are essentially two electrodes, called anode and cathode, combined with an electrolyte [16]. The electrolyte enables the flow of ions between these poles, so when the poles are connected through an external electrical circuit the negative electrons flow through the external circuit, while the positive ions flow in the electrolyte [16]. By doing so, the lithium-ions can be stored in the anode, creating a capacity that later could be used.

3.1 Battery parameters

The capacity of a battery is, defined by international convention, the charge of Ah that the battery can supply [17]. The State of Charge (SOC) is a metric of how much energy is left in the battery [17]. It's normally represented as a percentage, where 100 % is fully charged and 0 % is fully discharged.

The complement to the SOC is the Depth of Discharge (DOD), this represents how much energy has been used from the battery [17]. Hence, 0 % DOD is a fully charged battery and 100 % is fully discharged.

The voltage characteristics are an important parameter of a battery. The most common metric is the open-circuit voltage (OCV), this is the potential difference of the battery terminals when no current present [17]. This voltage is quite complicated and depends on many factors. For example, the current drawn from the battery, the chemistry of the battery, and SOC of the battery [16], [17]. This means that the voltage of the battery terminals is not constant.

Another parameter is the C-rate, which is a metric of large the charging/discharging current is compared to the battery size [16]. It's defined as the current drawn from the battery divided by the rated capacity in ampere hours, the unit is therefore h^{-1}.

3.2 Battery degradation factors

Degradation is a phenomenon where the capacity of a rechargeable battery decreases with use. A common metric of this phenomenon is the State of Health (SOH) which is calculated according to equation (3.1).

$$\mathrm{SOH} = \frac{\text{Present Battery Maximum Capacity}}{\text{Initial Battery Maximum Capacity}} \tag{3.1}$$

There is no standard when it comes to the end of life of a battery, but generally, a SOH of 80 % is the most common value [16]. A battery degrades, more or less, linearly down to this value of 80 % and after that the battery ages faster [16]. However, this value mainly comes from the automotive industry and other values can be considered.

There is a multitude of so-called stress factors that affect the SOH of a battery. The

DOD is one of these factors, a larger DOD per cycle will increase the degradation of a battery and reduce the number of cycles until the end of life. Hence, there could be a techno-economic dilemma where a larger battery would increase the lifetime of the battery, but at the same time, would cost more [16]. The operating range of the DOD will also affect the degradation, a charging interval between 50 % to 100 % will have a different effect than a charging interval between 0 % to 50 % [16].

One of the most important stress factors is the C-rate, a large C-rate reduces the number of cycles until the end of life of a battery. However, this is usually a much bigger factor to consider when the battery will be used in the transportation industry rather than grid connected a BESS [16].

Other factors like the cell temperature is also a major stress factor. Where the optimal operating temperatures is between 20 °C to 30 °C [16]. Charging the cells at low temperatures will reduce the technical performance of the battery, yielding lower efficiency and reduced cyclable capacity [18]. Operating at high temperatures will increase the side reactions inside the cell which will accelerate the degradation process of the cell [16].

3.3 Battery Management Systems

A Battery Management System (BMS) is a crucial part of the BESS in order to monitor- and manage the battery packs in a safe way [15]. A BMS monitors the voltage, current, and temperature of each battery pack and controls the current output according to the power demand. It can manage the battery in a safe way by knowing the limits, or upper and lower bounds, of the temperature, voltage, and current. The battery pack parameters can be controlled by the BMS by regulating the current [15].

BMS can contribute to prolong the battery lifetime and increase its performance, assuming information like SOC and SOH are known. If these internal variables of the battery pack are not known, then they can be quite accurately estimated by incorporating physics-based models [15]. To estimate the SOC a method of Coulumb counting can be implemented. This method measures the current from the battery and the time in order to estimate the SOC [19]. The Coulumb counting method is quite unreliable because of inaccuracies of current meters combined with variable losses inside the battery [15]. It also requires the initial SOC of the battery to be known, since it's a relative measure.

Instead, a more common strategy of determining the SOC is to measure the OCV, since the OCV varies depending on the SOC of the battery. This can be seen in figure 3.2 where the voltage of a battery varies during a charging cycle. This method is far better for some batteries than others since some chemistries have a very flat voltage profile [15]. The most optimal estimation method is to combine both methods of measuring the SOC with the help of a Kalman filter, which is a real-time estimation algorithm with a very low margin of error [19].

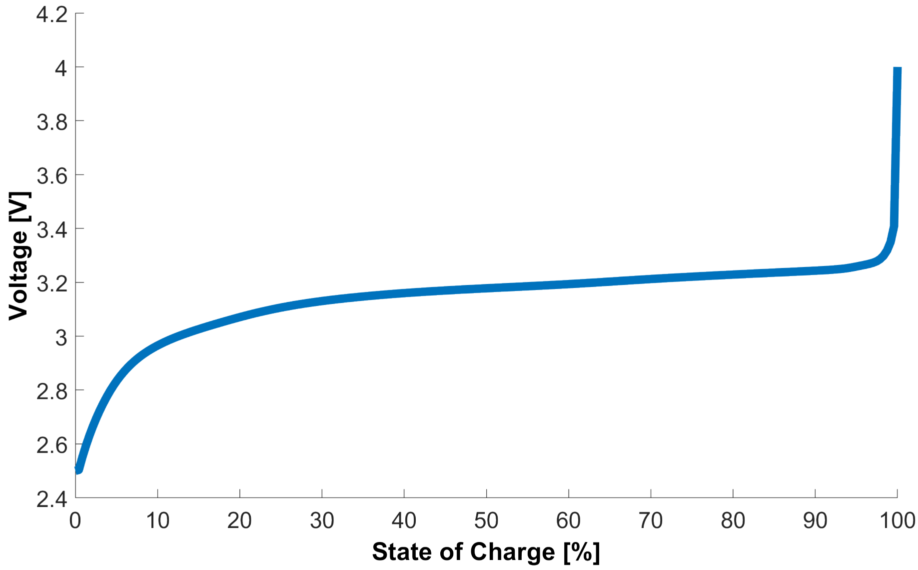

Figure 3.2: *Voltage characteristics of a battery cell with lithium iron phosphate (LFP) chemistry during a charging cycle.*

3.4 Grid connection interface

The battery in the BESS is DC energy storage and the electrical grid operates on an AC power system, so to be able to exchange the energy in between the battery and the grid, a bi-directional AC/DC inverter is essential for the BESS as a grid connection interface [20]. The inverter has the ability to convert AC power to DC power and vice versa. The power inverter mainly consists of power semiconductors like IGBTs, control components, heat dissipation components, and passive components like capacitors and indicators [21].

To assure a full integration and increase the utilization of the BESS, a proper grid connection interface should be used. Especially when considering the use of a BESS to provide ancillary services [22].

Grid-connected inverters (GCIs) should be able to fulfill three main functions. First, basic functions which is the ability to achieve grid synchronization, DC voltage control, and grid current control. Those functions are essential for the GCIs to meet the possible grid connection requirements as feeding units as they convert the energy stored from the battery to AC power at unity power factor with minimum current harmonic distortion [22]. Secondly, functions related to the application area, so in the case of a BESS, the GCI should have the ability to allow bi-directional power flow, so that the process of charging/discharging can be achieved and controlled. Lastly, additional functions are required for utility scaled BESSs which are related to grid supporting functions, like dynamic power control, dynamic reactive power control, low and high voltage ride through [22].

There are several kinds of topologies that exist for GCIs, but the most common topologies that are used in grid applications are voltage source inverters (VSI) [22]. Two-level VSI is broadly used in low voltage grids for the sake of simplicity and high reliability. In order to make the two-level inverter compile with medium and high voltage levels, several switching devices can be connected in series [23]. This creates higher switching losses and high total harmonic distortion [22], [23]. To mitigate the drawbacks in two-level VSIs, multi-level VSIs can be used, but the complexity in the control and modulation of multi-level VSIs increases with the number of levels [21], [22].

4

Ancillary services and market related aspects

The frequency in an electric power system is a continuous balance of the generated and consumed power [24]. If the consumed power is larger than the generated power, then the spare energy will come from the rotational energy of the generators and motors in the system [25], thus decreasing the frequency. If the generated power is larger than the consumed then the rotational energy will increase, and the frequency increases. It's important that the frequency in the power system stays constant since many loads are reactive and hence frequency dependant. By changing the frequency, the loads can malfunction because of high magnetization currents [25]. The balancing act can be described as

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a, \tag{4.1}$$

where δ rotor angle, ω_s is the angular velocity of the rotor at synchronous speed, and P_m, P_e and P_a respectively are the mechanical, electrical and accelerating power [25]. In equation (4.1), H is a inertia constant and can be represented as in equation (4.2).

$$H = \frac{1}{2}\frac{J\omega_m^2}{VA_{base}} = \frac{\text{Stored kinetic energy at rated speed in MW}\cdot\text{s}}{\text{MVA rating of the machine}} \tag{4.2}$$

According to equation (4.1), if the electrical and mechanical power is not balanced then the rotor will start to accelerate or decelerate. In order to balance the mechanical and electrical power, multiple control systems are implemented. A common way of controlling the electrical power output, in order to regulate the frequency, is droop control on the speed governor [25]. A droop control has a deadband where the frequency can vary and the power generated will be unaffected. If the frequency drops, then the power generated will increase linearly up to a maximum value. If the frequency is too high, the power output will decrease instead.

4.1 Frequency regulation markets

In Europe, the European Network of Transmission System Operators for Electricity (ENTSO-E) sets standards for the different markets that are used for regulating the system frequency. The markets are Fast Frequency Response (FFR), Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR), and Replacement Reserves (RR) [26], [27]. These markets have different activation times which is presented in figure 4.1.

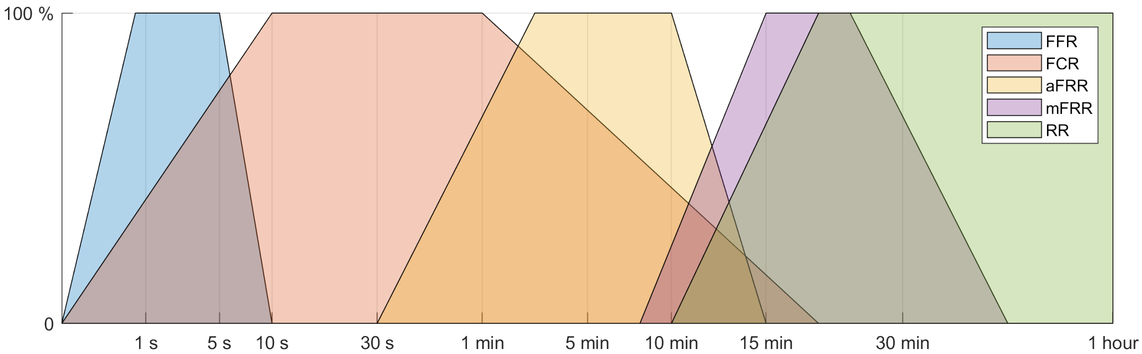

Figure 4.1: *Containment reserves and their activation times according to ENTSO-E [26]–[28].*

4.1.1 Fast Frequency Response

The fast frequency response is a type of frequency response where rapid injection of active power is supplied in a very short time [24]. Hence, FFR is faster than traditional frequency regulation reserves [26].

There's a multitude of different techniques for delivering FFR such as wind turbines, flywheels, HVDC, vehicle to grid, or BESSs [26]. Battery energy storage systems with an interface of power electronics is a way of providing FFR, the BESS provides a controlled inertia response, also called synthetic inertia or virtual inertia [24], [26]. This active power injection is emulated to mimic the response of a generator with rotating mass [26]. In the Nordic power system, the maximum activation time is dependant on the frequency drop [29], this can be seen in table 4.1.

Table 4.1: *The minimum activation time required for different frequencies according to [29].*

Alternative	Frequency	Maximum activation time
A	49.50 Hz	0.7 s
B	49.60 Hz	1.0 s
C	49.70 Hz	1.3 s

As seen in table 4.1, there are three different alternatives the operator can choose: A, B, or C. These alternatives are coupled with different activation times. According to [29], there are also two different activation lengths when it comes to FFR. The first is a short activation length where the generator needs to supply the power for a minimum of 5 seconds. The second is the long activation length where the minimum supplying time is 30 seconds. For the short activation length, the supply must ramp down the power injected with 20 %/s, whereas in the long activation time the supply can be deactivated in any way [29]. The operator can choose either the short or the long deactivation cycle. The FFR providing generators must be ready for another activation cycle within 15 minutes of the last one [29].

FFR is a new service and exists in the Nordic power system, it does not exist in the Continental European power system. The minimum bid for FFR in the Nordic power system is 0.1 MW [29].

4.1.2 Frequency Containment Reserves

Frequency containment reserves are defined as operation reserves with the purpose of balancing the frequency within the normal operation and in case of disturbances [28]. In the Nordic power system, FCR is divided into two categories: FCR-N and FCR-D. FCR-N has the purpose of controlling the frequency within the normal operating band $49.90 < f < 50.10$ Hz [24]. Since this is during normal operation, when the frequency deviation is not too significant, the activation time is within 2-3 minutes [24].

The goal for the FCR-D is to restore the power balance before the frequency deviates to 50 $\pm$ 1 Hz and to keep a steady-state frequency above 49.50 Hz and below 50.50 Hz [28]. This is a much more critical frequency deviation and hence, the response time is much shorter. The FCR-D supply should activate 50 % of the response within 5 seconds, and 100 % within 30 seconds [24]. This is presented in figure 4.2.

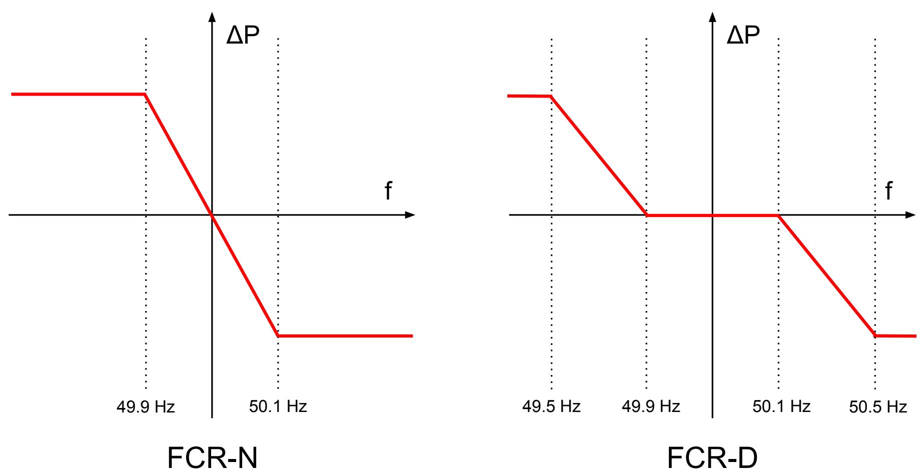

Figure 4.2: *Droop response of the FCR-N and FCR-D markets in the Nordic power system.*

In Germany the TSO is TenneT, and there is no FCR-D or FCR-N market, instead there is a combined market called FCR. ENTSO-E require a full activation after 30 seconds after the frequency has deviated between 50 ± 0.2 Hz [30]. The deadband for the FCR service is ± 10 mHz, which corresponds to between 49.990 Hz and 50.010 Hz. This is presented in figure 4.3.

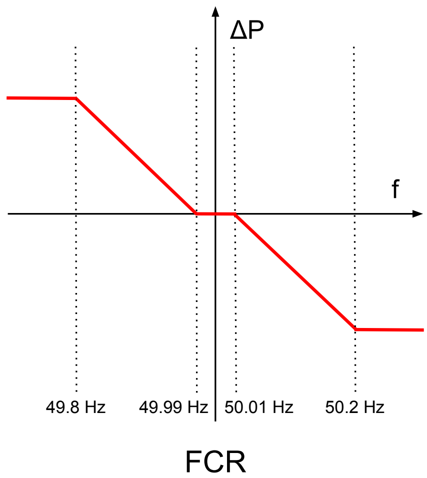

Figure 4.3: *Droop response of the FCR market in the Continental European power system.*

The market of FCR is organized by the transmission system operator (TSO). In both Sweden and Germany the FCR is obtained through a common tender process [24], [31]. The bids can be submitted one or two days before the operational day and are time-limited depending on when it's submitted [24]. In Sweden the minimum bid size is 0.1 MW [32], [33]. The minimum bid size in Germany is 1 MW [30].

4.1.3 Frequency Restoration Reserves

The frequency restoration reserve is defined as the operating reserves necessary to restore the frequency back to the nominal one. There are two different FRRs, automatic and manual, each denoted by aFRR and mFRR respectively [27].

The aFRR is an automatic spinning reserve and works faster than the manual counterpart mFRR. A larger disturbance is required in order to trigger this restoration reserve. After a larger disturbance, aFRR will work in congestion with FCR in order to bring back the frequency to 50 Hz while FCR gives sufficient stabilization [27]. The aFRR is handled by the TSO and must be fully activated within 120 seconds [34].

The mFRR is a manual reserve and is a non-spinning reserve, it is used for power balancing during congestions in normal and disturbing operations. mFRR is the main balancing reserve and replaces FCR and aFRR [27]. The Nordic power system is dependant on the mFRR due to the limited volume of FCR and aFRR. It's the main balancing resource and should be activated within 15 minutes [35].

The minimum bid for aFRR is 5 MW while the maximum is 30 MW [34]. While the minimum bid for mFRR is 5 MW with no maximum bid [35].

4.1.4 Replacement Reserves

The replacement reserve is the final reserve and replaces FRR and FCR. It helps manage congestions and restores or supports the frequency by relieving the FRR reserves when they're not able to restore the frequency to the nominal one [24]. RR is a completely manual service and is activated by the TSO in the control center. The timeframe varies widely between TSOs but the time span is usually between 30 and 120 minutes [24].

4.2 Voltage support

To maintain high power quality in the electrical network the voltage profile should be kept within the specified operating margins. Exceeding the voltage limits might cause damages to the electrical components [36]. Controlling the voltage profile is inherently coupled by controlling the reactive power [24], [36].

The production of the reactive power should be spread out through the network and closer to where it is needed. The reactive power can be controlled by the BESS in terms of absorption and production if the BESS is equipped with a proper grid-connected inverter [37]. The BESS will be then capable to have the four-quadrant operation and deliver active power and reactive power at the same time. [37].

There is no market formation for this service today, but it is suggested to change the way of thinking towards this service and consider remunerating the provider of such a service [38].

4.3 Peak shifting and energy arbitrage

The abundant consumption of electrical power during peak periods can affect the stability of the electrical network and can be costly for the TSO and DSO [39]. One solution that can be used to mitigate the strain on the electrical network during peak periods is a BESS [24], [39].

The stored energy in the battery can be used to minimize the peak demand fees. Peak demand fees are estimated based on the maximum demand during a given month. So in the event that the BESS is used for peak shifting the peak demand fees will be reduced [39].

Energy arbitrage is the ability to charge the battery during the off-peak period when the electricity price is cheap and use it later when the demand and the price is high [39]. If the price deviation between on-peak and off-peak, and the mitigation of peak demand fees is sufficient enough. Then owning a BESS will be more beneficial economically [39].

5
Methodology

Based on the inputs from Port of Gothenburg, Port of Kiel, and BatteryLoop, analysis of the two harbors: Majnabben in Gothenburg as well as Kiel was conducted. Three scenarios of ship battery size were considered, 20, 50, and 70 MWh. The battery size of 20 MWh corresponds to a hybrid ship. While the 50 MWh and 70 MWh batteries are conceptual sizes for a fully electric ferry. With this information, a study of the required capacity of the BESS was conducted.

