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Commissioning of frequency controlled reserve in Finland

Thesis submitted in partial fulfilment of the requirements
for the degree of Master of Science in Technology

Espoo, October 10th, 2016
Supervisor: Professor Matti Lehtonen
Advisor: Henri Makkonen, M.Sc. (Tech)

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Abstract of Master's thesis

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Abstract

Frequency controlled Frequency Containment Reserves (FCR) regulate automatically according to changes in the Nordic power system's system frequency. As the frequency declines from its nominal value, up-regulation commences by increasing the reserve providing unit's electricity production or by decreasing its electricity consumption. Additionally, the Frequency Containment Reserve in Normal operation (FCR-N) down-regulates by increasing the unit's consumption or by decreasing its production when the system frequency rises above the nominal value.

In Finland, hydropower has traditionally acted as the main source of FCR capacity. However, active power capacity from other resources may also be offered to the FCR market places. For example, even modest Demand Response (DR) capacity is sufficient for market utilization if it is incorporated into an aggregation of reserve power capacity, as long as the entire aggregated ensemble fulfills the market place's rules. Another modern resource especially suitable for FCR-N utilization are the Battery Energy Storage Systems (BESS). The energy capacity stored in the batteries is limited, however, and exhausted in continuous activation.

In this Master's thesis, the technical requirements currently applied to the Frequency Containment Reserves were examined. Based on the requirements, the necessary commissioning process including four regulating tests were formulated and pre-approved by the Finnish Transmission System Operator Fingrid Oyj. The regulating tests are universally applicable, thus allowing the verification of compliance to the requirements for both conventional and modern resources. Furthermore, the expected future evolution of the technical requirements was studied by interviewing Fingrid's specialist.

The suitability of the formulated tests was assessed by performing regulating tests on a BESS. The acquired results indicated that the BESS fulfills the regulating requirements of both FCR market places. Additionally, the regulating tests formulated in this thesis were verified as suitable for performing the official regulating tests.

Keywords Regulating tests, Battery Energy Storage System, aggregation of reserve power capacity, Frequency Containment Reserve in Normal operation, Frequency Containment Reserve in Disturbances

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Tiivistelmä

Taajuusohjatut käyttö- ja häiriöreservit reagoivat automaattisesti pohjoismaisen sähköjärjestelmän taajuuden vaihteluihin. Taajuuden laskiessa nimellisestä ne lisäävät tuotantoaan tai vähentävät kulutustaan, mitä kutsutaan ylössäädöksi. Lisäksi taajuusohjattu käyttöreservi alassäätää taajuuden noustessa nimellisestä vähentämällä tuotantoa tai lisäämällä kulutusta. Ylös- ja alassäädöllä pyritään siis tasaamaan sähkön kulutuksen ja tuotannon välistä eroa.

Vesivoima on perinteisesti toiminut Suomessa taajuusohjattujen käyttö- ja häiriöreservien lähteenä. Kuitenkin myös muu pätötehokapasiteetti soveltuu taajuusohjattujen reservien markkinapaikoille. Esimerkiksi pienimuotoinenkin sähkönkulutuksen kysyntäjousto voidaan hyödyntää, kun se liitetään osaksi suurempaa, aggregoitua kokonaisuutta. Aggregoimalla voidaan siis pienistä teholähteistä koostaa markkinavaatimukset täyttävä kokonaisuus. Toinen moderni, erityisesti käyttöreservikapasiteetiksi soveltuva tehonlähde ovat akkukäyttöiset sähkövarastot. Näiden erikoispiirre on akustojen jatkuvassa käytössä ehtyvä energiakapasiteetti, minkä vuoksi sähkövarastoille tulee antaa reservikäytössä palautumisaikaa.

Tässä diplomityössä tutustuttiin nykyisiin taajuusohjatuille käyttö- ja häiriöreserveille asetettuihin teknisiin vaatimuksiin. Nykyvaatimusten pohjalta muotoiltiin tarvittava käyttöönottoprosessi, mukaan lukien neljä yleisesti sovellettavissa olevaa säätökoekäyrää, joiden avulla niin perinteisten kuin uudempienkin taajuusohjattujen reservien ylläpitoon aiottujen yksiköiden soveltuvuus voidaan todentaa. Säätökoekäyrät hyväksytettiin Suomen kantaverkkoyhtiö Fingrid Oyj:llä. Lisäksi diplomityössä tutustuttiin vaatimuksiin tulevaisuudessa tehtäviin muutoksiin haastattelemalla Fingridin asiantuntijaa.

Laadittuja säätökoekäyriä testattiin hyödyntämällä niitä akkukäyttöisen sähkövaraston vaatimustenmukaisten säätöominaisuuksien todentamisessa. Säätökokeista saatujen tulosten perusteella sähkövarasto täytti sekä käyttö- että häiriöreserveille asetetut säätövaatimukset. Samalla todennettiin säätökoekäyrien soveltuvuus virallisten säätökokeiden suorittamiseen.

Avainsanat Säätökokeet, sähkövarasto, reservikapasiteetin aggregointi, taajuusohjattu käyttöreservi, taajuusohjattu häiriöreservi

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The thought of becoming an electrical engineer was rooted into my mind already in the comprehensive school. Thus, my journey to Aalto University and its School of Electrical Engineering was fairly straightforward, as I never actually considered any other education. Now that I am soon graduating, a long lasting project is finally coming to an end.

This thesis was written while I was working as a trainee in Siemens Osakeyhtiö in Espoo, Finland. The process already began in the latter half of year 2015, although the real work around the thesis was started in January 2016. I want to thank my superiors and colleagues as I was allowed to focus on the thesis work during my regular working hours, too.

I want to express my special gratitude to my thesis supervisor professor Matti Lehtonen and to my thesis advisor Mr. Henri Makkonen. Henri presented me with this very interesting topic, and his support was truly essential in realizing the technicalities involved in the regulating tests. Furthermore, I want to thank Mr. Mikko Kuivaniemi from Fingrid, whose input in drafting the test curves and commenting work during the later phases of the writing process were highly appreciated.

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in Espoo, October 10th 2016

Heikki Ojanen

Table of content

Abbreviations

BAC	Battery Available Capacity
BESS	Battery Energy Storage System
BMS	Battery Management System
DSO	Distribution System Operator
DR	Demand Response
ENTSO-E	European Network of Transmission System Operators for Electricity
EPAD	Electricity Price Area Differential
FCP	Frequency Containment Process
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve in Disturbances
FCR-N	Frequency Containment Reserve in Normal operation
FRP	Frequency Restoration Process
FRR	Frequency Restoration Reserve
FRR-A	Automatic Frequency Restoration Reserve
FRR-M	Manual Frequency Restoration Reserve
HVDC	High-Voltage Direct Current
kW	Kilowatt
kWh	Kilowatt-hour
LFC	Load-Frequency Control
MW	Megawatt
MWh	Megawatt-hour
NEMO	Nominated Electricity Market Operator
OTC	Over-The-Counter
PLC	Programmable Logic Controller
RR	Replacement Reserve
RRP	Reserve Replacement Process
SOA	System Operation Agreement
SOC	State Of Charge
TSO	Transmission System Operator
TWh	Terawatt-hour
VPN	Virtual Private Network

1 Introduction

The Nordic power system is facing changes. Nuclear power generation, for instance, has been utilized as base load provider for centuries. On the one hand nuclear power plants are facing threats of shutting down, but on the other hand more capacity is being built in larger scale facilities than ever before. Hence, preparing for a sudden loss in base load generation is essential. Another example comes from the opposite end of the Nordic power production structure. The increase in wind power generation capacity entails that more and more of fluctuating power generation is connected to the system. The fluctuations have to be responded to by utilizing reserve power capacity.

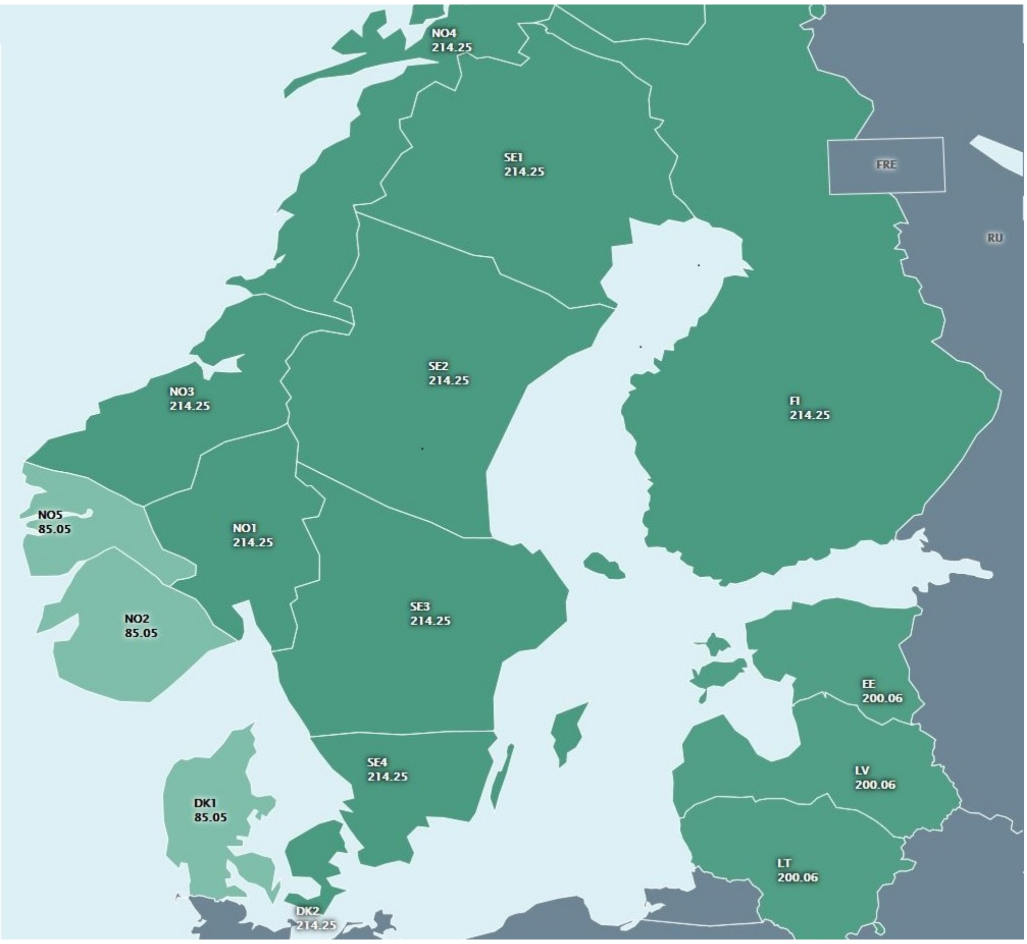

Figure 1: The Nordic and Baltic Elspot bidding areas. A screenshot from Nord Pool's website showing the Elspot prices for 8-9 EET on 21st of January 2016. [1]