In order to calculate the capacity of the BESS, some initial conditions, as well as assumptions, was required. These parameters were used while analyzing the BESS size and are shown in table 2.1. The BESS capacity was calculated firstly by calculating the power needed to charge the ship battery, with the capacity S_{ship}. This is presented in equation (5.1).

$$P_{charge} = \frac{S_{ship}}{\eta(t_{ship} - t_{connect}/60)} \tag{5.1}$$

If the required charging power that is needed is higher than the available power from the harbor grid, then a BESS on-shore is required to support the grid during the charging process of the ship. The power needed from the battery can be calculated using equation (5.2).

$$P_{BESS} = P_{charge} - P_{available} \tag{5.2}$$

Since the BESS needs to supply this power during the time which the ship is at the quay, the total energy needed can easily be calculated. To reduce the degradation of the battery the DoD also needs to be considered. The full expression is presented in equation (5.3).

$$S_{BESS} = \frac{P_{BESS} \cdot t_{ship}}{\mathrm{DOD_{BESS}}} \tag{5.3}$$

Now that the required energy from the BESS is known, the maximum energy that can be stored while the ship is not at quay can be calculated. By assuming that no other loads are connected to the high voltage connection the maximum energy can easily be calculated, this is shown in equation (5.4).

$$E_{BESS,max} = P_{max} \cdot t_{BESS} \tag{5.4}$$

If $E_{BESS,max} > E_{BESS}$ then a BESS can be used to support the charging of the ship. Otherwise, it's not possible to use a BESS since it can not be re-charged within the given time frame. Instead grid reinforcement is required.

The costs of purchasing these BESS with the corresponding capacities was also evaluated. Thereafter an economical evaluation of the grid reinforcement solution was conducted and compared to the BESS solution.

5.1 Modeling and simulation methodology

Two models in DIgSILENT PowerFactory were constructed. The first model was used to simulate the ancillary services peak shifting and voltage regulation. This model was also used to simulate the BESS compliance with the DSO requirements of fault ride through. The second model was used to simulate the potential benefit of the BESS to mitigate frequency deviations in the Nordic power system and the Continental European power system. Both of these models used and already build BESS module which was integrated in DIgSILENT PowerFactory [40].

The necessity of having two models is that the one is used for frequency response has an aggregated synchronous generator to represent the inertia and governor parameters of the external grid. While the other model represents the electrical connection setup for the harbor, where the actual electrical parameters are of interest.

For each battery size of the BESS, a set of simulations in DIgSILENT PowerFactory were be conducted. There were four simulations studies chosen for this thesis: peak shifting, system frequency stability, voltage support, and fault ride-through.

Simulations for the study of peak shifting is the primary simulation study where the charging of the ship and BESS are simulated according to the different cases in both harbors. This is required in order to evaluate if the BESS solution could solve the original problem formulation. By doing this simulation, a result is also obtained that gives an indication of how long time the BESS is inactive and fully charged. This time period can be used to estimate how long time the BESS can provide ancillary services for when the ship is not berthed.

In the simulation study of system frequency stability, the reference scenario of the Ringhals Block 4 outage was used to illustrate the BESS ability to provide FFR within the TSO requirements in the Nordic power system. The BESS is able to inject active power very fast as a response to mitigate the rapid changes of the system frequency, this makes the BESS a perfect candidate as an FFR service provider. In this simulation case, the alternative operation "C" was chosen from table 4.1 to simulate the potential grid benefit by providing FFR. The FFR service does not exist yet in the Central European power system, FFR was therefore not simulated in Kiel.

Another simulation was done to measure the potential of the BESS to provide FCR-N. The purpose of this is firstly to get a better understanding of how the BESS will operate in the FCR-N market. Secondly, to illustrate how the BESS might be more beneficial economically by providing FCR-N. In this simulation, the BESS will have an initial capacity of 50 % SOC and the droop settings are set according to the FCR-N market, delivering 100 % power at 50 ± 0.1 Hz. The BESS will operate between 10 % and 90 % SOC. The time when the BESS will stop providing FCR-N is calculated in order to have time to charge the BESS before the ship arrives back at quay. By knowing the time left until the ship arrives and the current SOC, a computer can calculate when the BESS should stop providing FCR-N.

The same reference scenario of Ringhals Block 4 was used to simulate the potential effect that BESS has on mitigating the frequency nadir of the system when operating in FCR-D market. So the droop was set to be activated at 49.90 Hz and to linearly increase to 100 % at 49.50 Hz, which is a requirement to operate in the FCR-D market in the Nordic power system.

The FCR simulations in the Central European power system are separated into two different simulation scenarios. One for disturbed operation where the same reference scenario of Ringhals Block 4 was used. And one for normal operation where the BESS operates during a longer time period, similar to the FCR-N market in the Nordic power system. The TSO in Kiel is named TenneT and has an united FCR market for both normal- and disturbed operations. According to [30], the droop setting in the frequency controller has a deadband of 10 mHz and linearly increases to 100 % at 50 ± 0.2 Hz.

The voltage support simulation was conducted in order to show the ability of the BESS to regulate the voltage in the PCC. The BESS will be able to inject reactive power in the grid and provide reactive power to the consumers in the electrical network. Two things can be achieved from this. First, a unity power factor at the PCC. Secondly, a slight enhancement for the voltage profile in the PCC.

The last simulation is the fault ride-through simulation. The sole purpose of this simulation is to validate the compliance of the DSO and TOS's requirements which are described in section 2.4. In this simulation, case 3-G is used to simulate a 3 phase short circuit at the PCC during a period of 2 seconds.

A simple economic calculation was conducted in order to illustrate the possible economic benefit from the frequency stability services. A lifetime analysis for the battery cells was conducted in order to estimate how many years the cells could operate before reaching the end of life. Calculations based on the system frequency stability simulations with the BESS were conducted in order to estimate potential earnings and savings.

6

Analysis and cost evaluation for charging solutions

In this section the result of the BESS sizing analysis is presented. The economics of the BESS and possible grid expansion is also presented.

6.1 BESS sizing analysis

In order to calculate the BESS size, there are parameters and assumptions needed, these are presented in table 2.1. It can be noted that the maximum available power in the terminal in Gothenburg is 4 MW and the power that is needed for the existing shore connection is around 2.2 MW, yielding a 1.8 MW power available to charge the ship while at berth. This available power and the required power are used to evaluate if a BESS is needed in order to fully charge the ship, this is evaluated in table 6.1.

Table 6.1: *Cases specifications in the port in Gothenburg.*

Description	**Variable**	**Case 1-G**	**Case 2-G**	**Case 3-G**	**Unit**
Battery capacity on ship	S_{ship}	20	50	70	MWh
Used energy with 60 % DOD	E_{ship}	12	30	42	MWh
Required charging power	P_{charge}	1.3	3.2	4.5	MW
Available charging power	$P_{available}$		1.8		MW
Is a BESS needed?	-	NO	YES	YES	-

It can be seen from the table 6.1 that the required charging power for the cases 2-G and 3-G are more than the available power for charging when the ship is at berth. So a BESS solution is needed for the cases 2-G and 3-G, while for case 1-G a charging power of 1.8 MW is deemed sufficient to charge a hybrid ship with 20 MWh capacity.

Since the ship will be away for around 14 hours, this allows the BESS to utilize the entire available power of 4 MW in the terminal for recharging. By using these parameters it can be calculated if the BESS can be fully recharged when the ships are not at the quay. This evaluation is presented in table 6.2.

Table 6.2: *Result of the BESS size required in the port in Gothenburg.*

Description	**Variable**	**Case 2-G**	**Case 3-G**	**Unit**
BESS capacity	S_{BESS}	18	34	MWh
Used energy with 80 % DOD	E_{BESS}	14	27	MWh
Required discharging power	P_{BESS}	1.4	2.7	MW
C-rate discharge	$C_{rate,dis}$	0.08		h^{-1}
VSI rated power	P_{VSI}	4		MW
C-rate charge	$C_{rate,charg}$	0.23	0.12	h^{-1}
Maximum possible capacity	$E_{BESS,max}$	66		MWh
Possible to recharge the BESS?	-	YES	YES	-

The chosen size of the voltage source inverter P_{VSI} is higher than the required discharging power that is needed to charge the battery on the ship as can be seen in table 6.2. This is done in order to fulfill two main objectives, first to utilize the full potential of the BESS capacity to provide ancillary services. Secondly, to re-charge the BESS as fast as possible and have it ready to provide the ancillary services when the ship is not berthed. Since the feeding cables from the external grid have a limited capacity of 4 MW, a bigger size of the VSI is not possible. Power of 4 MW under the time period of 14 hours results in maximum energy of 66 MWh. Yielding a maximum feasible capacity for a BESS of 66 MWh with respect for the assumptions in table 2.1.

According to the Port of Kiel, the maximum available power which is assigned to Stena Line is 5 MW. The power that is needed from the shore connection is around 2.2 MW, therefore the remaining available power that can be used to charge the battery on the ship is 2.8 MW. This available power and the required power are used to evaluate if a BESS is needed in order to fully charge the ship, this is evaluated in table 6.3.

Table 6.3: *Cases specifications in the port in Kiel.*

Description	**Variable**	**Case 1-K**	**Case 2-K**	**Case 3-K**	**Unit**
Battery capacity on ship	S_{ship}	20	50	70	MWh
Used energy with 60 % DOD	E_{ship}	12	30	42	MWh
Required charging power	P_{charge}	1.3	3.2	4.5	MW
Available power for charging	$P_{available}$	2.8			MW
Is a BESS needed?	-	NO	YES	YES	-

Since the available charging power is more than the required charging power for case 1-K, there is no need for a BESS solution for a hybrid ship with a battery of 20 MWh. While for cases 2-K and 3-K the BESS solution is necessary.

It can be noted that the available power for charging in the port in Kiel is 1 MW higher than the port in Gothenburg. This will yield smaller BESS sizes in cases

2-K and 3-K compared to the cases 2-G and 3-G. These BESS sizes are presented in table 6.4 below.

Table 6.4: *Result of the BESS size required in the port in Kiel.*

Description	Variable	Case 2-K	Case 3-K	Unit
BESS capacity	S_{BESS}	5	21	MWh
Used energy with 80 % DOD	E_{BESS}	4	17	MWh
Required discharging power	P_{BESS}	0.4	1.7	MW
C-rate discharge	$C_{rate,dis}$	0.08		h^{-1}
VSI rated power	P_{VSI}	5		MW
C-rate charge	$C_{rate,charg}$	0.99	0.24	h^{-1}
Maximum possible capacity	$E_{BESS,max}$	83		MWh
Possible to recharge the BESS?	-	YES	YES	-

The size of the power conversion system P_{VSI} is higher than the required discharging power that is needed to charge the battery on the ship as can be seen in table 6.2. This is done for the same purposes that are mentioned in section 6.1. The maximum feasible capacity for a BESS in Kiel is 83 MWh, taking into account the assumptions in table 2.1.

6.2 BESS cost analysis

The total cost of the BESS consists of different components cost; the lithium-ion battery racks including the BMS, power conversion equipment, energy control system, monitoring equipment, lastly the protection and safety system. Moreover, the installation costs should also be considered. Since the BESS will be provided by BatteryLoop in the "Sea Li-ion" project, a price for the BESS was provided. According to [6], the current cost of the BESS is 7000 SEK/kWh, this includes all the components of a BESS. Based on this, the total cost for the BESS is calculated and presented in table 6.5.

Table 6.5: *Cost for the BESS solution for the different cases in the ports in Gothenburg and Kiel.*

Case	Case 2-G	Case 3-G	Case 2-K	Case 3-K	Unit
BESS Capacity	18	34	5	21	MWh
Cost of BESS	123	236	36	128	MSEK

6.3 Cost analysis for grid reinforcement

Grid reinforcement is an alternative solution to provide the needed energy to charge the hybrid or electrical ship. This solution has been analysed, as it can be seen in figures 6.1 and 6.2, the possible cable paths in Gothenburg are marked with yellow lines. Two feeding cables are needed to meet the N-1 requirement, the first cable will be coming from the switch-gear in Rosenlund with 3.3 km pathway as depicted in figure 6.1. The second cable will be coming from another switch-gear located in Slottsskogen with a 2 km pathway which is shown in figure 6.2. According to [41] the total cost for the construction is 5.5 MSEK excluding municipal excavation fees and infringement compensation.

Figure 6.1: Demonstration for the new cable route from the 10 kV station in Rosenlund. Map data is provided by Imagery ©2021 Aerodata International Surveys, CNES / Airbus, Landsat / Copernicus, Lantmäteriet/Metria, Maxar Technologies, Map data ©2021.

Figure 6.2: Demonstration for the new cable route from the 10 kV station in Slotsskogen. Map data is provided by Imagery ©2021 Aerodata International Surveys, CNES / Airbus, Landsat / Copernicus, Lantmäteriet/Metria, Maxar Technologies, Map data ©2021.

Since it is not required to fulfill the N-1 requirement in Kiel, only one cable is needed to attain the alternative of grid reinforcement to deliver the charging power that is needed for the hybrid/electrical ship. The length of the new feeding cable is around 1.5 km, where it is assumed to be taken from the nearest substation to the harbor. Based on [41], the total cost for the construction is 1.5 MSEK excluding municipal excavation fees and infringement compensation. In figure 6.3 the possible cable path in Kiel is marked with a yellow line.

Figure 6.3: *Demonstration for the new cable route from the 10 kV station near the port in Kiel in Germany. Map data is provided by Imagery ©2021 AeroWest, GeoBasis-DE/BKG, GeoContent, Maxar Technologies, Map data ©2021 GeoBasis-DE/BKG (©2009).*

An additional cost in regards to grid extension is the subscription fee of the extra capacity drawn from the grid. This costs was obtained from [42] and [43]. The capacity used for the fee calculation is the missing capacity in the present connection in order to charge the battery on the ship within the given time frame. The results from this calculation are presented in table 6.6.

Table 6.6: *Subscription fee from [42] and [43] for the different connection sizes in Gothenburg and Kiel.*

Description	2G	3G	2K	3K	Unit
Cost	486		862		SEK/kW/year
Power needed	1.4	2.7	0.4	1.7	MW
Subscription fee	0.7	1.3	0.4	1.5	MSEK/year

7

Modeling the BESS and the electrical grid setup

In this chapter, the two models of the electrical network and one model of the BESS are presented and described. The first model of the electrical network represents the electrical connection setup for the harbor, where the actual electrical parameters are of interest. The second model is used for frequency response has an aggregated synchronous generator to represent the inertia and governor parameters of the external grid.

7.1 Modeling the electrical network

The electrical networks in both harbors are very similar, therefore one harbor network was modeled in DIgSILENT PowerFactory. The only diffracting factor between the network in Gothenburg and Kiel, which impacts the results, is the capacity of the external grid. This has to be taken into consideration, but the topology and parameters were assumed to be the same in both scenarios. The parameters of the electrical network are a combination of data given from [8] and assumptions. The electrical network used is presented in figure 7.1.

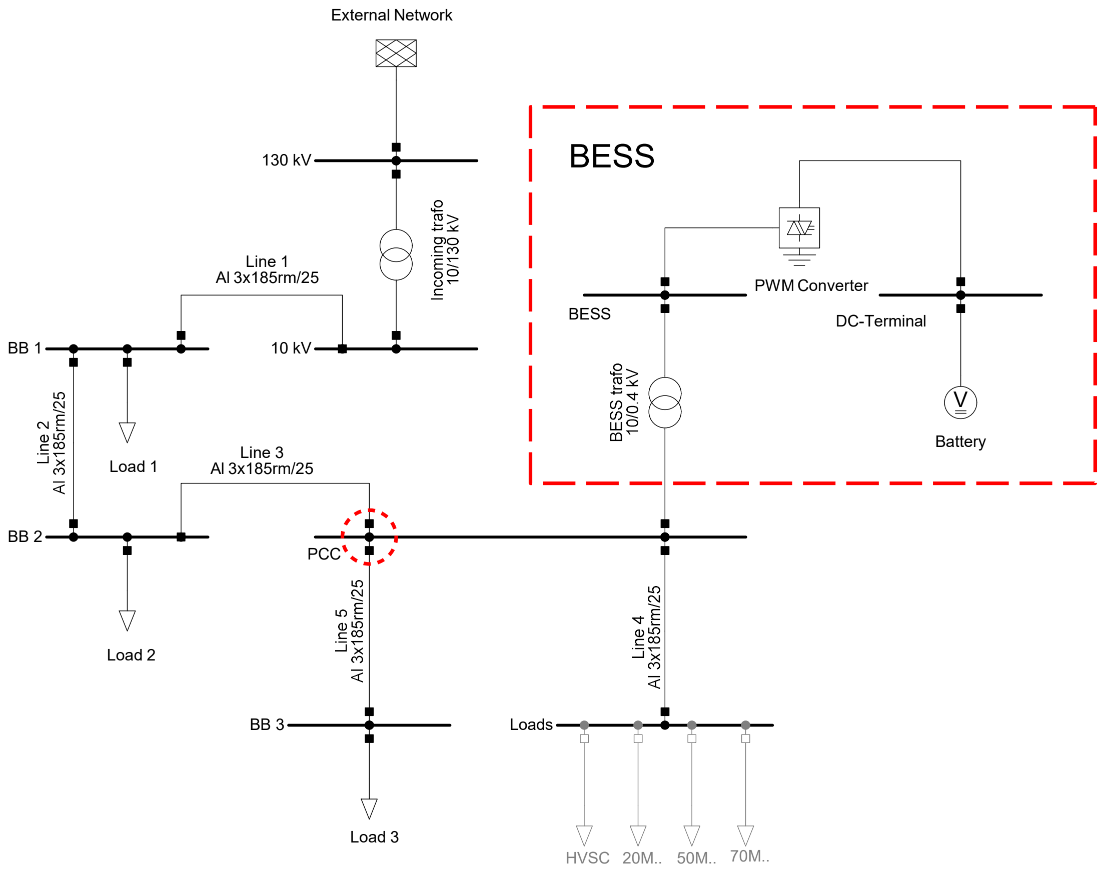

Figure 7.1: *The electrical network modeled in DIgSILENT PowerFactory, which was used for the peak shifting, voltage support, and fault ride-through simulations.*

The BESS is connected to the busbar of the incoming 10 kV line, called "PCC". Then there is a 90 m feeding cable called "Line 4" which connects the loads and the substation. The substation is connected to the 3.3 km long 10 kV feeding cable from the closest primary substation, shown in section 6.3. There are other loads connected to the same 10 kV feeder, these loads have the total combined capacity of 1 MVA and all these loads have a power factor of $\cos(\varphi) = 0.85$ lagging. This model was used to simulate the peak shifting, voltage support, and fault ride-through simulations.

In order to simulate a frequency response, there are some modifications needed to the network in figure 7.1. The external grid represents an infinite power source connected to the slack bus called "130 kV". Most importantly though the external grid has infinite inertia and does not use governor control, which means it's not reasonable to be used for frequency response. Instead, a more representative way of simulating a frequency response is to use a synchronous generator with its own governor. Therefore the external grid was replaced with a synchronous generator and the network was simplified immensely, this is presented in figure 7.2.

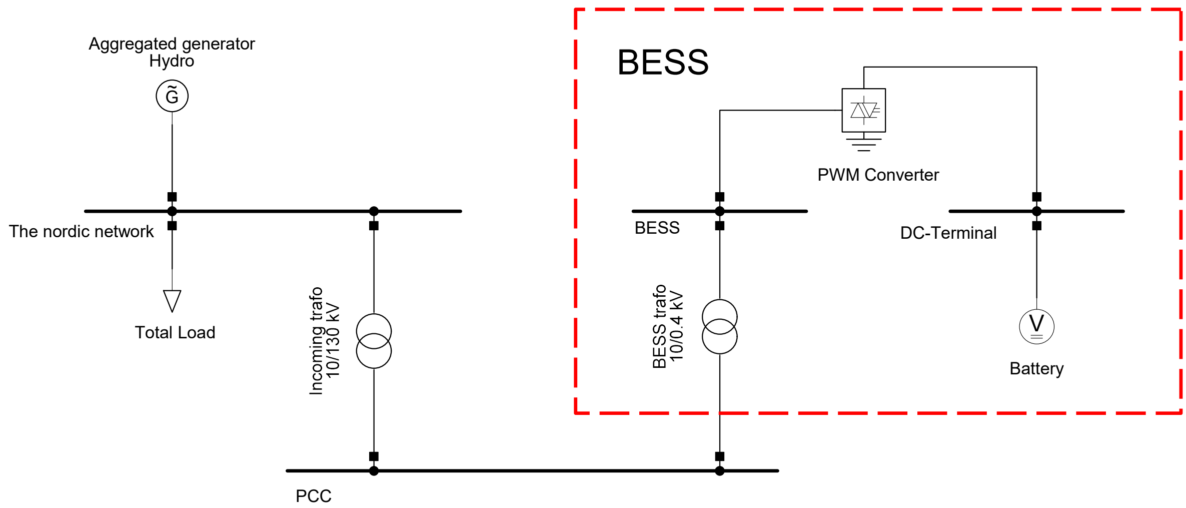

Figure 7.2: *The electrical network modeled in DIgSILENT PowerFactory, which was used for the frequency support simulations.*

The synchronous generator was based on a hydropower plant in DIgSILENT PowerFactory with an HYGOV governor, which is dynamic simulation model for a general hydropower generator. The reason for this is that the majority of the energy generated in the Nordic power system comes from hydropower [44].

7.1.1 Verification of model used for frequency support

In order to verify that the constructed model would be representative of an actual frequency response in the Nordic power grid, the model was compared to a reference scenario. The reference scenario occurred on 05-03-2015 when the nuclear reactor Ringhals Block 4 got disconnected due to a planned outage of 1110 MW [45]. The total consumption before the disconnection was 49 238 MW and it was assumed that the production was the same since the network used is much smaller and does not have a correct representation of the losses in the network. The initial response can be seen in figure 7.3.

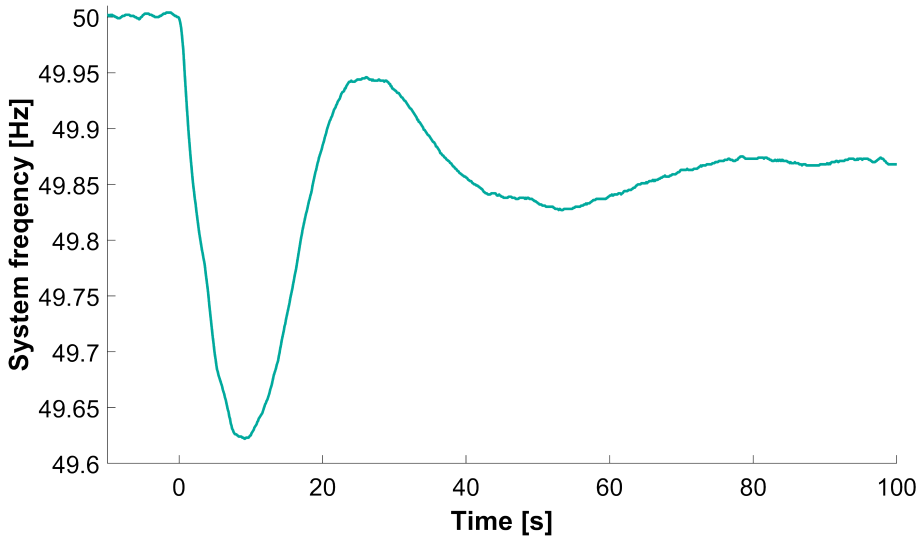

Figure 7.3: *Frequency response of the outage for Ringhals Block 4 of 1110 MW on 2015-03-05.*

In figure 7.3, it can be seen that the 1110 MW outage results in a frequency deviation reaching 49.622 Hz in 9.2 seconds. In order to replicate this behavior, a sensitivity analysis was performed which resulted in $H = 7$ s and the governor parameters shown in table 7.1 below.

Table 7.1: *Parameters for the governor used for frequency response simulation.*

Description	Variable	Value	Unit
Temporary droop	r	1.6	pu
Governor Time Constant	T_r	2	s
Filter Time Constant	T_f	0.1	s
Servo Time Constant	T_g	1.8	s
Water Starting Time	T_w	3.15	s
Turbine Gain	A_t	0.65	pu
No Load Flow	Q_{nl}	0	pu
Permanent Droop	R	0.22	pu
Minimum Gate Limit	G_{min}	0	pu
Maximum Gate Limit	G_{max}	1	pu
Gate Velocity Limit	V_{elm}	0.1	pu

The battery could potentially reduce the lowest value of the frequency response (nadir). Therefore it's important to represent the first frequency response of the network. The comparison is shown in figure 7.4, the data for the actual frequency response was acquired from [46].

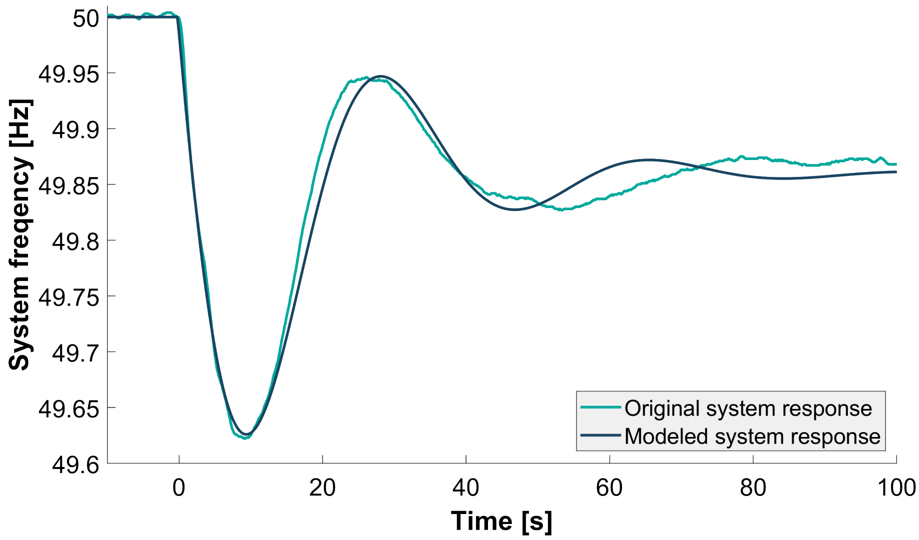

Figure 7.4: *Frequency response comparison of the model in DIgSILENT PowerFactory and the outage of 1110 MW on 05-03-2015.*

As shown in figure 7.4, the modeled frequency response has similar tendencies. The model reached the nadir at 49.625 Hz in 9.35 seconds which is almost the same as the original system frequency response. However, only the first frequency deviation has such low margins of error. The system oscillates faster than the original case and hence it recovers faster.

The model response comparison presented in figure 7.4 is not a perfect model. But considering that the synchronous generator is an aggregated model of the generators in the whole Nordic power system. The representation of the first frequency deviation is the most important part for this study to replicate, the resulting model behavior is considered adequate for this thesis.

7.2 Modeling the Battery Energy Storage System

A Battery Energy Storage System (BESS) is composed of three parts. Firstly there is the battery itself which can store energy through an electrochemical process. Secondly, there is the bidirectional inverter which is generally based on a Voltage Source inverter (VSI) with PWM [47]. Lastly, there is the control system which regulates the power flow and controls how the BESS should operate.

The BESS model is written in DIgSILENT Simulation Language (DSL) and consists of a Battery Model, a PWM inverter model, control models, as well as some measurement points. The control models are a Frequency Control, a Power Controller, and a Charge Controller. Lastly, there are measurement points that measure the frequency-, the power- and the voltage at the external busbar. This model is all presented in figure 7.5.

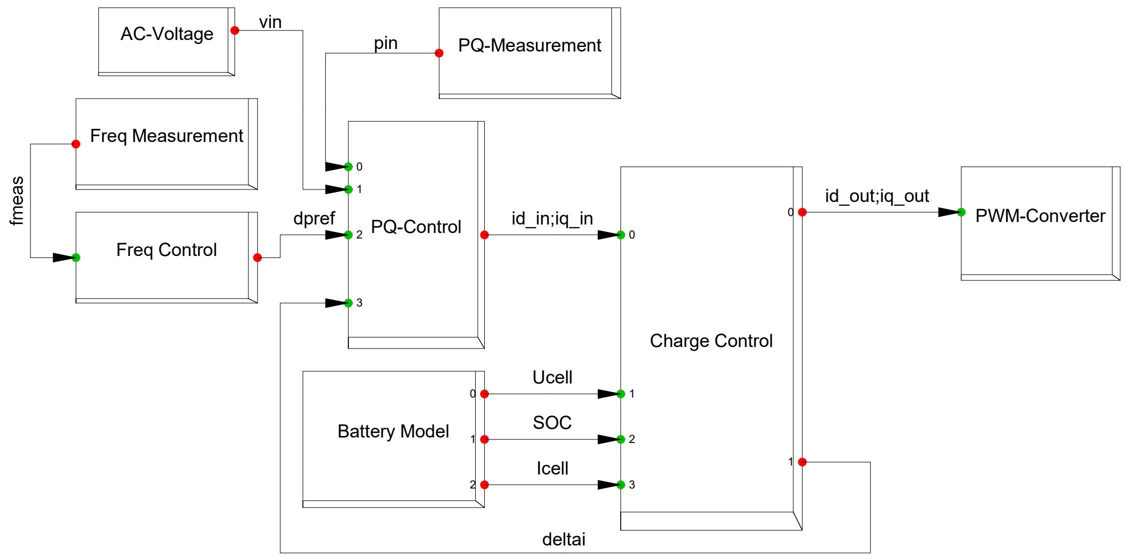

Figure 7.5: *Overview of the control system for the BESS model provided by DIgSILENT PowerFactory in [40].*

7.2.1 Battery model

When building a battery model there are usually two main difficulties. The first is to get a model that is accurate enough but not too complex. The second is to get realistic parameters for the model, either from a manufacturer or from your own experiments. The first problem is usually solved by using an equivalent electrical circuit as a battery model, this has a reasonable accuracy (95% - 99%) while keeping the computational effort low [47].

A battery model should represent the internal voltage as well as the internal resistance, which is a function of internal variables such as the SOC, C-rate, degradation, and temperature. The model used in DIgSILENT PowerFactory depicts this in a quite simple way by using the circuit presented in figure 7.6.

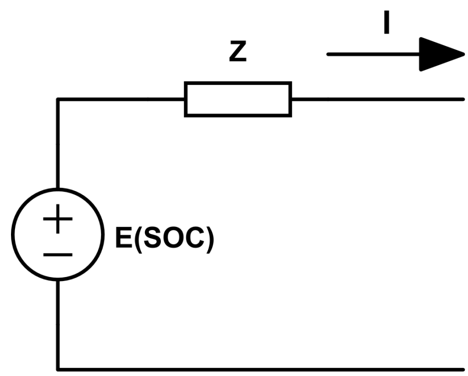

Figure 7.6: *Equivalent circuit of the battery used in the DIgSILENT PowerFactory model.*

In the model used in DIgSILENT PowerFactory it's assumed that the voltage is linearly dependant on the SOC. This is a dangerous assumption to make since the voltage is not linear throughout the whole range of 0 % to 100 %, which can be seen in figure 3.2. However, the battery used in this project only charges between 10 % to 90 %, therefore it's a more reasonable and accurate assumption to make. The impedance is also assumed to be constant because it's quite small compared to the high currents in the BESS.

In order to determine the SOC of the battery, the method of Coulumb counting is used. This is done by an integrator module which counts the input and output current and can thereby determine the relative change of SOC. In order to do so, an initial SOC needs to be set. When the SOC is known the terminal DC voltage can be calculated, this is presented in equation (7.1).

$$U_{term} = U_{max} \cdot SOC + U_{min} \cdot (1 - SOC) - I \cdot Z \tag{7.1}$$

7.2.2 PWM inverter model

The model represents a two-level voltage source inverter as an interface for the BESS to the grid and it converts the AC power to DC power and vice versa through fast switching of the IGBT valves. An overview of the PWM inverter can be seen in figure 7.7.

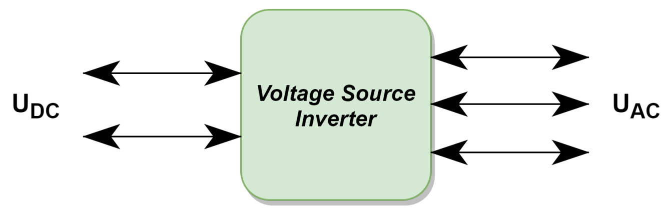

Figure 7.7: *Overview of the VSI used in the model in DIgSILENT PowerFactory.*

The control system of the inverter will generate a switching signal, which is called the amplification factor or modulation index P_m [40], [48], this makes the output voltage controllable. The definition of P_m can be seen in equation (7.2).

$$P_m = \sqrt{P_{mr}^2 + P_{mi}^2} \tag{7.2}$$

Where P_{mr} and P_{mi} are the real and imaginary part of the modulation index P_m respectively. The main objective of this model is to maintain the stability of the power system in terms of frequency and voltage, hence the equivalent model of the PWM inverter in the BESS model is a fundamental frequency model. This model operates in a stator voltage-oriented reference frame where the AC voltage can be represented as d-axis component and q-axis component. The relation between the AC voltage components U_{ACq} and U_{ACd}, and the DC voltage U_{DC} can be seen in equation (7.3) and (7.4) [48].

$$U_{ACd} = \frac{\sqrt{3}}{2\sqrt{2}} \cdot P_{mr} \cdot U_{DC} \tag{7.3}$$

$$U_{ACq} = \frac{\sqrt{3}}{2\sqrt{2}} \cdot P_{mi} \cdot U_{DC} \tag{7.4}$$

Where U_{ACq} is the imaginary part of the AC voltage and U_{ACd} is the real part of the AC voltage, and P_{mr}, P_{mi} are the real and imaginary part of the modulation index P_m respectively.

As long as the PWM inverter is operating in the linear modulation range $P_m \leq 1$, the equations (7.3) and (7.4) are valid. When the PWM inverter operating in a non-linear range ie. $P_m > 1$ problems with harmonics will arise. So to avoid that from occurrence the DC voltage should be always higher than a certain value according to equation (7.5) [40].

$$U_{DC} \geq \frac{2\sqrt{2}}{\sqrt{3}} \cdot U_{AC} \tag{7.5}$$

Moreover, in regards to the current, the id_{ref} and iq_{ref} are used as a representation for the current phasor of the inverter transformed in a dq-reference frame. Where the id_{ref} represents the active power and the iq_{ref} represents the reactive power of the PWM inverter. An advantage for such representation is the ease of applying a control for the BESS [40]. To generate the actual signal for the modulation index the provided model uses an internal current controller [40].

7.2.3 Frequency controller

The model of the frequency controller is shown in figure 7.8 and it consists of a proportional controller (droop) together with a deadband.

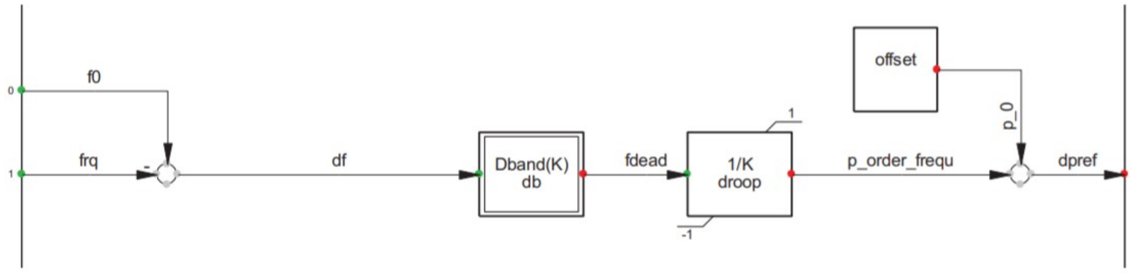

Figure 7.8: *The Frequency Controller used in DIgSILENT PowerFactory [40]. The red nodes are outputs and the green nodes are inputs, which are not connected in parallel.*

The droop controller decides how much active power should be provided in case of frequency deviation in the network. The frequency droop coefficient can be calculated according to equation (7.6).

$$R_{\text{droop}} = \frac{1}{K_{\text{droop}}} = \frac{f_{\text{ref}} - f_{\text{meas}}}{P - P_{\text{ref}}} = \frac{\Delta f}{\Delta P} \tag{7.6}$$

The parameter R_{droop} decides the amount of active power that should be provided or absorbed by the BESS to help mitigate the frequency deviation in the electrical network [47].The value of droop coefficient R_{droop} should be evaluated to meet the grid code requirements [40].

The dead-band represents the less sensitive region for the frequency deviation in the grid, where it is allowed for frequency to deviate in certain limits usually between 0.02 and 0.05 Hz [47]. The Offset block function is to indemnify "dpref" if the value of that signal is not zero after the load flow because the signal "p_order_frequ" is always zero after the initialization of the network [40].

The outcome from this control is an active power change signal "dpref" to the PQ controller. So when the frequency deviates above 50 Hz the output is negative and thus the battery system will initiate a charging process, and if the frequency deviates less than 50 Hz the output will be positive and the battery will start the discharging process.

7.2.4 PQ controller

The PQ controller consist of active power control and reactive power control. The upper branch in figure 7.9 represents the active power control which generates the d-axis reference current id_{ref} [40].

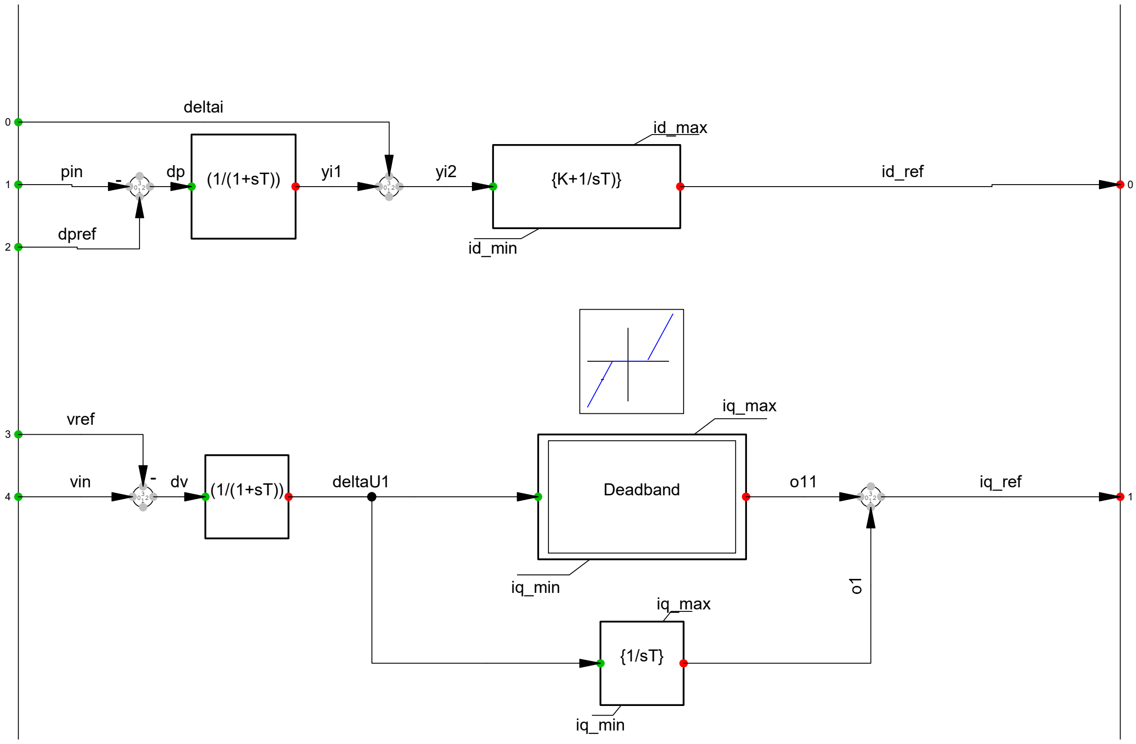

Figure 7.9: *The PQ-Controller used in DIgSILENT PowerFactory [40]. The red nodes are outputs and the green nodes are inputs, which are not connected in parallel.*

The input signals for this control is "dpref" which is the active power change signal to provide frequency support, "pin" which is the measured active power control as well as the "deltai". The "deltai" signal comes from the charge controller as it can be seen in figure 7.10, this signal prevents the PI controller from winding up whenever the "id_ref" (reference current) exceeds the limits [47]. The low pass filter is used for two reasons first, to take out the measurement noise and to set a limit for the active power rate of change.

The lower part in figure 7.9 represents the reactive power control which generates the q-axis current. The input signals for this controller are "vref" which is the voltage reference, and "vin" which is the measured voltage. The resulting signal is then processed through the low pass filter to obstruct the fast transients and for noise elimination. This controller has a slope with deadband acting as proportional control for voltage supporting and an integrating controller for set point tracing [40].

The output of the control loop is the signals "iq_ref" and "id_ref" which will be an input to the charge controller.