At present, the Nordic power system is occasionally driven close to its limits. Year 2016 began in very cold weather, which led to rising electricity prices in both the Elspot retail market place as well as in the ancillary service markets, see Figure 1. The cost of balancing power, for instance, reached an all time record of 3000€/MWh as every single bid on the market was utilized [2]. Additionally, on 7th of January, the total hourly average electricity consumption in Finland exceeded 15,000 MW for the first time [3]. Furthermore, hydropower has traditionally acted as the main source of Frequency Containment Reserves (FCR). However, as presented in the final chapter of this thesis, changes to the currently applied technical requirements are foreseen. The changes might hinder hydropower's capability to participate in FCR use, especially in Finland due to the Kaplan-type turbine generally employed in the Finnish power plants. [4]

Hence, the Finnish ancillary service markets are facing a challenge of finding new sources of Frequency Containment Reserve capacity. One solution is to utilize smaller scale generation and load-shedding capacity than before. Today, even modest Demand Response (DR) resources could be harnessed for FCR market use: in March 2016, the first aggregation of reserve capacity consisting of purely household consumption was approved to bidirectional regulation on the Finnish Frequency Containment Reserve in Normal operation (FCR-N) market place [5]. Another modern solution could be to employ Battery Energy Storage Systems (BESS) in ancillary service provision. The BESS's viability to FCR use in Finland was simulated in 2015, and the study indicated that the BESSs are especially suitable for FCR-N markets [6].

As a technology provider, Siemens Osakeyhtiö is naturally interested in the aforementioned development in the ancillary service markets. First, a lot of potential is seen in reserve capacity aggregation, especially now that different market models are been investigated by the Finnish Transmission System Operator (TSO) Fingrid Oyj [7]. Thus, Demand Response could become more widely employed in the private households and in smaller scale industry, which entails that new technical solutions are required. Secondly, Siemens has already delivered the first utility scale Battery Energy Storage System in Finland [8] and, naturally, new BESS orders are sought after. The first BESS is installed in the Viikki Environment House in Helsinki, and its excellent regulating capabilities are shown in the regulation tests performed in chapter 5 of this thesis.

1.1 Scope of the thesis

In order to verify that a resource intended for FCR use complies with the technical requirements, a set of regulating tests are performed. However, Fingrid's Application Instruction for the Maintenance of Frequency Controlled Reserves includes no complete descriptions of the regulating tests, especially ones that would be applicable to more modern reserve providing resources, such as aggregated capacity. Hence, the primary goal of this thesis is to define the verification processes utilized in commissioning of FCR resources in Finland. This includes formulating the necessary regulating tests in a way that they are as close to universally applicable as possible. Thus, the technical requirements and rules currently applied to Frequency Containment Reserves in Finland are examined.

Another goal of this thesis is to take an outlook into the future evolution of the technical requirements. Acknowledging the foreseen changes prior to they come into effect would allow implementing the required changes into the commissioning process beforehand. Especially, being able to perform future-proof regulating tests already before the changes would be beneficial.

1.2 Structure of the thesis

In chapter 2, the Finnish electricity markets are introduced. Both the retail and ancillary service market places are introduced, although the focus will be on the ancillary service markets.

In chapter 3, the European and Nordic terminology and structures related to frequency regulation and reserves are examined. The different rule setting documents and their hierarchy are studied. Finally the Nordic operational reserves are introduced.

Chapter 4 focuses on the current technical requirements set for FCR resources in Finland. Additionally, the necessary verification processes are studied and a simple commissioning process is created. Finally, the regulating tests formulated in the thesis are presented.

In chapter 5, the regulating tests presented in chapter 4 are performed on a Siemens SieStorage Battery Energy Storage System and the acquired results are analyzed.

In chapter 6, the regulating tests performed in chapter 5 are summarized and the significance of the acquired results are discussed. Additionally, an alternative FCR-N activation characteristic is proposed. Finally, an outlook into the future evolution of the Finnish FCR requirements is taken.

2 The Finnish electricity markets

Today, the Finnish electricity markets are versatile. Several market places for traditional trading of electrical energy are available and, additionally, it is possible to offer active power capacity to the markets.

In Finland, the physical trading of electricity is realized on two market places or by separate contracts. First, Nord Pool Spot is the primary market for hourly electricity wholesale. It offers means for electrical energy trading either by day-ahead or intraday deals. [9] The second market is the Finnish TSO Fingrid Oyj’s ancillary service markets, on which the trading of reserve products is realized. Trading on reserve power capacity is based on yearly and hourly contracts. [10] In addition to trading with actual physical electricity delivery, there are electricity market derivatives available on Nasdaq OMX Commodities financial market [9].

In this chapter, the Finnish electricity wholesale and ancillary service markets are introduced. Nord Pool's market places and Nasdaq OMX Commodities financial derivative markets are reviewed. Moreover, the focus will be on Fingrid's ancillary service markets.

2.1 Nord Pool Spot

Nord Pool Spot is the most common electricity wholesale market place in the Nordic and Baltic countries. It is operated by Nord Pool Group, which in turn is owned by the appointed national transmission system operators: Fingrid Oyj in Finland, Svenska Kraftnät in Sweden, Statnett SF in Norway, Energinet.dk in Denmark, Elering in Estonia, Litgrid in Lithuania and Augstsprieguma tikls in Latvia. In addition to trading in the Nordic and Baltic regions, Nord Pool also operates the N2EX electricity market in the United Kingdom and is appointed as the Nominated Electricity Market Operator (NEMO) in another four European countries. [11] Founded initially in Norway in 1993 [12], Nord Pool is now Europe's leading power market with a total of 489 TWh of traded electrical energy in year 2015 [11].