7.2.5 Charging controller

In the charging controller, there are two different components. The first component is the current limiter which prevents overcurrent of the battery. The second is the actual charging controller where all the logic is placed. Here there are four parameters used as well as two inputs. The parameters are the minimum charging current, the maximum- and minimum SOC, and the maximum absolute current [40]. These parameters and the two inputs inputs "Id_ref_in" and SOC, combined with the logic in the charging controller determines if the battery should charge or discharge and what the current should be. The full scheme can be seen in figure 7.10 below.

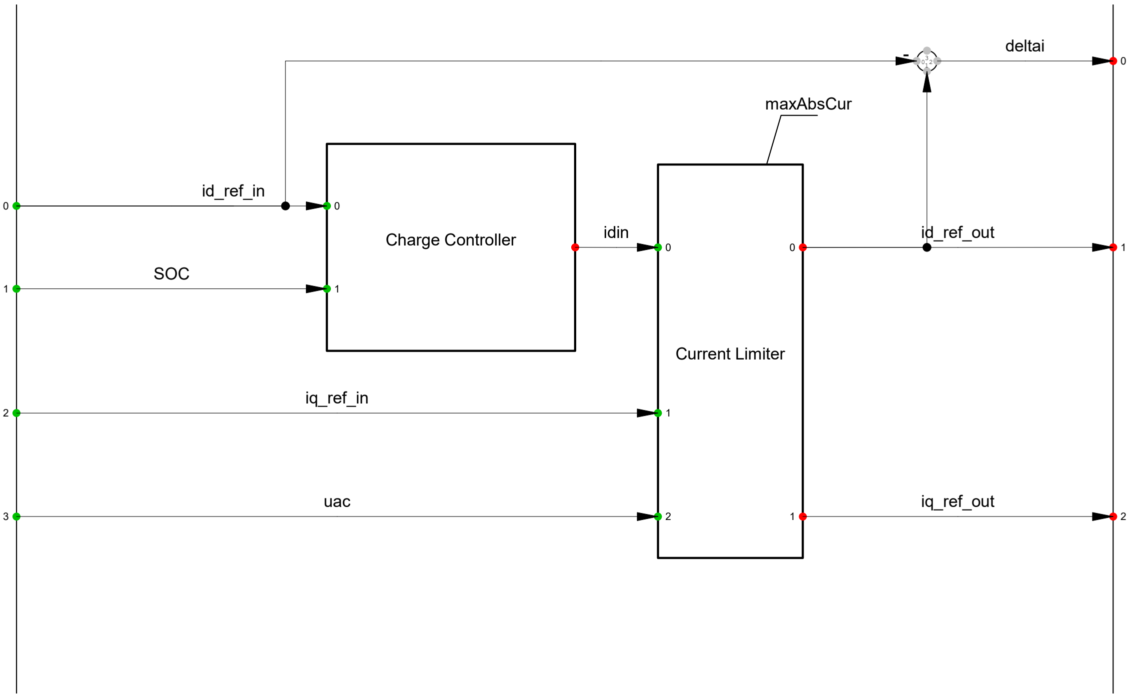

Figure 7.10: *The charging controller used in DIgSILENT PowerFactory [40]. The red nodes are outputs and the green nodes are inputs, which are not connected in parallel.*

The logic implemented in the charging controller is quite simple. First the current is calculated based on the value of "Id_ref_in". Then there is logic which compares the value of the SOC and "Id_ref_in" in order to determine of the BESS should charge or discharge. Lastly the output of the charge controller logic is set.

7.3 Implementation of a power controller for peak shifting

The maximum available power P_{max} in Gothenburg and Kiel is 4 MW and 5 MW respectively. An approach is to measure the power at the external grid, and then calculate if the power is higher than the available power. If the power from the external grid is higher than the available power then the BESS can deliver the differential power. In order to implement this, the Frequency Controller was replaced with a Power Controller, which can be seen in figure 7.11.

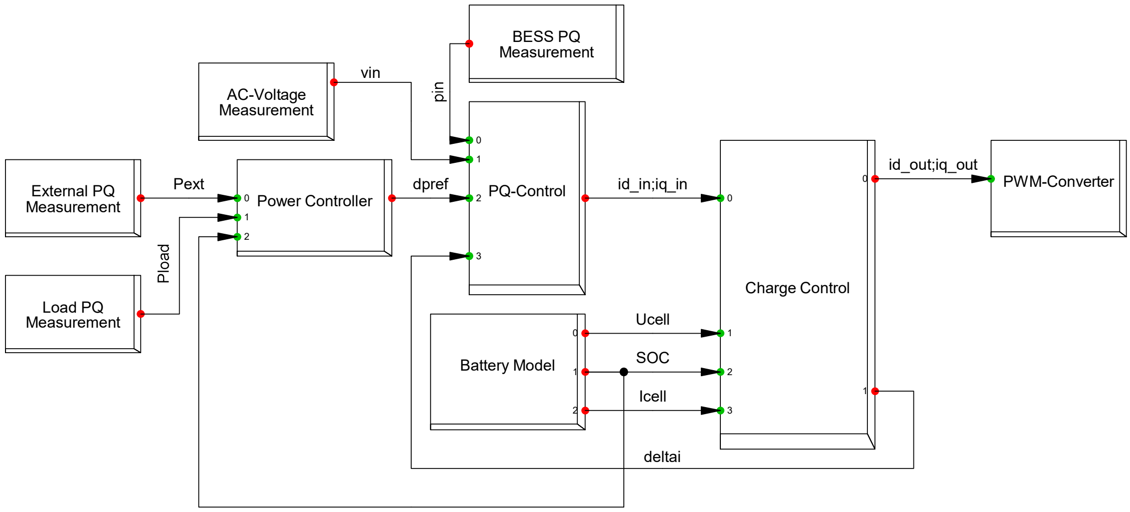

Figure 7.11: *The modified model in DIgSILENT PowerFactory.*

Inside the Power Controller, logic was implemented in order to decide if there was a ship at quay needing charging or if the BESS itself needed charging. This logic required some measurement signals: the power from the external grid P_{grid}, power drawn from the loads P_{load}, maximum available power P_{max}, the rated power of the inverter P_{rated}, and the SOC of the battery.

The logic implemented is based on 3 simple steps. Firstly a variable is declared with a value of 0, if the power drawn from the external grid is higher than the maximum power available, this variable will be set to 1. This variable is fed into the S input of an RS flip-flop with $R = 0$ permanently, so the output of this flip-flop can only be set to 1 and never be reset to 0 afterwards. The output of this flip-flop determines if there is a ship at quay needing charging.

If the output of the flip-flop is 1 and the power consumed by the loads is higher than the maximum power, then the BESS will supply the diffracting power. But if the power consumed is lower than the maximum power, and the output of the flip-flop is 1, then the ship has left the quay. Then, if the SOC < 90 %, the BESS should start charging up to 90 % SOC again. The power, that the BESS is charged with, is the maximum power available from the grid.

8

Simulating the implementation of the BESS model

The BESS and grid model described in chapter 7 was utilized in order to conduct a set of simulations described in chapter 5. These simulations were chosen in order to evaluate the potential benefit of a BESS in the power system.

8.1 Peak shifting

The results from the 2-G simulation of peak shifting are shown in figure 8.1. Here, a ship with a 50 MWh battery arrives, and after 5 minutes the ship is connected and starts charging.

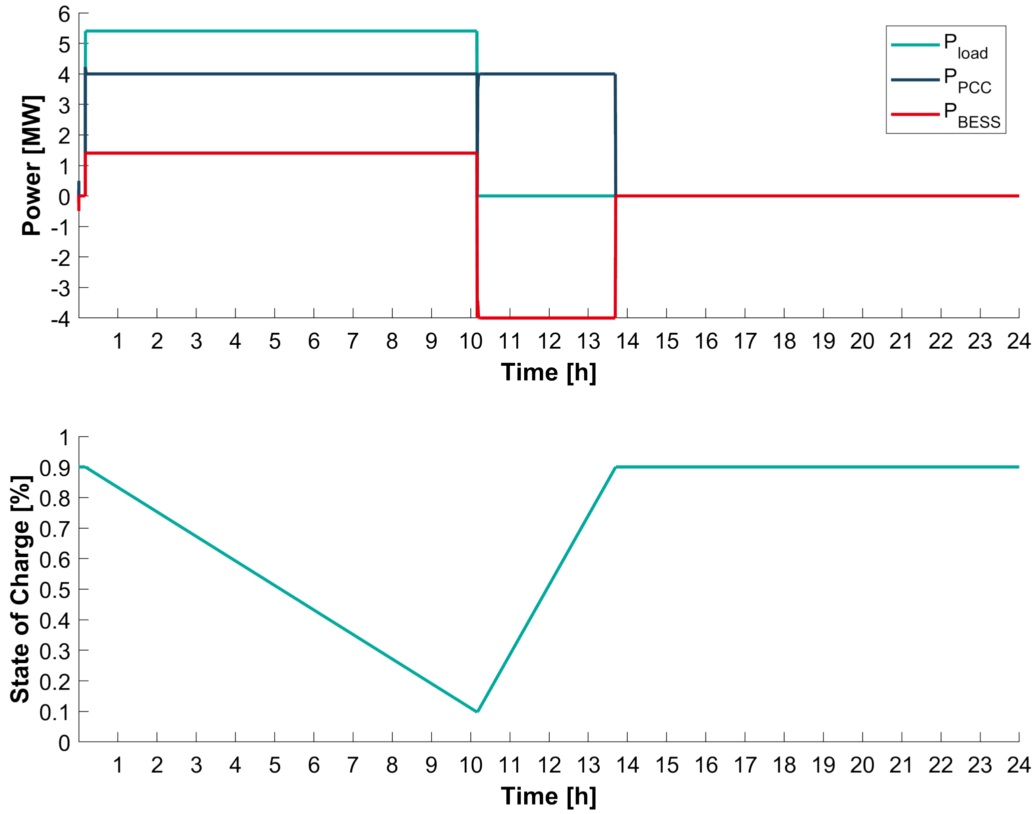

Figure 8.1: *Charging cycle of the ship and BESS for the case of 2-G. The power P_{load} is the power drawn from the charging ship, P_{PCC} is the power drawn from the grid in the PCC, and P_{BESS} is the power delivered from the BESS.*

As presented in figure 8.1, the BESS supports the grid with 1.4 MW of power. The BESS successfully supplies the missing power in order to not overload the grid. After 10 hours, when the ship is fully charged, the resulting SOC of the BESS is 9.8 %. When the ship has finished charging the BESS instantly starts charging with the maximum available power of 4 MW, it takes 3.57 hours to reach 90 % SOC.

For the 3-G case with a 70 MWh battery on the ship, the results are presented in figure 8.2 below. Here the ship with 70 MWh battery arrives is connected for charging after 5 minutes.

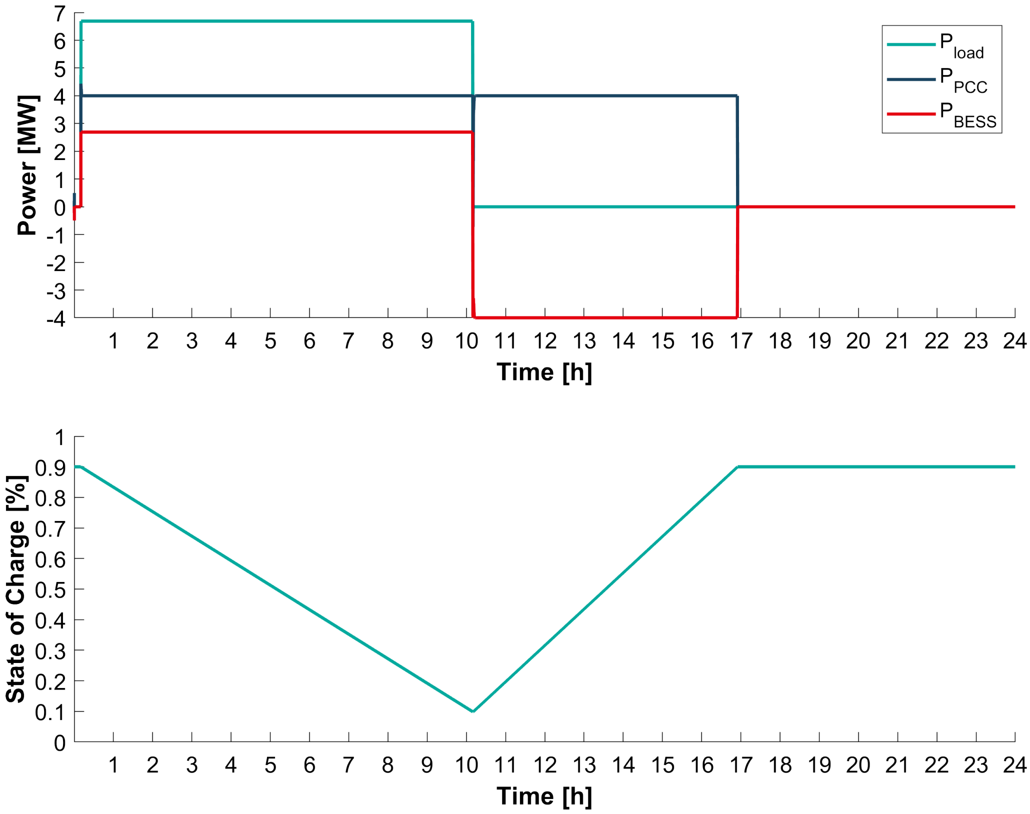

Figure 8.2: *Charging cycle of the ship and BESS for the case of 3-G. The power P_{load} is the power drawn from the charging ship, P_{PCC} is the power drawn from the grid in the PCC, and P_{BESS} is the power delivered from the BESS.*

In figure 8.2 the BESS supports the grid, limiting the power drawn from the grid. After the ship is fully charged, the remaining SOC of the BESS is 9.8 %. The BESS then charges to 90 % SOC again in 6.77 hours.

For the case of 2-K, the results are presented in figure 8.3. In this case, the ship with a 50 MWh battery arrives and starts charging after 5 minutes.

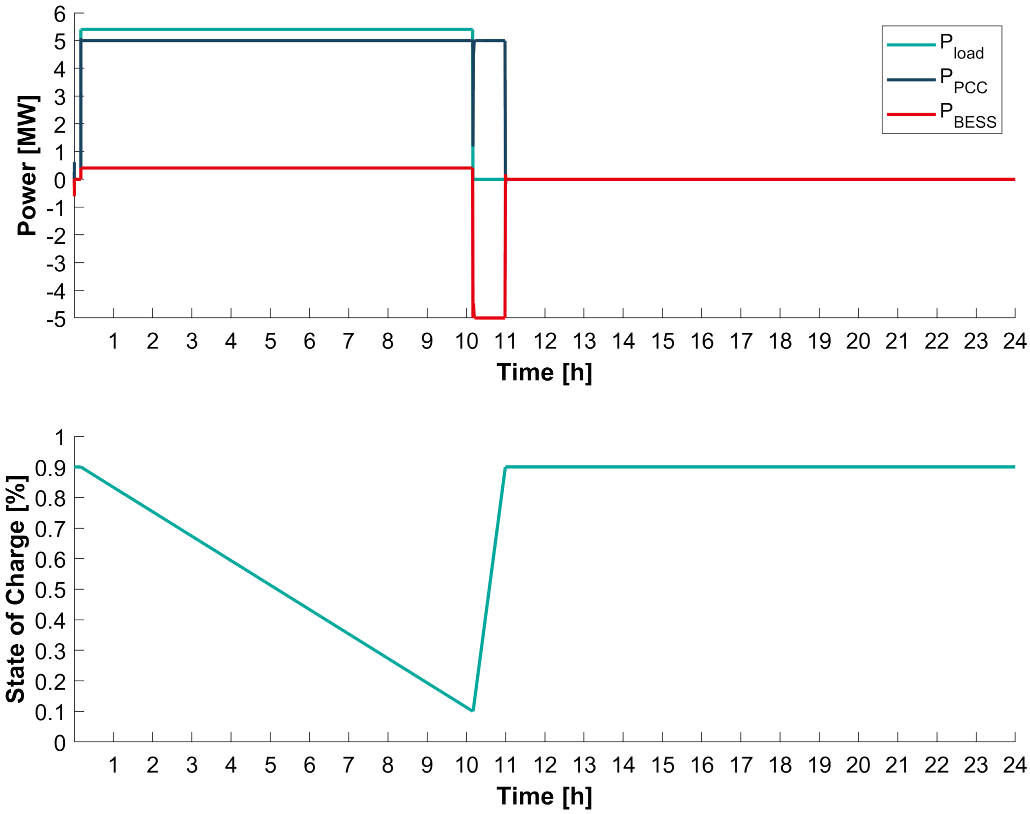

Figure 8.3: *Charging cycle of the ship and BESS for the case of 2-K. The power* P_{load} *is the power drawn from the charging ship,* P_{PCC} *is the power drawn from the grid in the PCC, and* P_{BESS} *is the power delivered from the BESS.*

As seen in figure 8.3 the BESS supports the grid, limiting the power drawn from the grid to 5 MW. In Kiel, the maximum available power is 1 MW higher than in Gothenburg. Hence, when the ship arrives the power needed from the BESS is less than for the 2-G case. After 10 hours the BESS SOC is 10.0 %. The BESS starts charging with the maximum power of 5 MW and charges to 90 % SOC in 0.83 hours.

The results from the 3-K simulation of peak shifting are presented in figure 8.4. The ship with the 70 MWh battery arrives and after 5 minutes the ship is connected and starts charging.

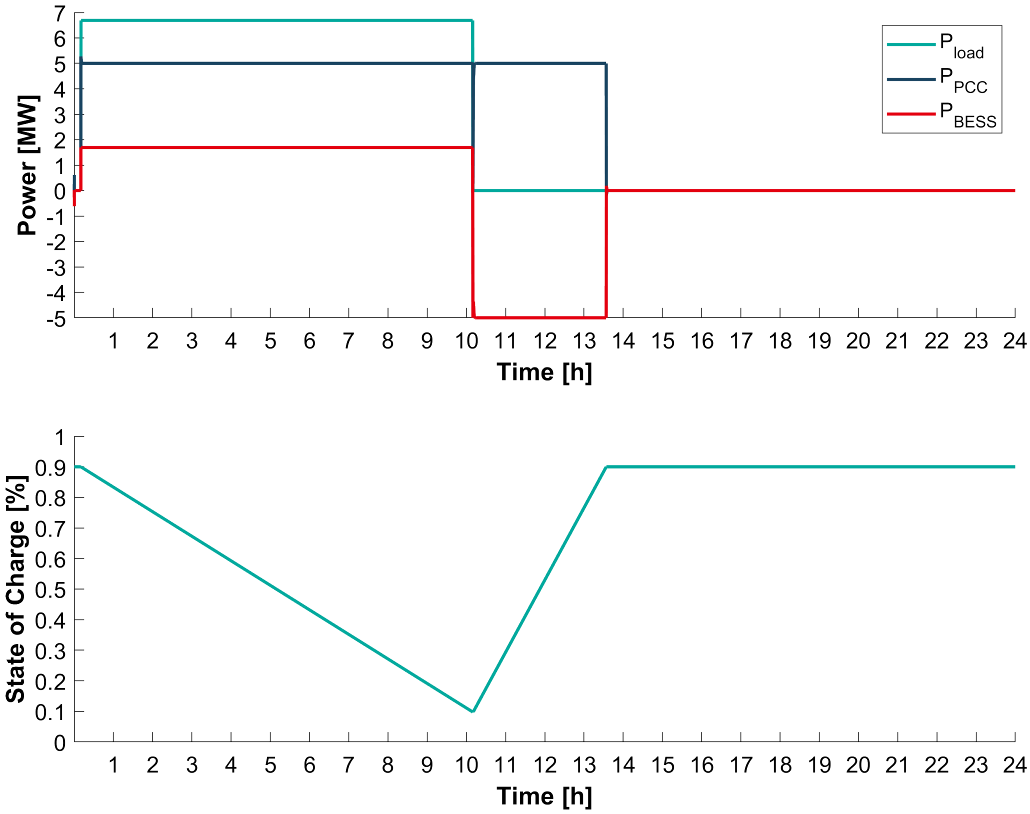

Figure 8.4: *Charging cycle of the ship and BESS for the case of 3-K. The power P_{load} is the power drawn from the charging ship, P_{PCC} is the power drawn from the grid in the PCC, and P_{BESS} is the power delivered from the BESS.*

In figure 8.4 the BESS supports the grid, limiting the power drawn from the grid. When the 70 MWh battery on the ship is charged to full the SOC of the BESS is 9.9 %. The BESS charges to 90 % SOC in 3.43 hours.

8.2 System frequency stability

In this section, the BESS is used to support the system frequency. First, the BESS is operating in the FFR market in the Nordic power system. Thereafter, simulations of operation in the FCR-N and FCR-D market are conducted. Lastly, operations in the FCR market in the Continental European power system are simulated.

8.2.1 Operation within the FFR market in the Nordic power system

In this simulation, the fast-acting battery is simulated in the FFR market. The scenario of the outage of Ringhals Block 4 will be used, therefore, the alternative operation "C" is chosen from table 4.1. The reason for this is that the frequency nadir is 49.625 Hz in the scenario of the outage of Ringhals Block 4, so only operation alternative "C" will require the BESS to activate in the FFR market. Therefore, 100 % of the active power must be delivered within 1.3 seconds when the frequency deviates to 49.7 Hz. At 0 seconds Ringhals Block 4 is disconnected and 1110 MW of generation is lost in the Nordic power system. The results from this simulation are presented in figure 8.5.

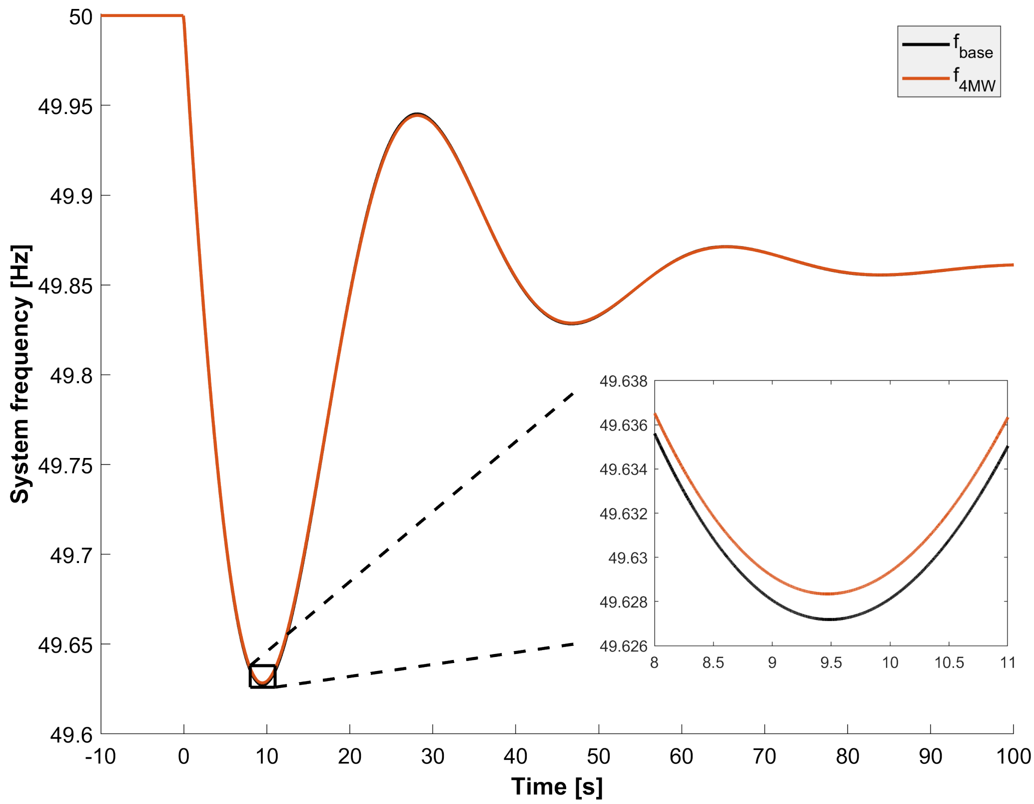

Figure 8.5: *Results for a frequency deviation when the BESS is operating in the FFR market, with 4 MW rated grid connection interface. The alternative operation "C" in the Nordic power system as chosen.*

As depicted in figure 8.5, the BESS is able to improve the nadir during the frequency deviation. The nadir is improved with 1.2 mHz according to the simulation. The power output from the BESS is presented in figure 8.6.

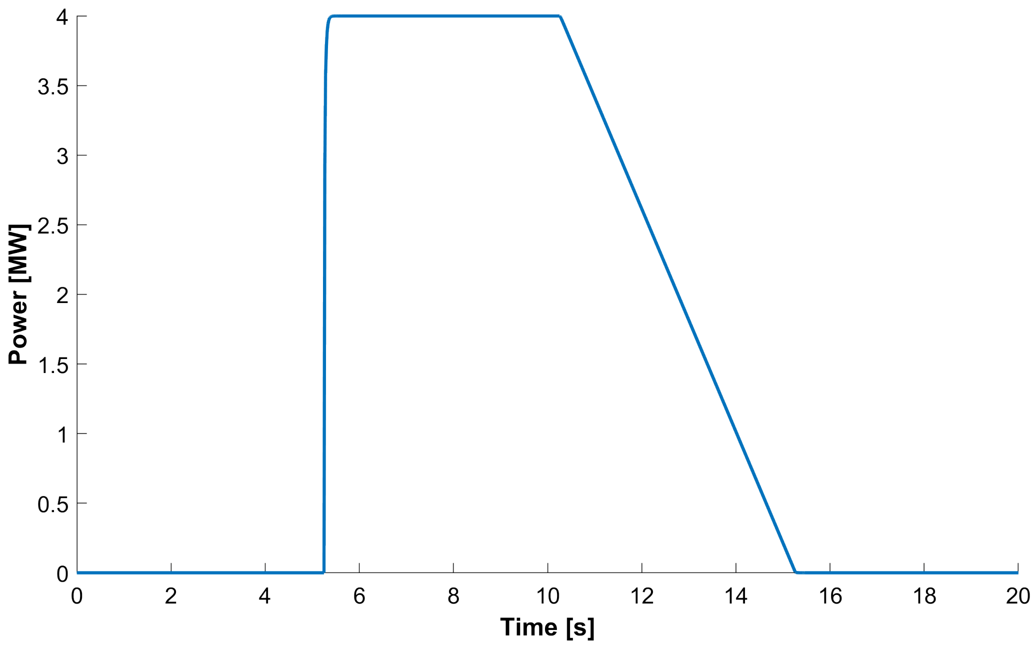

Figure 8.6: *The resulting output power of the BESS during the frequency deviation when operating in the FFR market in the Nordic power system, with 4 MW rated grid connection*

The output power presented in figure 8.6 shows that when the frequency drops to 49.7 Hz after 5.25 seconds, the BESS starts injecting active power. The response of the BESS is within the time limit of 1.3 seconds since the BESS delivers 100 % active power within 200 ms according to figure 8.6. Since the control system of the BESS is able to reduce the power with 20 %/s an activation period of 5 seconds was chosen. 15.29 seconds after the trip of Ringhals Block 4 the power output of the BESS reaches 0 MW again.

8.2.2 Operation within the FCR-N market in the Nordic power system

In order to simulate the operation of the BESS in the FCR-N market, the operating time frame must be known. Since the charging power of the BESS is the same for different battery sizes, the time to charge the BESS to 50 % will not be constant. Hence, the starting time when the BESS is ready to provide ancillary services will change. By studying the results in section 8.1 the charging times and the time left to provide FCR-N can be calculated. This is presented in table 8.1 below.

Table 8.1: *Time table for the FCR-N simulations. The parameters were based on simulations in section 8.1.*

Description	**2-G**	**3-G**	**Unit**
Time to charge from 10 % to 50 %	1.80	3.41	hours
Time left for ancillary services	12	10.45	hours

In order to simulate the BESS operating in the FCR-N market, data was used from [46]. The frequency samples used were collected during the night, when the ship is not berthed, between 09-01-2021 and 10-01-2021. The time when the BESS should stop providing FCR-N is computed and is marked by an orange line. The results from the first FCR-N simulation, the case of 2-G, are presented in figure 8.7 below.

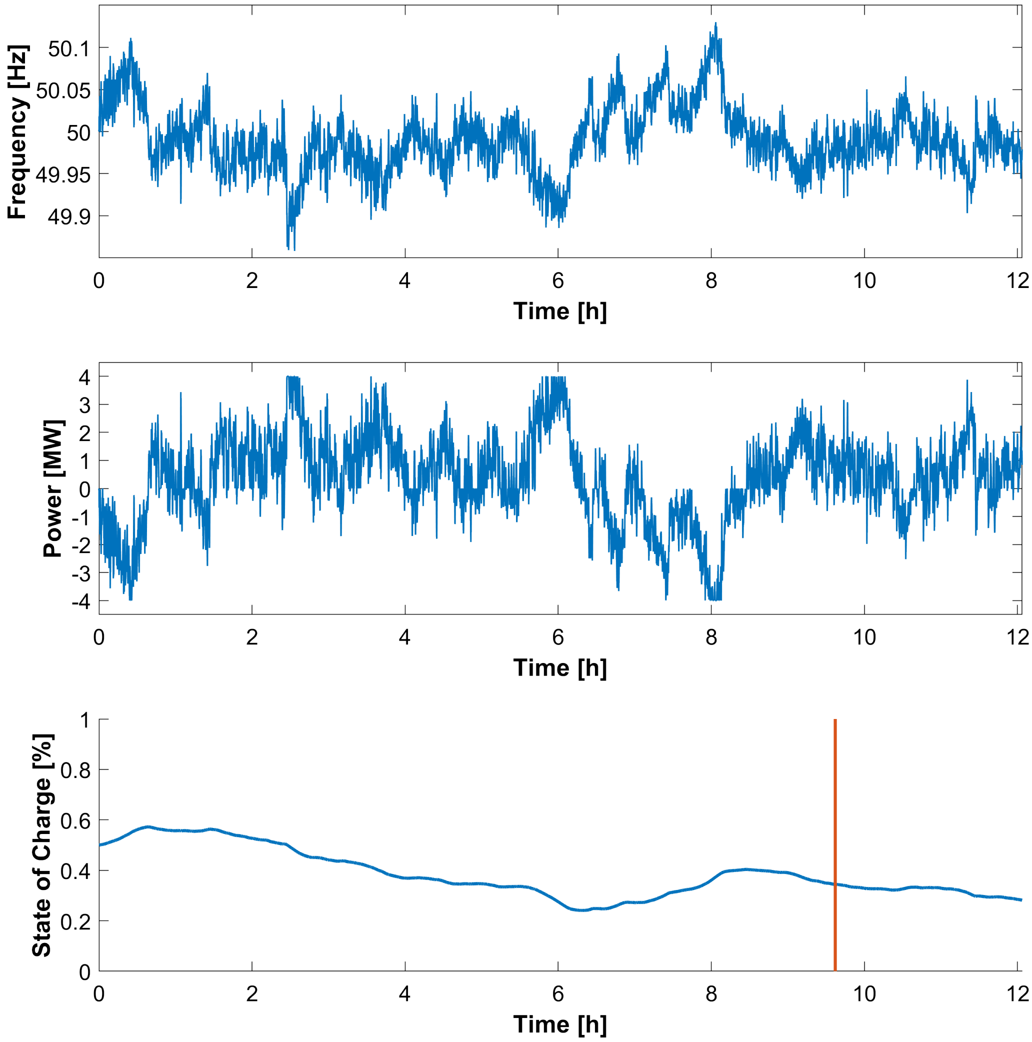

Figure 8.7: *Simulation of the BESS with a 18 MWh battery size operating with in the FCR-N market for 12.06 hours. The orange line is the time when the BESS should stop providing FCR-N in order to have time to fully charge to 90 % before the ship arrives at quay.*

As illustrated in figure 8.7, the battery charging and discharging process is dependent on the system frequency deviations. The battery is in charging mode when the system frequency is deviating above 50 Hz, and in discharging mode when the system frequency deviating below 50 Hz. During this time period, it can be seen that the average frequency is lower than 50 Hz since the SOC has a declining trend. The BESS can operate for 9.62 hours until it needs to be stopped for recharging.

For the case of 3-G, the time when the BESS can provide FCR-N is much less than for the case of 2-G. The reason for this is that the BESS takes a much longer time to charge to 50 % SOC. Hence, the BESS will start providing FCR-N later than for case 2-G. The results of the FCR-N simulation for case 3-G are presented in figure 8.8.

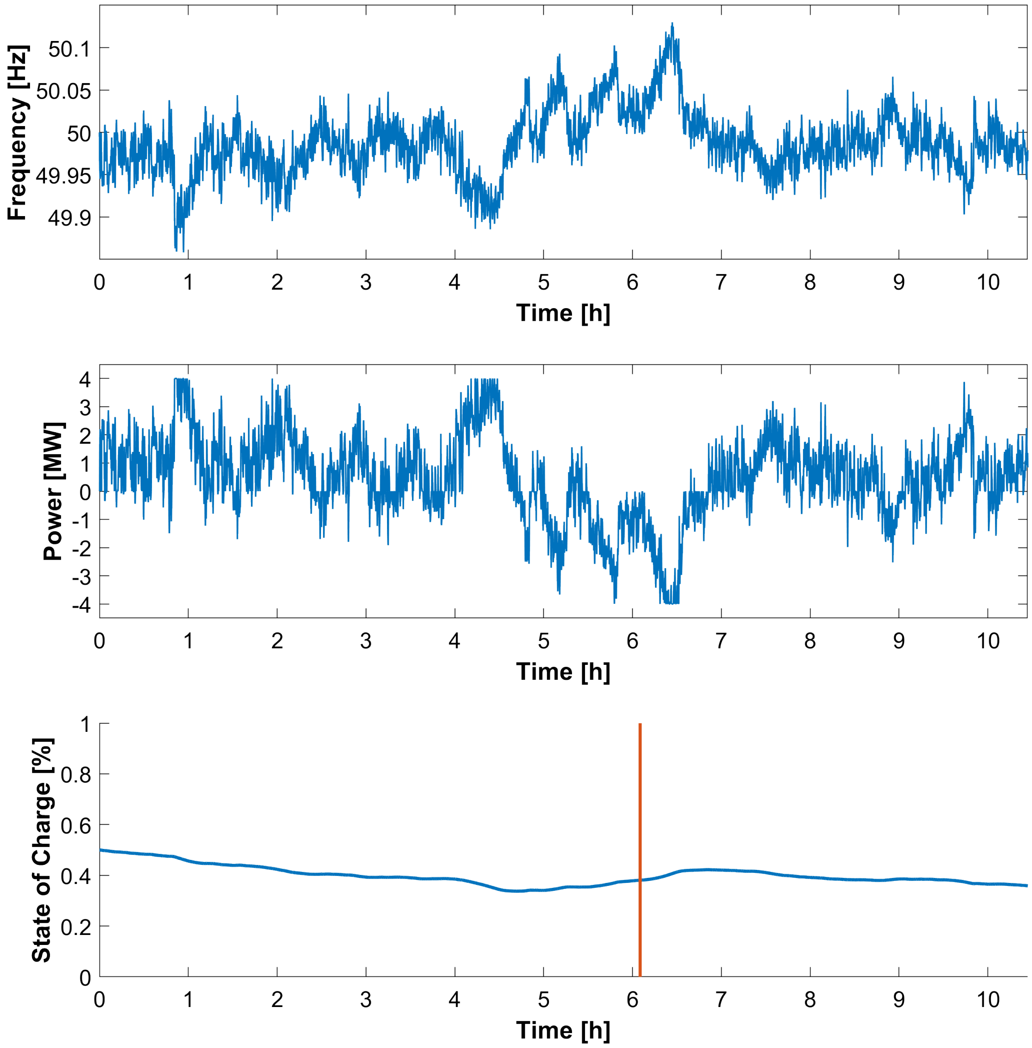

Figure 8.8: *Simulation of the BESS with a 34 MWh battery size operating with in the FCR-N market for 10.45 hours. The orange line is the time when the BESS should stop providing FCR-N in order to have time to fully charge to 90 % before the ship arrives at quay.*

As seen in figure 8.8, the operation time of the BESS is much shorter. But the behavior of the BESS charging- and discharging process is the same as for case 2-G. However, the SOC profile is much flatter because the capacity of the 3-G BESS is higher. The BESS is also only able to provide FCR-N for 6.08 hours, which is significantly less than for the case of 2-G.

8.2.3 Operation within the FCR-D market in the Nordic power system

In this case, the BESS will supply FCR-D regulation in order to improve the system frequency during a disruptive event. In order to do so, there needs to be sufficient capacity in order to provide the contracted power for 20 minutes according to [28]. Therefore, the BESS needs to charge for 20 minutes before it can provide FCR-D. Leaving the BESS available for FCR-D support for a total of 13.58 hours for all BESS sizes. In this simulation, 1110 MW from Ringhals Block 4 is disconnected at time 0 seconds and the frequency response is measured for 100 seconds. The results from the simulation are presented in figure 8.9.

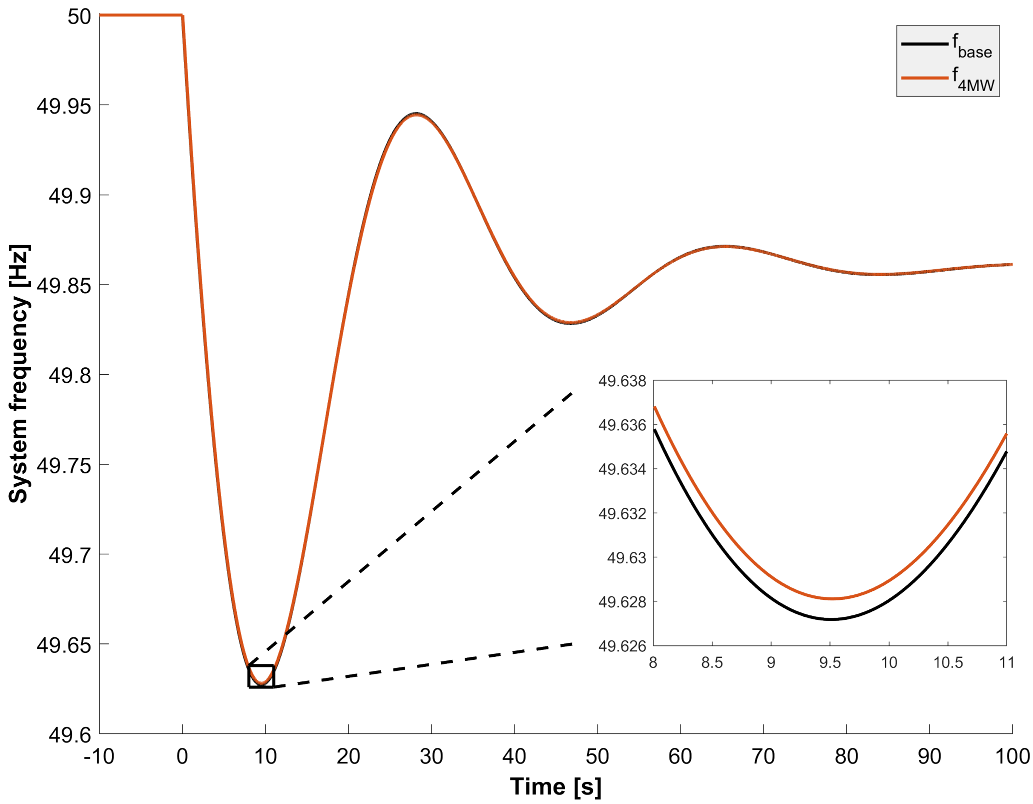

Figure 8.9: *Results for a frequency deviation when the BESS is operating in the FCR-D market, with 4 MW rated grid connection interface.*

It can be seen from figure 8.9 the BESS is able to improve the nadir during the frequency deviation. By studying the figure closely, it can be seen that the frequency improvement is 0.932 mHz higher with the BESS support power of 4 MW, compared to the base case. The reason for this small improvement is that the BESS contribution is limited to the rated output power of the grid connection interface of 4 MW. The output power from the BESS is very low compared to the total outage of Ringhals Block 4. Higher power is required in order to mitigate the frequency nadir furthermore. In figure 8.10 the output power of the converter is illustrated during the outage of Ringhals Block 4.