2.1.1 Day-ahead Elspot

The day-ahead Elspot is the primary electricity market in the Nordic and Baltic countries. In year 2015, the total volume of traded energy was 374 TWh [11], and in 2014 circa 63% of all electricity consumed in Finland was purchased from Elspot [13]. The market works on a closed auction principle: players taking part in the bidding place their electricity sale or purchase orders for the next day before 13.00 EET. The orders are made for either single hours or blocks of three or more hours, and their minimum volume is 0.1 MWh. The players do not get access to other players' bids, hence the name closed auction. [9] After the bidding ends, single market wide system price is calculated for next day's each individual hour. The system price is determined by the intersection of aggregate supply and demand curves that represent all the placed sale and purchase orders. [14] Figure 2 illustrates the aggregate supply and demand curves, and the determination of the system price for a certain hour of the day.

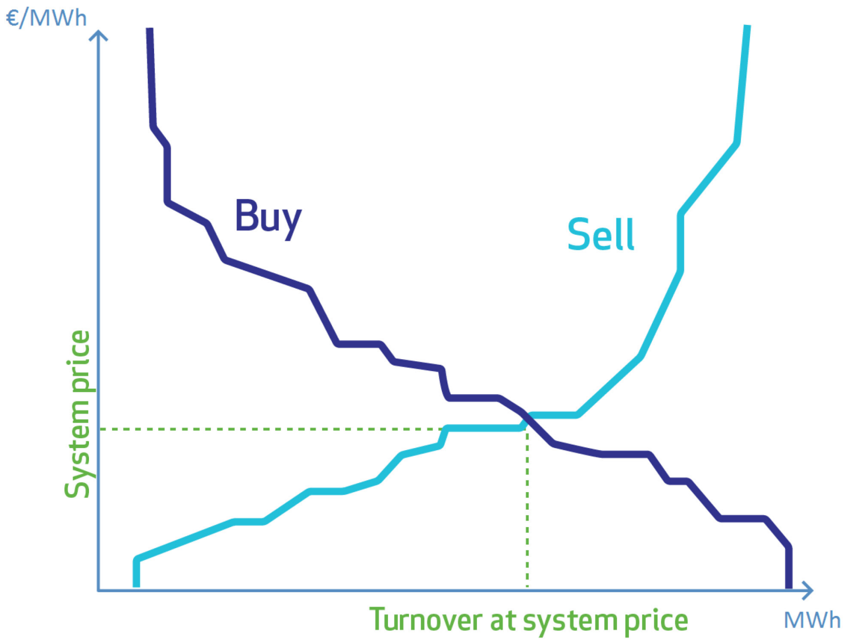

Figure 2: Determination of Elspot system price. The sell curve represents the aggregate supply and the buy curve the aggregate demand. Figure from Nord Pool's website (modified) [14].

Despite the formation of a single market-wide system price for each hour, the price paid for a megawatt by different purchasers on the Elspot market may vary greatly. This is due to bottlenecks in electricity transmission networks. That is to say, there is not always sufficient electricity transmission capacity available, as production and consumption rarely occur in the network evenly. As a result, areas with surplus or deficit of electricity may appear. The Elspot market has been divided into several separate bidding areas for which the price of electricity will be determined individually, which in turn allows the area prices to differ. The division of Elspot bidding areas is illustrated in Figure 1 on page 1. [14]

The actual determination of area prices is done by shifting the supply curve according to occurring oversupply or undersupply in a bidding area. The price is then determined by the new intersection of supply and demand curves, and it may be significantly above or below the system price. In general, the price of electricity will be lower in areas with surplus, whereas areas with deficit have to pay more for their electricity in order to compensate the transmission constraints. [9, 14]

At present, Finland imports a significant share of its electricity. In 2015, 21.5 TWh was imported which answered for circa 26% of all electricity supply [15]. However, Finland suffers from limited transmission capacity between it and its neighboring countries and, consequently, the electricity prices are generally higher in Finland. During the first eleven months in 2015, Elspot's price for the Finnish FI area averaged 8.78 €/MWh above the system price, which is in line with the recent trend. Figure 3 shows how the FI area price has lately had a tendency to stay notably above the system price.

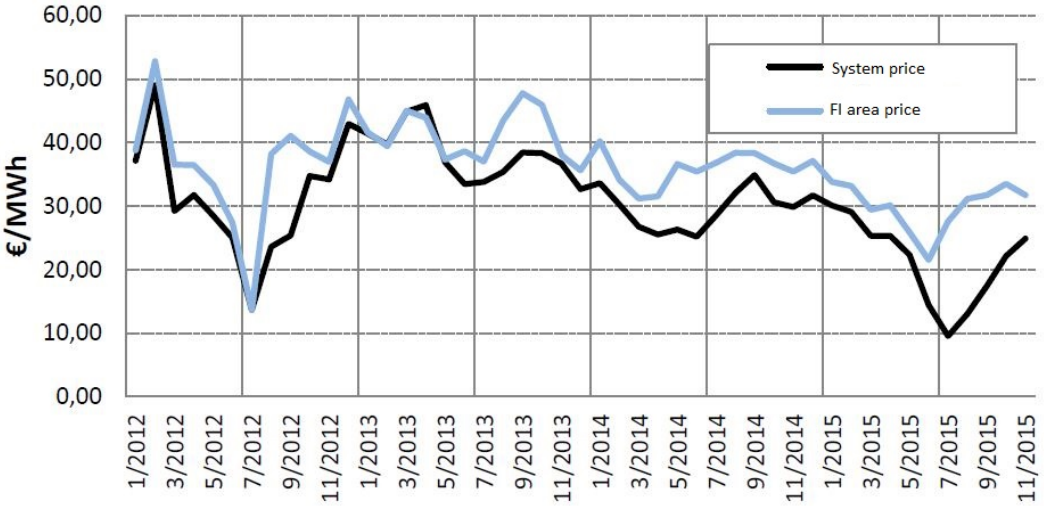

Figure 3: The Finnish FI Elspot area price (blue) and the system price (black) between January 2012 and November 2015. The FI price has stayed above the system price except during few months in 2012 and 2013. [13]