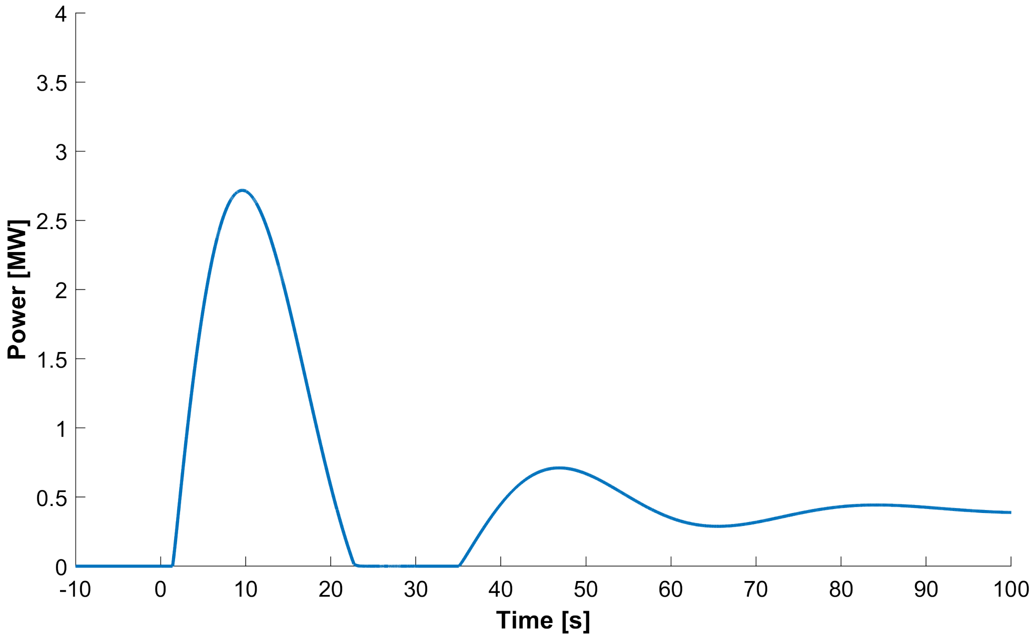

Figure 8.10: *The output power when the BESS is operating in the FCR-D market, with 4 MW rated grid connection interface.*

The output power of the BESS is increasing while the frequency decreases in accordance with the droop settings in the BESS frequency controller. During the time instant between 23-36 seconds, the frequency is above 49.9 Hz, and therefore, the output power of the converter is zero during that time period. It can be seen that the output power does not reach its maximum rated power and that is because the frequency does not drop below 49.50 Hz, which is the requirement when the output power needs to be maximum in the FCR-D market.

8.2.4 Operation within the FCR market in the Continental European power system

In this simulation study, the BESSs contribution while providing FCR service was simulated. In order to simulate the behavior of the BESS while operating in the FCR market during normal operation, the operation time frame must be known. By following the same approach in section 8.2.2, the charging times and the time left to provide FCR during normal operation can be calculated. This is presented in table 8.2 below.

Table 8.2: *Time table for the FCR simulations during normal operation. The parameters were based on simulations in section 8.1.*

Description	**2-K**	**3-K**	**Unit**
Time to charge from 10 % to 50 %	0.42	1.74	hours
Time left for ancillary services	13.42	12.12	hours

In order to simulate the BESS operating in the FCR market during normal operation, the same frequency data from section 8.2.2 was used for this study case. The time when the BESS should stop providing FCR is computed in real-time and is marked by an orange line. The results from the first FCR during normal operation simulation, the case of 2-K, are presented in figure 8.11 below.

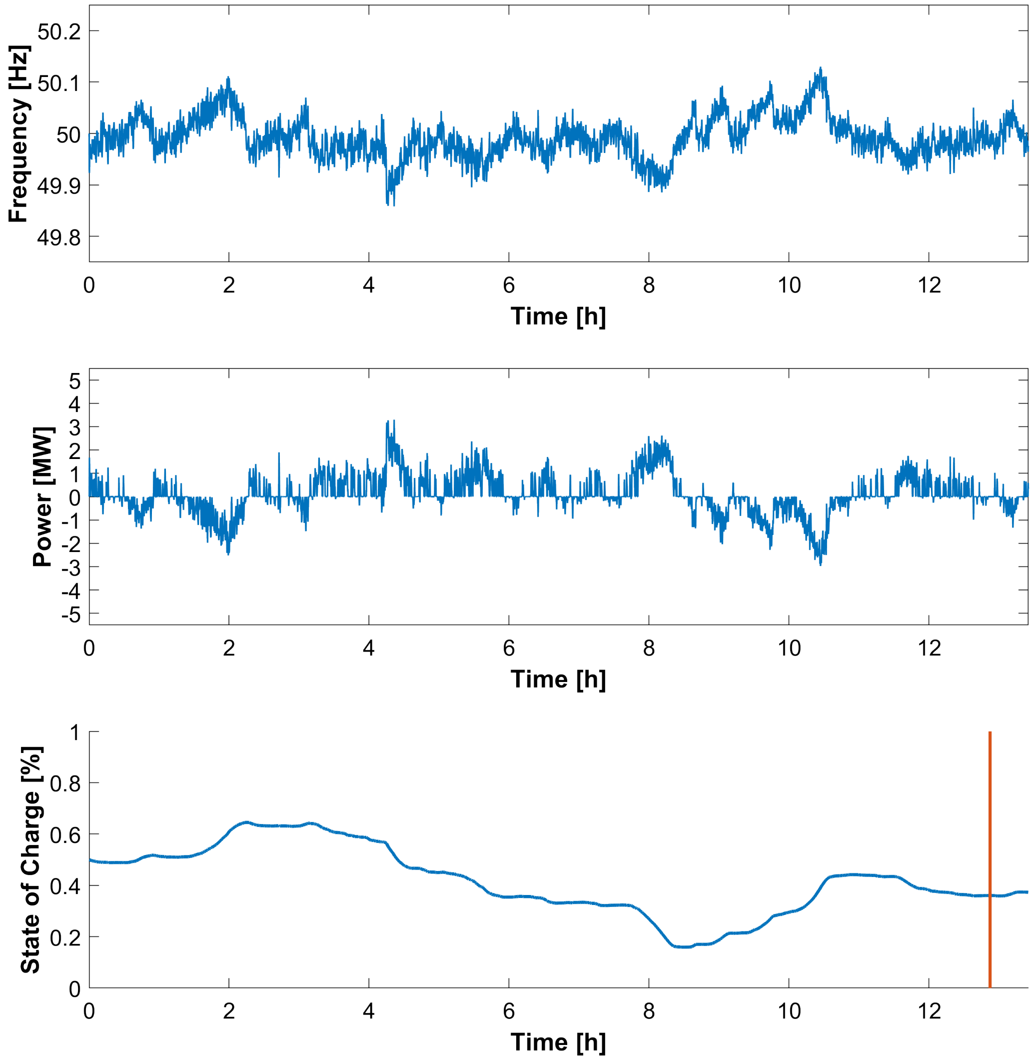

Figure 8.11: *Simulation of the BESS with a 5 MWh battery size operating with in the FCR market during normal operation for 12.88 hours. The orange line is the time when the BESS should stop providing FCR in order to have time to charge to 90 % before the ship arrives at quay.*

As illustrated in figure 8.11, the battery charging and discharging process is dependent on the system frequency deviations. According to the droop setting, the battery is in charging mode when the system frequency is deviating above 50.01 Hz, and in discharging mode when the system frequency deviating below 49.99 Hz. During this time period, it can be seen that the average frequency is lower than 50 Hz since the SOC has a declining trend. The BESS can operate for around 12.88 hours until it needs to be stopped for recharging. For the case of 3-K, the results for simulation is illustrated in figure 8.12.

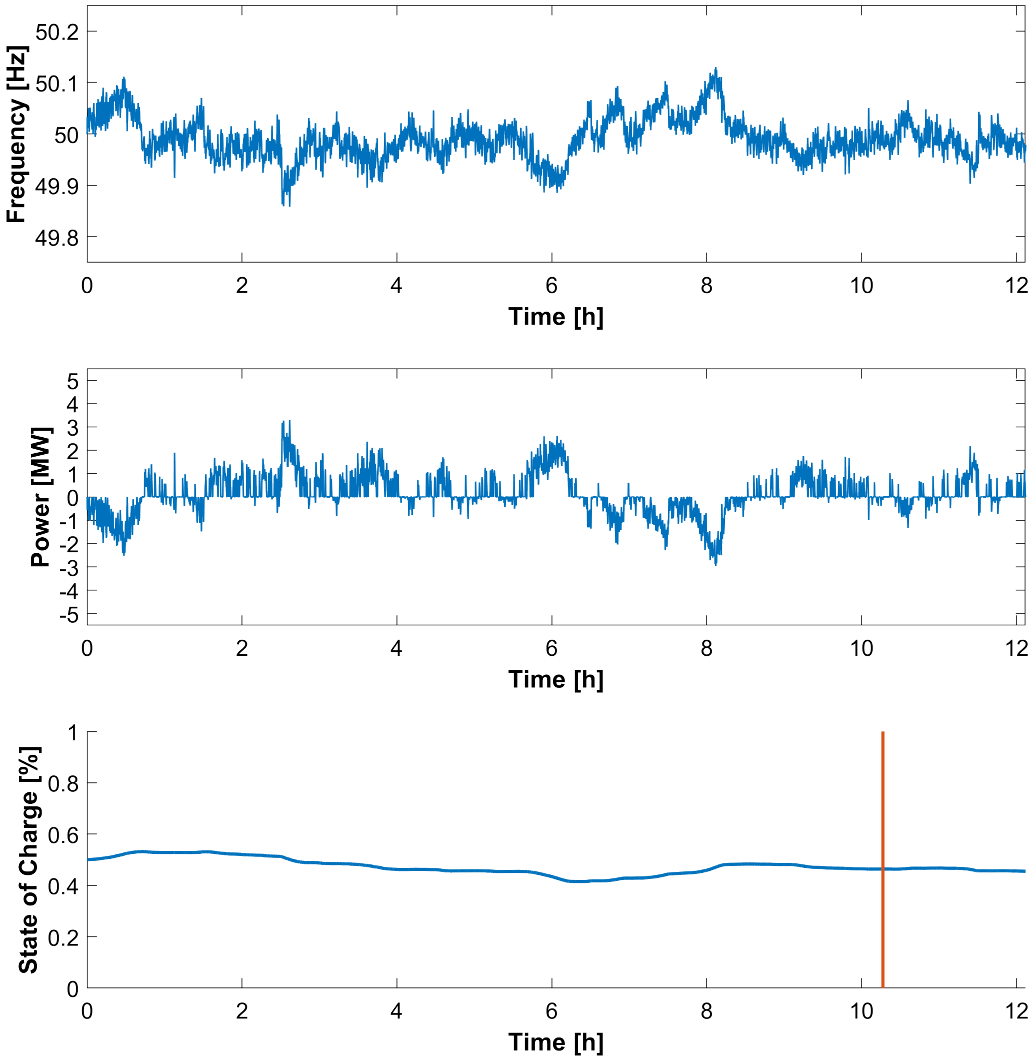

Figure 8.12: *Simulation of the BESS with a 21 MWh battery size operating with in the FCR market during normal operation for around 10.28 hours. The orange line is the time when the BESS should stop providing FCR in order to have time to fully charge to 90 % before the ship arrives at quay.*

The behavior of charging and discharging is still the same as the case for 2-K. The SOC profile for the BESS in case 3-K is much flatter than case 2-K since the BESS capacity is much higher. Moreover, the final value for the SOC is roughly the same as the initial operation SOC of 50 %. The BESS is also only able to provide FCR-N for 10.28 hours, which is less than for the case of 2-K.

The BESS was also simulated during a disruptive event. A generation power of 1110 MW was disconnected at time 0 seconds and the frequency response is measured for 100 seconds as it is illustrated in figure 8.13. The black line represents the system frequency response during the disruptive event without a BESS. The orange line represents the system frequency response with the BESS contribution of active power.

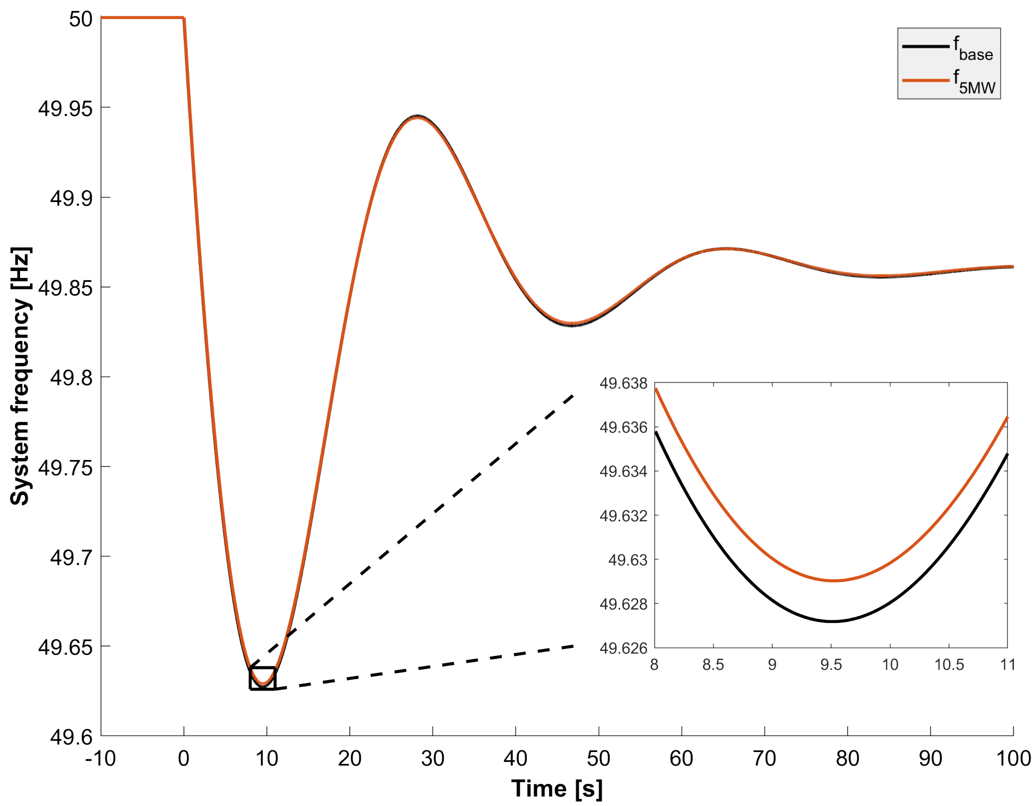

Figure 8.13: *Results for a frequency deviation when the BESS is operating in the FCR market during a frequency disturbance, with 5 MW rated grid connection interface.*

Since the output power from the BESS is relatively low compared to a loss of 1110 MW generation power, mitigation of the frequency nadir can be seen in figure 8.13. By examining the figure closely it can be seen that the frequency nadir is 1.8 mHz higher than the base case. In figure 8.14 the output power of the converter is illustrated during the disturbance.

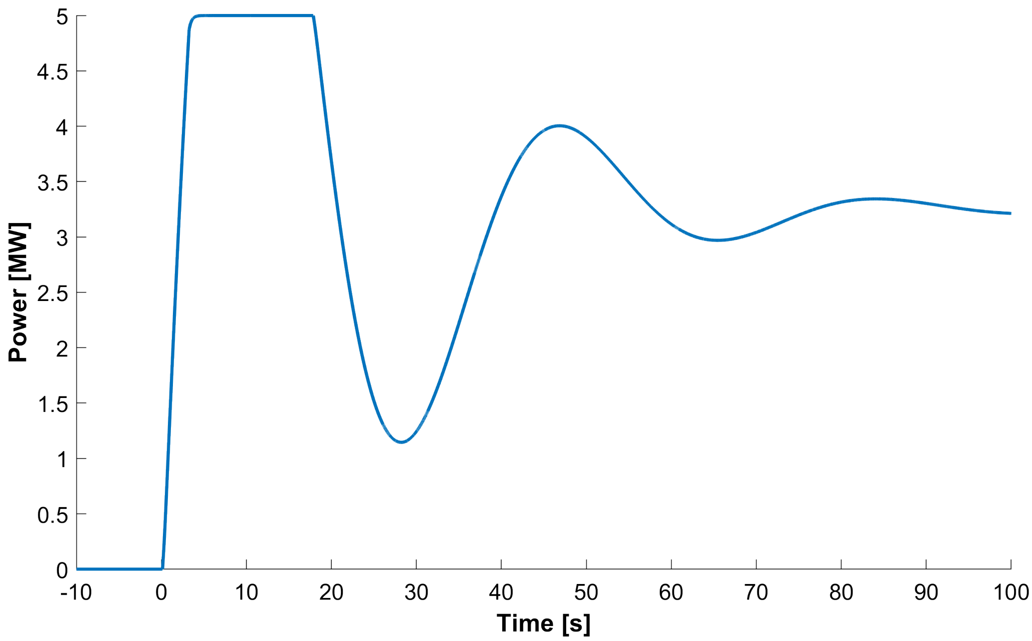

Figure 8.14: *The output power from the BESS is operating in the FCR market during a during frequency disturbance, with 5 MW rated grid connection interface*

In figure 8.14 it can be seen that the output power of the BESS is increasing while the frequency decreases in accordance with the droop settings in the BESS frequency controller. At time 3.2 seconds the frequency drops to 49.8 Hz and stays below 49.8 Hz until time 18 seconds. According to the droop settings, the output power of the converter should be maximized once the frequency deviates to 49.8 Hz. This can be observed in the figure where the converter output power is 5 MW during the time period between 3.2 and 18 seconds.

8.3 Voltage support

In this section, the potential for the BESS to provide voltage support is simulated. In this simulation, neither the size of the BESS nor the size of the battery on the ship has an effect on the voltage profile at the PCC. Since the maximum power that is allowed to be drawn at the PCC is limited to 4 MW and 5 MW in the port in Gothenburg and the port in Kiel respectively, all the extra power that is needed to charge the ship will be provided by the BESS. Therefore, the voltage drop is a result of the power drawn from the external grid, which will be the same for all the cases. Hence, case 3-G can be used to show the BESS contribution to enhancing the voltage profile at the PCC.

In this case, the electrical load of the ship and the charging of the battery on the ship starts at 0 seconds. The simulation results are recorded until the time reaches 2 seconds. The results of the voltage support simulation are presented in figure 8.15.

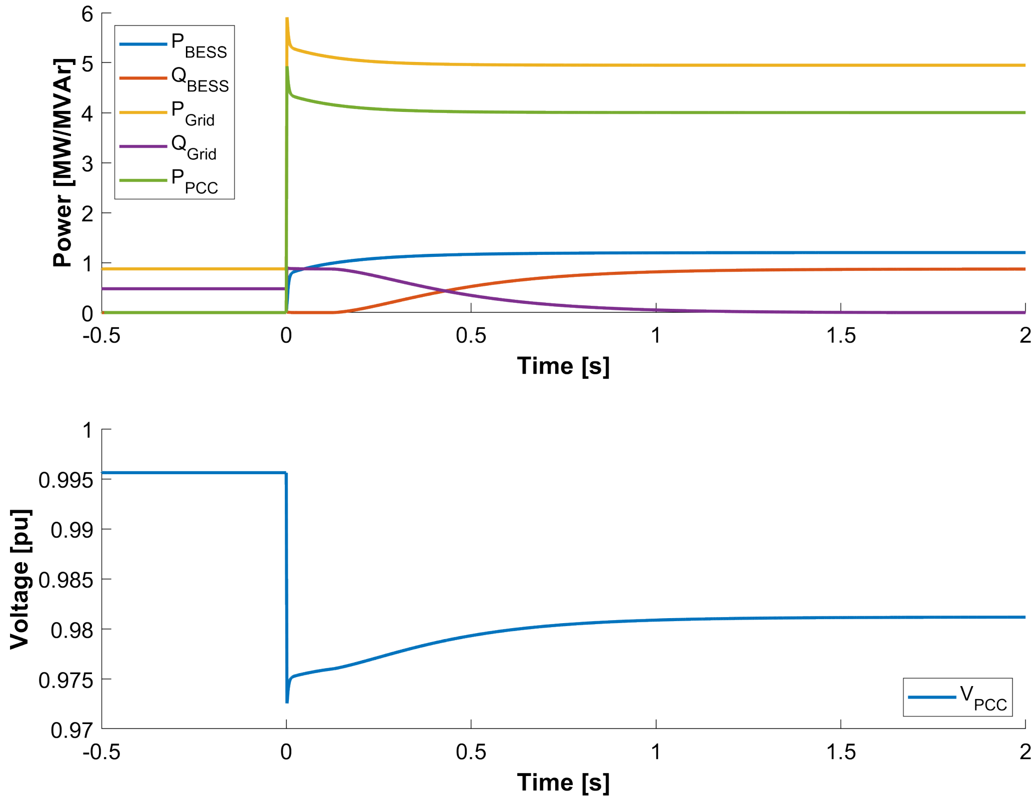

Figure 8.15: *Measurement data for the active and reactive power for the BESS, the grid and the PCC. The voltage profile when the BESS supports the grid with reactive power is illustrated in the lower section.*

In the time interval between -0.5 to 0 seconds, the ship is not connected yet and the external grid is providing active and reactive power to the other customers that are connected to the network. The corresponding voltage profile can be observed in the lower part of figure 8.15 and it is around 0.996 pu. In the time period between 0 to 2 seconds, the ships' electrical load and the charging process are initiated. The external grid reaches its maximum capacity and the BESS starts to support the external grid by two actions. First, injecting active power to partially provide the charging power for the ship. Secondly, providing reactive power to the consumers instead of supplying it from the external grid as it can be seen in figure 8.15. This results in a smaller voltage drop throughout the network and a unity power factor can be achieved at the PCC.

At time 0 seconds the voltage in the PCC drops to 0.972 pu and recovers in two steps, which can be seen in figure 8.15. The first step is when the BESS starts to support the grid by providing active power and the voltage recovers to 0.976 pu. The second step is when the BESS starts to inject reactive power and the voltage at the PCC reaches 0.981 pu. During this whole process, the voltage never drops more than 3 %/sec. Hence, the voltage drop is within the DSO requirements.

Providing reactive power from the BESS reduces the apparent power drawn from the external grid. In figure 8.16, a comparison is illustrated for the voltage profile in the PCC with the reactive power injection and without it.

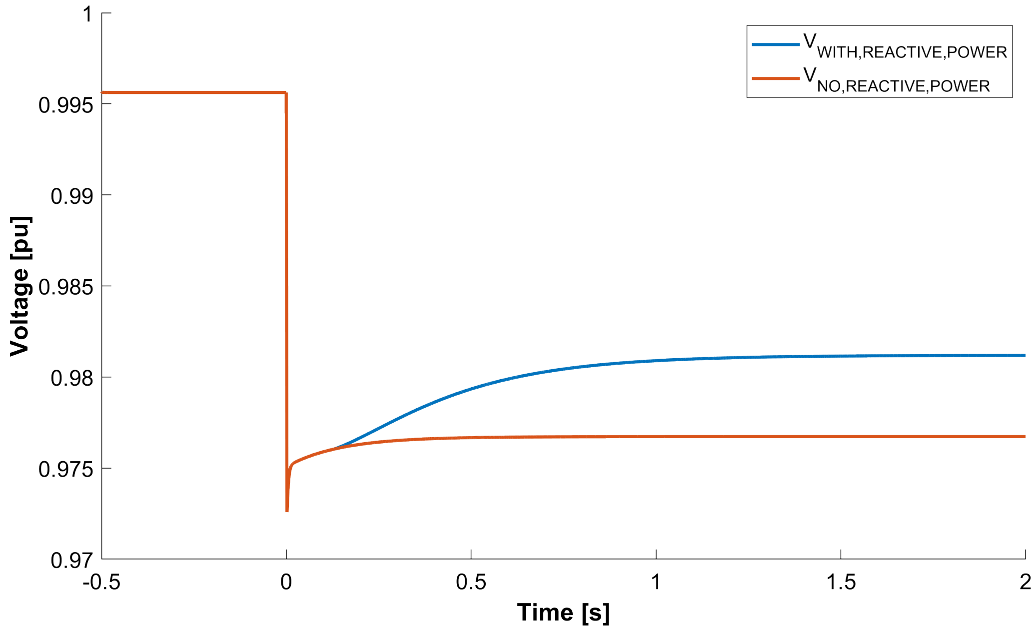

Figure 8.16: *Comparison for the voltage profile in the PCC with and without reactive power support from the BESS.*

As presented in figure 8.16, the voltage profile at the PCC is slightly enhanced with the reactive power injection, the voltage advances from 0.976 to 0.981 pu. It can be seen that the voltage profile without reactive power support from the BESS is still within the DSO requirements.

In order to avoid any voltage transients at the PCC, a solution could be to ramp up both the charging power of the ships' battery and the shore power supply during the first seconds. Therefore, a simulation was conducted where the power of the loads slowly increases during 30 seconds. The resulting voltage profile at the PCC is illustrated in figure 8.17.

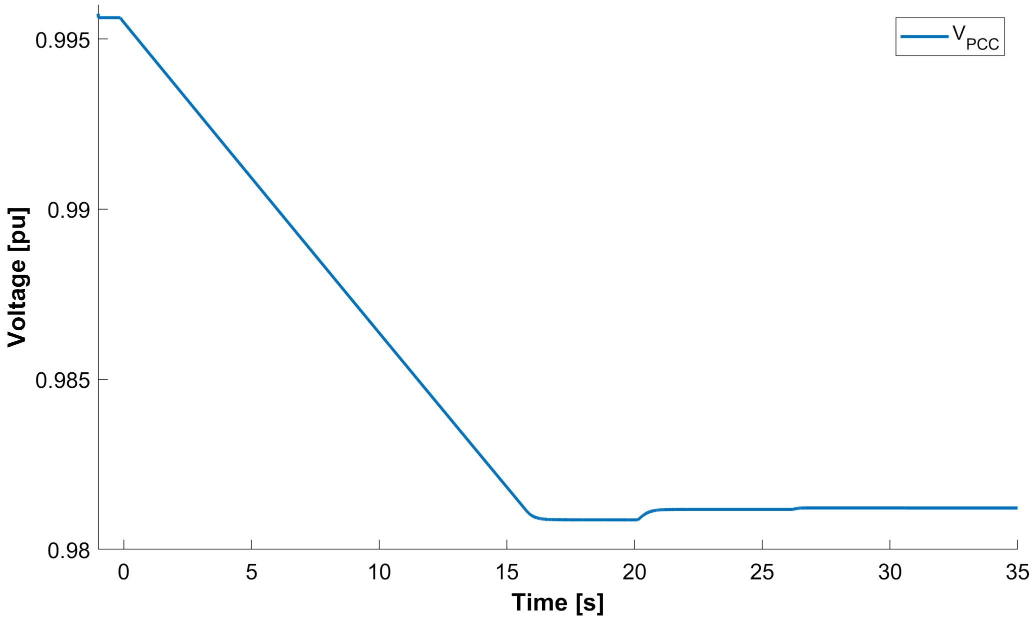

Figure 8.17: *The resulting voltage profile at the PCC during ramping of both charging power of the ships battery and shore connection power supply.*

As illustrated in figure 8.17 the voltage change rate is much lower than the case with instant maximum power supply for both the shore connection and charging of the ship. With this method, the voltage could drop to 0.9 pu and it would still be according to the DSO requirements.

8.4 Fault ride-through

In order to validate that the BESS compiles with the requirements described in section 2.4, a simulation of how the converter would react in such a scenario is performed. In this simulation, the BESS starts supplying the needed power for the ship at time 0 seconds. After 1 second a three phase short circuit in the PCC occurs, after another 3 seconds the fault is cleared. In figure 8.18 the results for the fault ride-through simulation are presented.

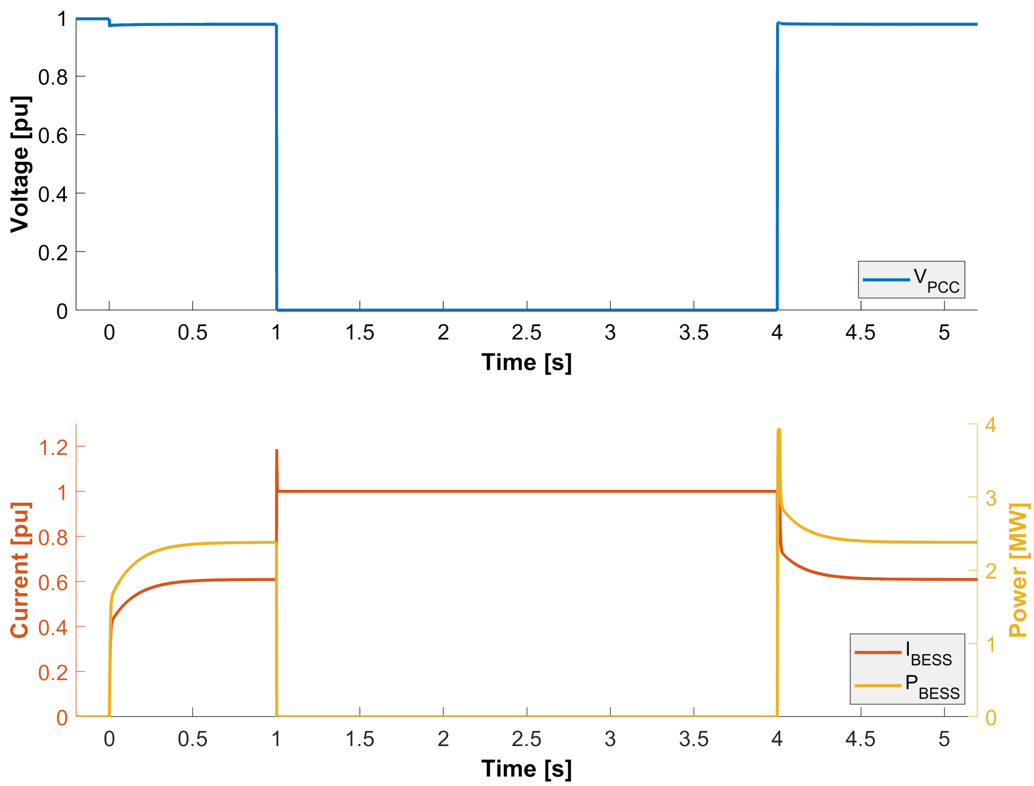

Figure 8.18: *Simulation results from the low voltage ride-through. The BESS case of 3-G is simulated with a three phase short circuit in the PCC for a duration of 3 seconds.*

As depicted in figure 8.18, the BESS successfully compiles with the requirements described in section 2.4. When the short circuit occurs, the BESS delivers a current of 1 pu. However, since the voltage is 0 pu there is no power delivered during this time period. After the fault is cleared there is a sudden increase of power from the BESS, but after roughly 500 ms the power returns to nominal.

In this simulation, the voltage during the short circuit is lower than the required voltage described in section 2.4. After 4 seconds the voltage also recovers instantly. During the fault, the BESS provides the short circuit current of 1 pu, based on the converters rated current. However, there is a high peak of power from the BESS right after the fault has been cleared. The reason for this is that the current output from the BESS does not instantly change. Most likely there is a delay in the BESS control system, which causes a delay in the current recovery process. However, the output power of the BESS recovers to its pre-fault value within 200 ms after the fault is cleared. If there is a requirement from the TSO of providing short circuit current during the FRT, then the BESS will probably meet these requirements since the short circuit current is 1 pu. So the BESS shows good compliance with the requirements from the TSO in this simulation.

9

Assessment of economic benefit from the BESS in the Nordic and Continental European electricity markets

In this section, a simple economic calculation will be conducted in order to illustrate the possible economic benefit from the ancillary services. In order to do so, the end of life of the BESS needs to be assessed. The end of life definition and the aging factors of the lithium-ion batteries were discussed in section 3.2. In this project, the C-rates for the BESS are lower than 1C for all the cases and the temperature is assumed to be around 20 °C, knowing also that the DOD is 80 %. Based on these assumptions and according to [16] this will yield around 5000 cycles of a lifetime for the battery in such operating conditions. This combined with the fact that there is only one cycle per day means that the BESS can operate for 13.7 years until its end of life.

9.1 Potential savings from energy arbitrage

When operating a BESS, one can buy the needed energy for the charging of the ship during a time period when the electricity price is cheap. With this method, the owner of the BESS can save money on the electricity bill. Since the prices are published one day ahead of the operation, the operator can pick when they want to charge the BESS in order to minimize the costs. The ship leaves quay at roughly 19:00 and arrives in the other harbor at 09:00. So if the prices are cheaper at night, savings can be made.

By studying statistics published by [49], the average prices per hour can be calculated for each city during the year 2020. This is presented in figure 9.1.

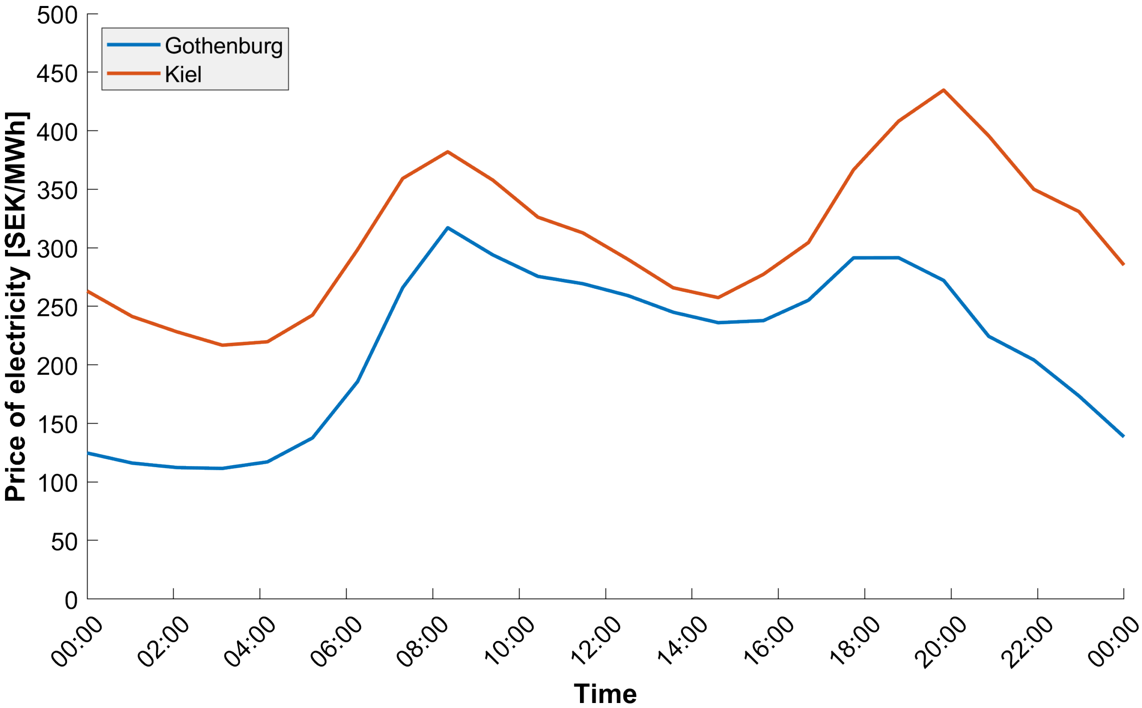

Figure 9.1: *Average prices in Gothenburg and Kiel for each hour during the year of 2020. The data was gathered from [49].*

As presented in figure 9.1, the average prices per hour can be seen to vary during the day. The price during the night is significantly lower than the price during the day. The average price in Gothenburg between 23:00-06:00 is 123 SEK/MWh, and the average price between 09:00-19:00 is 268 SEK/MWh. In Kiel, the average price between 23:00-06:00 is 242 SEK/MWh, and the average price between 09:00-19:00 is 314 SEK/MWh. The difference between these prices is 145 SEK/MWh and 72 SEK/MWh in Gothenburg and Kiel respectively. An estimated calculation can be done with these values, which is presented in table 9.1.

Table 9.1: *Estimated savings based on data from [49] for the energy arbitrage operation of the BESS.*

Description	**2-G**	**3-G**	**2-K**	**3-K**	**Unit**
BESS capacity	18	34	5	21	MWh
Energy used per trip	14	27	4	17	MWh
Average savings	145		72		SEK/MWh/h
Savings per night	2037	3928	286	1217	SEK/night
Savings per year	0.743	1.434	0.105	0.444	MSEK/year
Savings during lifetime	10	19.5	1.5	6	MSEK

9.2 Ancillary services in the Nordic electricity market

The potential benefit from the Nordic market can also be calculated in a similar fashion to the energy arbitrage. Data from the simulations in section 8.2 can be used in conjunction with data from [50] and [51] in order to calculate the potential economic benefit. In order to calculate the average price for FFR, data from [51] was used to estimate the average price paid per MW per hour between 19:00-09:00. The data was only available during the summer, between week 23 and 32. The reason for this is that the FFR is activated when there is low inertia in the power system, which usually occurs during the summer [29].

The average price for FCR-D and FCR-N during every hour between 19:00-09:00 throughout the year 2020 was used for the calculations. The results from the calculation of the economic benefit from FFR, FCR-N, and FCR-D can be seen in table 9.2.

Table 9.2: *Estimated earnings, based on the simulations in section 8.2 and data from [50] and [51], for operation in the Nordic electricity market.*

Description	2-G			3-G			Unit
	FFR	FCR-N	FCR-D	FFR	FCR-N	FCR-D	
Time in markets	9	9	13	9	6	13	Hours
Power sold	4			4			MW
Average price of service	1219	173	165	1219	173	165	SEK/MW/h
Earnings per night	44	6	9	44	4	9	kSEK/night
Earnings per year	2.8	2.2	3.2	2.8	1.5	3.2	MSEK/year
Earnings during lifetime	38	31	43	38	21	43	MSEK

For the earning from FFR, 9 hours was used as the time in the market, even though the BESS can be ready for 14 hours. The reason for this is that the average number of hours when SvK requested FFR activation between 19:00-09:00 was 9 hours per day between week 23 and 32. The earnings per year for the FFR service also took into consideration that the FFR service only is activated for 9 weeks every year.

The total operation time in the FCR-D market was calculated to be 13 hours which is the same for both cases, as seen in section 8.2.3. In the calculations for the earnings from FCR-N, the time in the markets which were used were calculated in section 8.2.2. This results in fewer earnings than FCR-D for both cases.

A possible option is to operate the BESS in the FFR market whenever there is demand for it. Then when there is no demand the BESS could operate in the FCR-D market. With this assumption, if the BESS operates during the 9 weeks every year, and in the FCR-D market during the rest of the time. The potential earnings from this should be 5.35 MSEK/year or 73.30 MSEK during the 13.7 years of the BESSs lifetime.

9.3 Ancillary services in the Continental European electricity market

The potential economical benefit from operating the BESS in the Continental European electricity market. Since the BESS starts operating when it has charged to 50 % SOC, the time in the markets will change for this simulation.

By using data from [52] in conjunction with results from the simulation in section 8.2.4, the average price of FCR in Germany can be calculated. The average price of FCR was calculated between the hours 19:00-09:00 during the whole year of 2020. The results from this calculation are presented in table 9.3.

Table 9.3: *Estimated earnings, based on the simulations in section 8.2 and data from [52], for operation in the Continental European electricity market.*

Description	**2-K**	**3-K**	**Unit**
Time in markets	13	12	Hours
Power sold	5		MW
Average price for FCR	501		SEK/MW/h
Earnings per night	33	30	kSEK/night
Earnings per year	12	11	MSEK/year
Earnings during lifetime	162	150	MSEK

The potential earnings from the FCR market are more than three times higher than the earnings in the Nordic electricity market. The cases of 2-K and 3-K are substantially more profitable than the respective cases of 2-G and 3-G.

10 Discussion

10.1 Battery size and connection setup

From the results of the BESS size calculation seen in table 6.1 and 6.3, it can be seen that no BESS is needed in the ports in Gothenburg or Kiel for a hybrid ship with a 20 MWh battery. Therefore, only a fully electric ferry would be a problem for the electrical network in the ports in Gothenburg and Kiel, if the terminal location stays the same. If the fully electric ferry is not docking at these terminals, a new investigation needs to be conducted.

For the calculation of the BESS size, the value of the maximum power peak during 2019 was assumed to be the required power for the ships' hotel load. This does not consider that the power is aggregated. This means that usually there will be more power available from the external grid than presented in table 6.1 and 6.3. The reason why the maximum power peak of 2019 was chosen is because it's the worst case scenario. And the BESS must be dimensioned to supply the required charging power to the battery on the ship during the worst case scenario as well.