2.1.2 Intraday Elbas

Nord Pool's secondary market place for electricity wholesale is the intraday Elbas market. Elbas acts as a balancing market for the primary Elspot and it offers the electricity traders the possibility to adjust their selling or purchasing after Elspot market has already closed. [9] Contrary to the closed auctioning utilized in trading on the Elspot market, the Elbas market functions on a pay-as-bid principle. This entails that the price paid for the same Elbas market product for a given hour may not be the same for all players. [16] Furthermore, the dead lines regarding trading on coming hour vary between the market areas. For example, on the German intraday market, the trading is closed as late as only twenty minutes before the actual electricity delivery takes place. [17]

2.2 Over-the-counter trading and financial markets

In addition to Nord Pool’s market places, it is possible to purchase electricity outside of the wholesale market. This can be realized in two ways. First, it is possible to establish separate contracts between selling and purchasing parties. Similarly to trading in Elspot or Elbas markets, these bilateral contracts lead to actual physical delivery. However, the price paid for electricity by this kind of over-the-counter (OTC) trading may differ greatly from the prices on the wholesale markets. [9] Secondly, on financial markets there are several long-term electricity market products available that help securing the electricity price in the future. In contrast to wholesale and OTC markets, trading on the financial market products does not lead to actual physical electricity delivery. In the Nordic and Baltic countries, the Nasdaq OMX Commodities market offers a range of electricity market derivatives, such as futures, options and EPADs (Electricity Price Area Differentials). The Elspot system price acts as a reference to the pricing of the financial market products. [9, 18]

2.3 Ancillary service markets

Power consumption and production in the grid are constantly fluctuating. The momentary system frequency in the grid is determined by the difference between the consumption and production, thus the total production in the system should as closely as possible correspond to the total consumption. In Finland, as well as in the whole Nordic power system, the nominal system frequency in balanced operation is 50 Hz which, however, cannot be maintained at all times. The frequency is allowed to fluctuate around the nominal value in a controlled way, but only in a certain range, as underfrequency, especially, could cause serious problems in the grid. [19]

In order to maintain the power balance and thus the nominal system frequency, the players taking part in electricity wholesale markets are required to plan their consumption and production in advance. However, it is not possible to accurately predict the exact future consumption or production, which leads to imbalances occurring in the system. Consequently, corrective measures have to be taken so that the system remains stable at all times. The Finnish Energy Authority has appointed Fingrid Oyj in its electricity network license as the transmission system operator responsible for Finland's electricity transmission grid [20, 21]. Thus, acting as the system responsible, Fingrid is required to maintain the system security and power balance in Finland as decreed in the Finnish electricity market act [20, 22]. In order to be able to fulfill its responsibilities, Fingrid has arranged market places for essential ancillary services.

2.3.1 Operational reserves

The Finnish power system is an integral part of a larger system, defined as the Northern Europe (NE) Synchronous Area. As part of the measures for sustaining the system security, the appointed transmission system operators have agreed upon maintaining necessary operational reserves. Both the amounts of these reserves and their utilization are defined in the Nordic System Operation Agreement (SOA) and its appendices. [23, 24]

Currently, the operational reserves stated in the appendix two of the System Operation Agreement involve several reserve types. First, the automatic active reserve includes the frequency controlled normal operation and disturbance reserves, referred to as the Frequency Containment Reserves (FCR) in this thesis. These reserves are activated automatically according to variations in the synchronous area's system frequency. Secondly, the fast active disturbance reserve, referred to as the Frequency Restoration Reserve (FRR), is maintained in order to restore the frequency containment reserves on the occasions that they are fully utilized or their capacity is lost otherwise. Since year 2013, the fast active disturbance reserves in the Nordic system included both automatic and manual products. [24, 25] Procuring of Automatic Frequency Restoration Reserve (FRR-A), however, was discontinued at the turn of the year 2016 due to lack of inter-Nordic market place [26].

Fingrid's reserve maintaining obligations and the total amount of each operational reserve type maintained in the NE synchronous area are shown in Table 1. The operational reserves and their dimensioning in the NE synchronous area are discussed in chapter 3 of this thesis.

Table 1: The operational reserves maintained in the Northern Europe synchronous area in 2016 [24, 27].

Reserve product	Fingrid's obligation	Total in the Nordic system
Frequency Containment Reserve for Normal operation (FCR-N)	Circa 140 MW	600 MW
Frequency Containment Reserve for Disturbances (FCR-D)	220 - 265 MW	Varies, maximum 1 200 MW
Automatic Frequency Restoration Reserve (FRR-A)	Not applicable	Not applicable
Manual Frequency Restoration Reserve (FRR-M)	880 - 1100 MW	Varies, maximum 4 100 MW

As shown in Table 1, Fingrid's reserve maintaining obligations are less than one third of the total volume in the system, yet the Finnish ancillary service markets are still sizable. There are separate market places for each of the reserve types. The market places for Frequency Containment Reserve in Normal operation (FCR-N) and Frequency Containment Reserve in Disturbances (FCR-D) are well specified but the Manual Frequency Restoration Reserve (FRR-M) market includes the newly introduced regulating power market [28] and the balancing power market reviewed later in this chapter. As mentioned earlier, during the writing process of this thesis the procurement of FRR-A was halted, due to slow progress in developing of common Nordic market place for the reserve type.