If an aggregated power was to be chosen and there is an anomaly, such as warm weather, that would require more power, then the ship might not be able to leave the harbor fully charged. However, since the depth of discharge is 60 % there would most likely still be energy left to complete the trip. But the battery on the ship would need to violate the depth of discharge it was designed for. One could argue that it's also beneficial to have extra capacity available from the grid to leave room for future expansions, such as the charging of electric trucks and cars.

Since there are plans to move the Stena Line terminal in Gothenburg in the future [53], it could be beneficial to have a mobile BESS. A proposed solution is to implement the BESS on a separate boat or barge. If there is a shortage of capacity in other parts of the port, the BESS can simply move to that location during the time period. However, building a floating BESS would mean that there are more requirements that the BESS needs to comply with for safety reasons. It would therefore be more complicated and probably more expensive to implement as well.

10.1.1 Harmonic pollution

The harmonic impact of the PWM inverter was not investigated in this thesis work. However, the size of the inverter that will be used for the BESS is not a conventional inverter that can be found in-store rack, rather it will be custom made. Therefore the harmonic compliance described in section 2.3.2 could be a requested design requirement. This will guarantees that the PWM inverter follows the DSO requirements.

10.2 Modulation and simulation of the electrical network and BESS

The electrical network used in the peak shifting and voltage support simulations were based on the information given from [6], [8]. However, the information given was not complete. Some parameters were assumed, such as parameters of the cables used, the power factor and aggregation coefficient of the other loads in the network, and transformer parameters. The assumptions made should not substantially affect the result. However, having the exact parameters would give a more accurate result.

Moreover, only one model of the electrical network was build in order to represent both harbors. This can be justified by arguing that the purpose of this thesis work is to build a method of how to implement a BESS in ports, and what possible benefits a BESS has. So it is not that important to prove that the BESS can improve the system frequency in an exact model representation of the Nordic and the Continental European power system. Rather, the model should prove that the BESS can improve the system frequency in a power system. A better model would give a more realistic result, however that is not the focus of this thesis work.

The battery model in DIgSILENT PowerFactory is based on a simple voltage source with an internal resistor which varies based on the SOC. A more complex model, such as the ZARC model could describe a more realistic behavior of a battery [47]. However, this would require more computational power from the control system.

10.2.1 Peak shifting

The results from the peak shifting simulation are important, and it confirms that the calculations made in section 6.1 are correct. It also verifies the model and gives an indication of how long the BESS can provide ancillary services. By buying power during the evening, the owner of the BESS can buy electricity for a cheaper price since the average price, during the night is cheaper than during the day. This energy arbitrage revenue is an added benefit of this implementation.

10.2.2 System frequency stability

As seen from the frequency support simulations in section 8.2.1, the BESS has a minor effect on the system frequency when providing frequency support during a disturbance. This result is as expected since the BESS power output is minuscule compared to the total outage of 1110 MW generation power. Increasing the output power of the BESS reduces the accelerating power described in equation (4.1). However, this reference scenario represents the system frequency response in the Nordic power system and was used to simulate the BESS operation while providing FCR-D and FCR during a disruptive event. Thus, the simulation results for FCR during disruptive event in Kiel might be more accurate if a more representative model of the Continental European power system was used to perform this simulation.

Since the BESS has to provide the power for such a short time period, the SOC of the BESS is not significantly affected. Therefore, when providing frequency support during a disturbance, the BESS can provide this service for a longer time period than when the BESS is operating in the frequency support during normal operation.

In the simulations of frequency support in normal operation, the BESS is able to successfully provide frequency support in the cases of 2-G, 3-G, 2-K, and 3-K without exceeding the upper and lower SOC limitations for the BESS.

In the simulations for normal operation in the FCR market, it can be seen that there is a trend of the output power from the inverter in figures 8.11 and 8.12. This trend shows that the output power is zero very often. The reason for this trend is that the FCR market in the Continental European power system has a deadband of $\pm$ 10 mHz, this requirement does not apply in the FCR-N market.

The frequency data which were used for normal operation in the FCR market were actually samples in the Nordic system frequency. The reason for this was that the project had no access to system frequency samples from the Continental European power system. This could affect the results since the frequency data in the Continental European power system could have different statistical trends, such as the normal distribution of the frequency data. The results would be more accurate if the correct frequency data was used.

10.2.3 Voltage support

Based on findings from 8.3 the BESS will be able to enhance the voltage profile at the PCC but will not advance to 1 pu. The electrical network in the harbors has a resistive profile, i.e. $R/X > 1$, and the reactive power consumption is relatively low. Hence, the voltage drop is mainly caused by the active power transmission from the external network to the PCC. Thus the reactive power contribution to the voltage drop is not significant.

Overcompensation of reactive power should be avoided. This is something that is not desirable because the circulating reactive power will increase the burden on the network, increase the harmonic pollution and the BESS owner might get penalties according to [54], [55].

It can also be noted that there are no violations for the fast voltage variations in the DSO requirements, during the charging process of the ship. However, charging the BESS instantaneously with max available power might violate this requirement. This issue can be solved by increasing the charging current of the BESS stepwise under the first few seconds of the charging process, where the BMS is applicable for controlling the charging process accordingly.

This ancillary service will not add any benefit for the economic aspect of the BESS but it might be required in order to compile with the DSO and TSO voltage requirements in case of voltage sags.

10.2.4 Fault ride-through

The main goal with this simulation was to verify that the BESS can ride through faults during the worst case scenario that was described in section 2.4. This will assure that the BESS will meet the FRT requirements for the TSOs in Kiel and Gothenberg, since it passed the worst case scenario possible according to [14]. However, the simulation scenario would not be likely to occur in a real case scenario since the protection equipment should have a response time shorter than 3 seconds.

10.2.5 Combined operation of ancillary services

The technical possibility of providing combined operation of ancillary services was analyzed and it can be divided into two scenarios. First, when the ship is berthed. Secondly, when the ship is not at the quay.

When the ship is berthed, the BESS is supporting the grid by providing charging power to the ship as it was illustrated in section 8.1, which is the primary objective for the BESS. The BESS will be able to provide voltage support during this process as it was illustrated in section 8.3. The BESS can not provide FCR-D, FCR-N, or FCR simultaneously while providing charging power for the ship. Because of the limitation for the thermal capacity of the feeding cable as mentioned in section 2.2.

The BESS could technically provide FFR, FCR-N, FCR-D, and FCR when the ship is berthed. However, this will require turning off the charging process of the battery on the ship. This will allow the BESS to inject 1.8/2.8 MW in Gothenburg and Kiel respectively at the PCC to support the system frequency without violating the limits of the thermal capacity for the feeding cable. However, the BESS capacity will be reduced during the time period when it's providing those services. Hence, the BESS might not have sufficient energy to fully charge the ship at quay during the given time frame. The BESS has either to violate the design requirements regarding the DOD, by discharging below 10 % SOC. Or the ship at quay would need to be delayed, this decision is ultimately up to Stena Line to decide.

FFR, FCR-N, and FCR-D or FCR can be provided in combination with voltage support while the ship is not at the quay. If the BESS operator wants to provide FFR, FCR-D, and FCR-N at the same time, the total combined output power must be within the limit of the thermal capacity for the feeding cable. The droop curve for the frequency controller in the combined operation of FCR-N and FCR-D can be seen in figure 4.2.

While only providing FCR-D, the BESS can be charged when the frequency is above 49.90 Hz. When there is an anomaly that disturbs the frequency below 49.90 Hz, the charging should stop and the BESS could provide FCR-D according to the droop. With this operation strategy, the BESS could charge during the time when the ship is not at quay since the frequency does not drop below 49.90 Hz too often.

Each BESS size needs an operation strategy in order to have as much up-time as possible when supplying frequency support. In order to maximize the profits, the BESS should supply the maximum power without ever discharging completely. And the BESS should be fully charged before the arrival time of the ship. Considering that the bids for frequency support market during normal operation needs to be settled at least 1 day before operation and that the frequency variations of the future are unknown, makes this problem quite complex to solve. Further research is needed in developing an operational strategy that would maximize the earnings from these ancillary services. This is also needed to properly calculate the revenue which can be gained from the ancillary services.

Until future research is completed, one possible solution is to only provide FCR-D and FFR in the Nordic electricity market. As described in section 9.2, the BESS operator can provide FFR during the time period when it's needed. During the time when FFR is not needed the BESS operator can provide FCR-D. This results in earnings of 5.35 MSEK/year.

10.3 Economic benefit from the BESS

The cost of the BESS was made with a very simple method. No consideration was taken to many factors that affect the cost. For example, if a loan was taken to buy the BESS then the interest and amortization need to be included in the calculations. The inflation of the currency is also a factor that needs to be considered. No consideration was taken to the costs of operation and management.

The cost calculations of grid reinforcement in section 6.3 is based on assumption that Stena Line is the only customer that will be connected to the new feeding cable. According to [8], this means that Stena Line has to pay for the total cost of the new cable. However, this cost might be reduced if other customers would connect to the new cable as well.

The analysis of the lifetime was taken from data from [16], the operation conditions in this study were not the same as the assumed operation conditions of the BESS. For example, the C-rates for the BESS in all the study cases were lower than 1C. Also, the tests in [16] did not use reused cells which the BESS does. In order to do a proper lifetime assessment, the actual cells used in the BESS should be tested with the same test conditions in order to do a proper lifetime assessment.

When calculating the price for energy arbitrage, the average price per hour during the year 2020 was used. These statistics were based on the day-ahead prices, which are known one day before the time of operation. By using the average price, one ignores peaks and valleys of individual days. Another method is to calculate the potential savings for each individual day instead. Then the average savings could be calculated based on this data, which would give a more accurate result.

If the BESS would discharge completely while providing FCR-N or FCR support, there would be a fine for not providing the contracted power [56]. It's important to take this into account when calculating the earnings of FCR-N and FCR during normal operation. As mentioned, there are many factors that are not considered. Therefore, a more comprehensive analysis is required for a better understanding of the total costs and earnings of the BESS.

By taking the average price during a year and assuming that the price is the same, one ignores that the prices in the FFR, FCR-N, FCR-D, and FCR market are settled with actual bids. Therefore it could mean, that the BESS operator could find favorable bids which are of different sizes in all of the markets during a time period. This could, in the end, result in different profit margins than calculated in chapter 9.

In 2020, there was a pandemic of COVID-19 which affected many industries [57]. This could have affected the price of electricity during 2020. Since this study used data from 2020, this could make the calculation results less accurate and less applicable for the future. Or more accurate, since it's quite unknown how the society will act and what trends in the way of living which could be changed in the future [57]. So it's unknown if the data from 2020 is a better or worse representative of the future.

10.4 Environmental and ethical aspects regarding lithium-ion batteries

The electrification process of the transport sector has escalated significantly in the past decade, this trend is seen to continue or increase in the next decade [58]. The vast development for the energy-optimized lithium-ion batteries with higher energy densities has made those cells attractive even for heavy vehicles and sea vessels [58]. A problem is arising in parallel with this extensive electrification process which is providing the charging power that is needed from the grid. In some cases, the grid will not be able to provide the required charging power in the given time frame. BESSs are suggested as a solution in such cases [58].

The demand for lithium-ion batteries will probably increase significantly. This will raise concerns for the environmental and public health issues that are related to the production chain of lithium-ion batteries [58].

The lithium-ion batteries manufacturing process requires a huge amount of many different metals and non-metals [58]. For example, the most popular battery chemistries that are used in EV and grid-scale energy storage are lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) cells [59]. The metals that are needed for the production are lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), and iron (Fe). The non-metals used in the production are phosphate (P) and graphite (C).

Increasing battery production will affect the access for the natural resources and the economics in the region where its located, because of the dependence of the geographical location of the mines which is often located in regions where the economies are controlled or unstable [58]. This will expose the natural resources which have easy access to get drained in order to achieve high profitability from the mining process [58].

Moreover, to meet the demand for raw materials like phosphate (P), more quantities need to be mined and new mines are needed to get prospected. The mining industry has its own substantial issues regarding the social and environmental aspects, especially in the low developed countries where corrupted governments control such businesses [58]. Most of the Cobalt (Co) demand is being supplied from the Democratic Republic of Congo, where the mining industry has a lot of issues related to human rights. For example poor labor conditions, artisanal hand mining, and child labor [59]. Also, 65 % of the global natural graphite (C) is mined and processed in China. This has an environmental impact in form of air pollution caused by the graphite dust, leading to respiratory diseases and pollution in local water sources including drinking water from the acids that are used in the purification process [59].

The proposed actions and strategies are to control the activities of the international mining companies and make sure that they are following the international human rights laws and standards, including child labor prohibition [59]. The communities around the prospecting area should be well informed by the mining company on the environmental impact of its operation in the affected area. According to UN Declaration on the Rights of Indigenous Peoples, exposed communities have the right to take decisions in projects that will affect their environment and livelihoods [59].

One of the most important mitigation strategies for the environmental impact of the Lithium-ion batteries, is to reuse the cells in other applications and thereby start a "second life". Grid-scale energy storage system like BESS is one of the applications that are appropriate and suitable utilization for the reused cells [60].

The cells will spend around 10 years in an electric car and the battery maintains 50 to 90 % of its capacity after spending its first life in a car. The battery pack is then disassembled from the electric car, collected, and delivered to the diagnosis center. Cells that meet the criteria for a second life are dismantled and rearranged into homogeneous modules after being tested. Battery modules that have been refurbished are integrated into large stationary storage systems to provide a variety of ancillary services to the grid [60]. This strategy will mitigate the environmental burden since the lifetime of each produced lithium-ion cell is extended.

10.4.1 Social aspects regarding grid extension

The location of the harbor in Gothenburg raises a few concerns related to the social aspects of this project. Since the cables will pass through the city, as it is illustrated in figures 6.1 and 6.2, excavation of the streets inside the city will affect the communities around the excavated streets. People who usually use these streets in their daily activities, and might be forced to take other routes which might add extra distance to their commute. Which could result in more travel time and extra costs.

The case is not the same for Kiel, the 130 kV switch-gear is located near the harbor with roughly 1.5 km distance between the switch-gear and the terminal, as it's illustrated in figure 6.3. Therefore, excavating the harbor in Kiel will not have a big impact on the social life as in the case of Gothenburg.

10.5 Discussion of BESS vs. grid extension

The connection setup differs between Gothenburg and Kiel. In Gothenburg, there is a requirement of N-1, which means that if one line would get disconnected, there must be another connection available to supply the power. This requirement is not required in Kiel. It's not reasonable to implement the N-1 requirement for a BESS because of two reasons. First, there is no requirement for the BESS operator to implement the N-1 for such a system. Secondly, installing two identical systems might not be economically feasible. Therefore, implementing a BESS solution will make the charging solution less redundant.

Based on the cost calculations from section 6.2 and 6.3 it's clear to conclude that it's much cheaper to reinforce the harbor network with extra feeding cable from the overlaying network compared to the cost for installing a BESS. This is true for both ports. But one needs to consider the potential earnings from ancillary services. The payback period for the BESS is presented in table 10.1 and the total cost for grid expansion is presented in table 10.2.

Table 10.1: *Total prices of the BESS, earnings and savings during BESS per year from section 6.2 and chapter 9 respectively.*

Description	**2-G**	**3-G**	**2-K**	**3-K**	**Unit**
BESS capacity	18	34	5	21	MWh
Savings from energy arbitrage	0.743	1.434	0.105	0.444	MSEK/year
Earnings from frequency stability services	5.4		11.9	11.0	MSEK/year
Total earnings and savings	6.1	6.8	12.0	11.4	MSEK/year
Cost of the BESS	123	235	35	148	MSEK
Payback period	20	35	3	13	Years

Table 10.2: *Total costs of grid expansion alternative if a BESS is not implemented. The information is taken from section 6.3.*

Description	**2-G**	**3-G**	**2-K**	**3-K**	**Unit**
Cost of grid expansion	5.5		1.5		MSEK
Subscription fee	0.7	1.3	0.4	1.5	MSEK/year

The difference in prices between the solutions is significant, it is clear that it is much cheaper to expand the grid capacity in Gothenburg than to implement a BESS. In Kiel, it's actually cheaper to implement a BESS since the earnings from FCR are significant. This can be seen in the payback period in table 10.1 for the different BESS cases where cases 2-G and 3-G have longer payback periods compared to 2-K and 3-K. However, a more detailed economical comparison needs to be conducted before a decision on whether or not to invest in a BESS is taken.

Grid expansion has a great social impact on the population as discussed in section 10.4.1, and it takes 5 to 7 years to fully complete the grid expansion as well whilst the BESS can be delivered in one year. This combined with the fact that the terminal in Gothenburg is moving to another location makes the BESS implementation more feasible in Gothenburg. Moreover, the extra capacity from grid expansion will not be needed when the terminal is moved.

While in Kiel the case is not the same. The overlaying substation is located in the harbor area as illustrated in figure 6.3, this means that the grid expansion in Kiel has little to no social impact. However, the BESS has great potential earnings as presented in table 10.1. So Stena Line might be interested in implementing a BESS in Kiel as well.

11 Conclusion

This master's thesis investigated if the harbors in Gothenburg and Kiel are in need of a BESS in order to provide charging power for three different hybridization scenarios. In these three scenarios, the conceptual battery size on the Stena Line ship is assumed to be 20, 50, and 70 MWh.

The results from this investigation showed that there is no need for a BESS in the ports in Gothenburg and Kiel for a ship with a 20 MWh battery. The power from the HVSC is sufficient to charge the battery on the ship when the ship stays at the quay for 10 hours. If the ship at quay has a battery size of 50 MWh and 70 MWh then a BESS is needed if grid reinforcement solution is not considered. These BESSs need to have a capacity of 18 MWh and 34 MWh in Gothenburg, and 5 MWh and 21 MWh in Kiel respectively, considering an 80 % DOD of the BESS. The costs of the BESS sizes were calculated and compared to the costs of grid expansion.

The simulations for the system frequency stability like FFR, FCR-N, FCR-D, and FCR showed small improvement for the system frequency deviations, but the BESS operator still gets paid for providing the mentioned services. The earnings from the frequency stability services in the Nordic electricity market indicated in a payback period longer than the estimated BESS lifetime. In the Continental European market, the frequency stability services resulted in a potentially shorter payback period than the estimated lifetime of the BESS.

The simulation results for voltage support showed that the BESS is able to enhance the voltage profile at the PCC. Moreover, the results showed good compliance with the DSO requirements regarding the fast voltage variations. The fault ride through simulation showed that the BESS compile with TSO requirements during a three phase short circuit fault with 3 seconds duration.

The results from the conducted analysis showed that in Kiel it is more beneficial economically to implement a BESS solution since the payback time is short compared to the lifetime of the BESS. In Gothenburg, the BESS could be a better solution since Stena Line plans to move the terminal in the near future, and the fact that grid expansion has a big social impact on the civilians. However, a more comprehensive economic analysis is required since there are many parameters that were not considered in this thesis.

11.1 Future Work

To make the BESS solution more environmentally friendly, a combined operation with renewables is an ideal proposition to be investigated. The harbors' geographical location by the ocean makes wind and solar power interesting candidates to be combined with the BESS. This will potentially result in lower CO_2 emissions since the BESS is partially or fully charged from the renewable energy sources, this might also result in lower operating costs for the BESS as well.

Another interesting research opportunity is the vehicle to grid (V2G) concept [61], but for ships instead. By turning off the charging power to the battery on the ship, one can provide frequency stability services such as FFR and FCR-D when the ship is at quay. Then the BESS and the ship can both provide the frequency stability services with their full capacity. This is very suitable in the FFR market since the activation period is only 5 seconds. This would however require a much more complex control system in the battery on the ship and in the 50/60 Hz converter.

The connection setup between the BESS and the ship was not within the scope of this report. However, the megawatts of charging power required combined with the actual mechanical connection interface between the ship and the port creates a huge engineering challenge. A feasible state of art solution needs to be researched in regards to this question.

Due to the complexity of the bidding system for the frequency stability services, the conducted economic evaluation in this study was based on rough assumptions regarding the bidding mechanism. Therefore, comprehensive research to investigate the economic aspects of the BESS is needed in order to evaluate the cost-benefit of the BESS more accurately. This can be combined with an investigation for a better operation strategy to maximize the economical potential of the BESS.

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