2.3.2 Frequency Containment Reserve market places

Finland's obligations to maintain the Frequency Containment Reserves are fulfilled by purchasing capacity from the domestic markets, other Nordic countries, and from Russia and Estonia via High-Voltage Direct Current (HVDC) interconnections. As shown in Figure 4, the main share of the FCR capacity, however, is procured from generation and loads located in Finland on Fingrid's own domestic reserve markets. Individual market places are available for FCR-N and for FCR-D, although the markets work similarly and both offer two types of contracts. [29] In 2015, the total combined volume of the Finnish FCR-N and FCR-D markets was slightly more than 30,000,000 € [30].

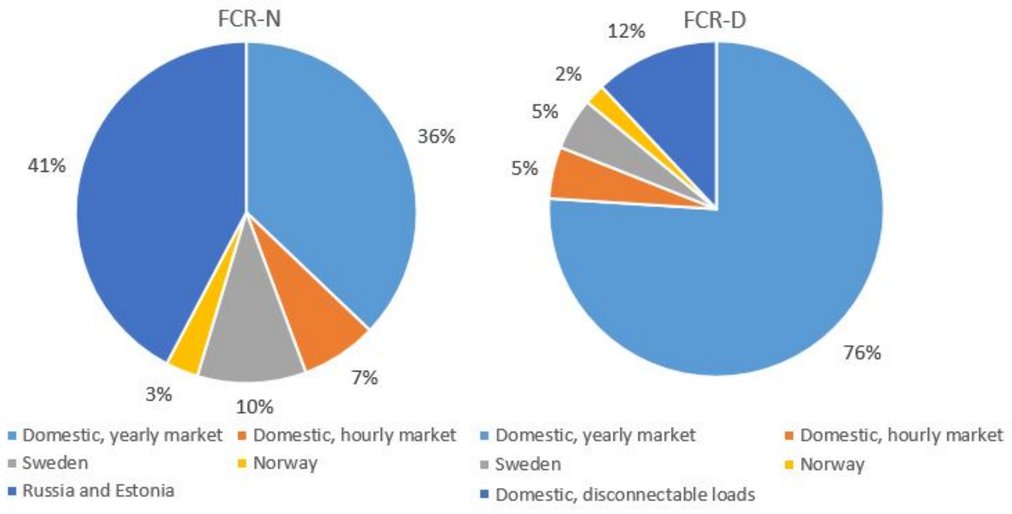

Figure 4: Frequency Containment Reserve procurement per source in Finland in 2015. [30]

First, players may participate in the yearly markets. Every year in September-October a competitive bidding is held, where players offer the FCR capacity they are willing to maintain throughout the next calendar year, priced as €/MW,h (Euros per Megawatt per an hour of availability). The contract sizes start from 0.1 MW for FCR-N and 1 MW for FCR-D. Entering the yearly markets is only allowed through taking part in the bidding: that is, no new players are allowed on the FCR markets in the middle of the calendar year. Fingrid makes contracts for procuring certain amounts of each reserve type, starting from the lowest priced bids. All players participating in the yearly market are guaranteed an equal compensation which is finally determined by the most expensive activated bid. This capacity fee is constant for all hours of the calendar year. The yearly contract players are required to submit their plans for next day's available reserve capacity each day by 18.00 EET. The volume is reported at an accuracy of 0.1 MW and may not exceed the volume stated in the contract. [29, 31]

The second option is to participate in the hourly markets. The hourly market contract allows the player to participate in the daily auction bidding for next day's supplementary reserve procuring in case the reserve capacity available from yearly market contracts is insufficient. Hence, in order to fulfill its obligations, Fingrid purchases the required extra reserve power capacity from the hourly markets once a day. The bidding on hourly markets is made for blocks of single hours and the bids are submitted by 18.30 EET. The bid volumes may range from 0.1 MW to 5 MW in case of FCR-N and from 1 MW to 10 MW for FCR-D, at an accuracy of 0.1 MW. Again, the offered capacity is priced as €/MW,h. For each hour, Fingrid arranges the bids in price order starting from the lowest, and the capacity fee for the hour is determined by the most expensive activated offer. Players participating in the yearly markets are allowed to take part in the bidding, provided that the volumes stated in their yearly contracts are fully supplied for that hour. [29, 32]

As indicated above, all participants on the FCR markets are compensated with a capacity fee, regardless of the contract type. For capacity participating through yearly contracts, the annually constant capacity fee is paid for the hours the offered capacity is actually supplied to the markets. Thus, only the capacity indicated in the daily submitted reserve plan is eligible for compensation. On hourly market, all activated offers for the specific hour are paid the capacity fee determined the previous day. On the other hand, if the offered reserve power does not activate when needed or activates only partly, Fingrid pays the capacity fee for only the activated share. Additionally, a charge of 50% of the capacity fee for the hour is issued as a penalty for capacity not supplied. [31, 32]

In addition to the capacity fee, the FCR-N market involves a fee connected to the electrical energy supplied to or consumed from the grid in the reserve providing process. This energy fee is necessary due to the nature of the reserve: unlike in FCR-D use, FCR-N use requires the reserve providing resource to be able to down-regulate as well as up-regulate, and FCR-N also activates more frequently, typically several times within an hour. The energy fee is calculated according to Fingrid's FCR application instructions. In principle, the reserve provider is paid for the up-regulating energy and charged for down-regulating respectively. The up- and down-regulation prices formed on the Nordic balancing power market are applied for both hourly and yearly contract markets. [29, 31]

Table 2: Yearly contract volumes in the Finnish FCR markets [33].

Year	FCR-N capacity (MW)	FCR-D capacity (MW)
2011	71	244,3
2012	72,7	346,9
2013	73,5	299,8
2014	75,4	318,7
2015	73,6	297,5
2016	89	367

The majority of FCR capacity in Finland is procured by the yearly contracts whereas hourly bidding is only used as a supplement in order to ensure the availability of adequate capacity and fulfilling of reserve maintaining obligations. This can be noticed when comparing Fingrid's total obligations indicated in Table 1 and the yearly contract volumes on FCR markets shown in Table 2. Additionally, the realized procurement volumes illustrated in Figure 4 support this notion. What is more, in Figure 5 a slightly rising trend in FCR capacity procured through yearly contracts is noticed, although the total reserve obligations have remained fairly constant.

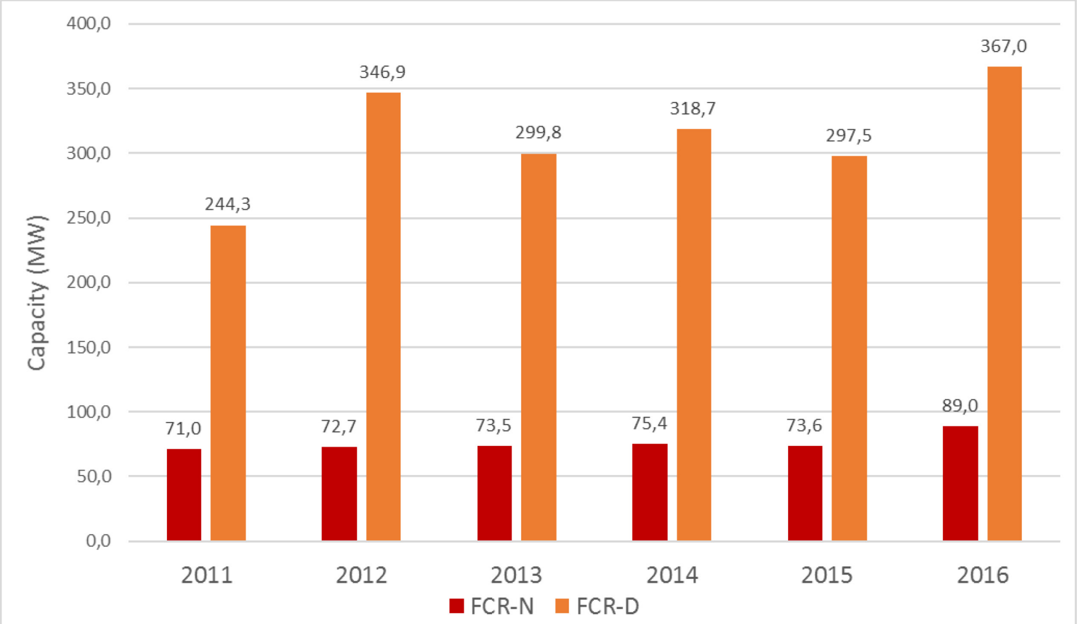

Figure 5: The FCR capacity procured through yearly contracts in Finland between 2011 and 2016. [33]

Regardless of the contract type, the same technical requirements for the offered reserve capacity apply. Especially the functioning of the control systems is pre-specified: the offered capacity has to be reliably available and thus the control system needs to react correctly according to deviations in the grid's frequency. Therefore, a set of regulating tests are performed to all systems entering the FCR markets. The technical requirements are introduced and studied in detail in chapter 4 of this thesis.

2.3.3 Procurement of Frequency Restoration Reserves

Fingrid procures the required manually activated Frequency Restoration Reserve capacity mainly by utilizing its own and leased reserve power plants scattered around Finland and by acting on the Nordic balancing power market. The reserve power plant capacity, however, may not always be available due to, for example, annual maintenance periods. Consequently, in order to ensure the availability of adequate FRR-M capacity at all times, Fingrid introduced a new reserve capacity market place in the beginning of year 2016. This regulating power market works hand in hand with the balancing power market to the extent that the participating players are required to have a valid balancing power market contract. Additionally, most of the balancing power market's bidding rules are applied. [34]

The balancing power market is a common Nordic market place held by the Nordic TSOs. Players taking part in this market offer their adjustable active power production or consumption resources as either up or down-regulating bids. In up-regulation the player offers to increase power production or to cut down on its power consumption, whereas in down-regulation the player decreases its production or increases its consumption. Hence, with upper balancing power bids the player offers to sell power to its TSO and with lower balancing power bids it offers to purchase power from its TSO. [19, pp.393-394] The principle of bidding on balancing power market is illustrated in Figure 6.

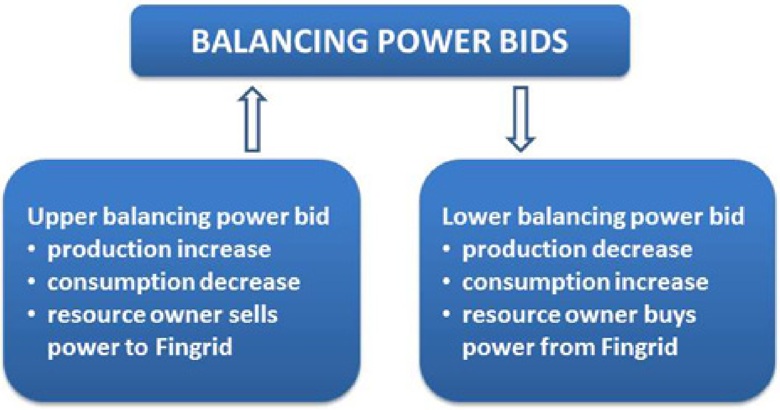

Figure 6: Bidding on balancing power market. [35]

Participating in the balancing power market requires a production or consumption resource of at least 10 MW that is available in 15 minutes after the order. The offered amount of power has to remain activated for the whole hour and then return to initial state in 15 minutes respectively. The resource may be aggregated: that is, it may consist of more than one units of less than 10 MW in power. In addition to proper power source or load, participating requires the player to have an existing balance service agreement or to make a separate balancing power market contract. In case of a Finnish player, the contracts are made with Fingrid. [19, 36]

On the balancing power market the bidding is made for blocks of single hours. For each hour a single bid list for the Nordic system is prepared and the bids are placed in price order. In principle, the upper balancing bids will be used starting from the cheapest ones and lower balancing bids starting from the most expensive ones. However, this may not always be possible due to congestion and other reasons related to the state of the power system. In such cases, bids are activated in the order allowed by the power system and some bids may be left partly or completely unused. [36]

Schedule for bidding is decreed in the balancing power market contract. Players may place their bids as early as in the beginning of the day preceding the target hour but no later than 45 minutes before the hour of use. This is also the deadline for cancellations and any amendments to the bids. It is possible to bid after the closing time via telephone but these bids are not guaranteed to get activated. Contents of a bid are also predefined: in addition to information on pricing and amounts of offered up or down-regulating capacity, the bid must also include the name of the resource and, in order to avoid possible congestion in power transmission, whether the resource is located North or South of the 64° latitude. [19, 36]

The actual price paid for up or down-regulating power is determined individually for each hour of use, and it applies to all of the activated bids. That is to say, each player participating in the balancing process is compensated equally. In case of up-regulation, the upper balancing power price is the most expensive offer activated. Respectively, for down-regulation the lower balancing power price is the lowest activated offer. However, Elspot’s FI area price acts as a limit in both cases: it defines the minimum up-regulation and the maximum down-regulation prices. The realized prices are published on Nord Pool’s website after the hour of use. In addition to compensations from the activated power, the electrical energy produced or consumed in the regulating process is either paid for or charged by Fingrid, depending on the direction of the regulation. Again, the realized up or down-regulation price for the hour of use is applied. [36]

3 Frequency regulation and reserves

One of the most important ancillary services utilized in controlling power systems is Load-Frequency Control (LFC). The Load-Frequency Control entails the processes of controlling the power flows between the zones in the power system, and more importantly from the point of view of this thesis, controlling the system frequency in the power system. [37] In order to maintain the system frequency between the limits set for normal operation and to avoid blackouts, arranging a sufficient supply of reserve power capacity is needed to adjust the continuously occurring imbalances in the system.

In this chapter, the system frequency control and the active power reserves in European power systems is studied. Different concepts and processes related to frequency control, including the respective reserve types, are reviewed. The chapter begins with explaining the key concept of operational security, as it is essential in understanding the necessity of arranging effective frequency control in a power grid. Next, the documents guiding the application of load-frequency control in European countries are introduced before the main technical terminology is discussed. Finally, a view into the process structures adopted into use in the local Northern Europe synchronous area is taken.

3.1 Operational security

One of the major concepts often utilized in evaluation of a power system's performance level is operational security. It is closely related to two other concepts, operational reliability and stability. Operational reliability refers to system's long-term ability to adequately supply electricity to the customers, whereas stability describes its dynamic ability to withstand disturbances and remain intact. [38] Operational security, on the other hand, describes the system's ability to maintain operation during and after disturbances without losing stability, regardless of the resulting operating conditions. That is, in order to be secure, the system must withstand the possible over-loading of equipment and power lines after the disturbance. Moreover, it is noteworthy that a power system's security and stability are variable factors reflecting the present state of the grid, whereas reliability is an average calculated over a longer period of time. [19, pp.276-277]

Guidelines for maintaining the operational security in the NE synchronous area are decreed in the System Operation Agreement. The Nordic TSOs have agreed upon following the N-1 criterion in both planning and operating their subsystems. [24] The criterion is based on a simple principle: in normal operating conditions no single fault is allowed to cause an interruption in electricity supply nor significantly affect the power quality, that is, substation busbar voltages and system frequency. Additionally, the system must recover in 15 minutes and be able to withstand another fault afterwards. The direst fault that may occur in the system, called the dimensioning fault, varies over time according to power system's changing operating conditions and acts as the yardstick against which the system has to be secure. [19, pp.74-75]

Sometimes the operational security if a power system is safeguarded by other methods. In the Continental Europe (CE) synchronized area, for example, N-2 criterion is applied in dimensioning of Frequency Containment Reserves due to the significantly larger size of the system when compared to the Nordic system. The greater volumes of generation and consumption in the system lead to an increased risk of another disturbance occurring before the system has managed to recover from the initial disturbance, hence the inadequacy of merely following the N-1 criterion. The reference incident of two direst disturbances occurring at the same time is no longer called the dimensioning fault but the dimensioning incident when the N-2 criterion is concerned. [39, pp.57-58]

As mentioned, the magnitude of the dimensioning fault or the dimensioning incident is not a constant. The operating conditions of a power system are changing continuously due to fluctuations in power generation and demand, switching operations and faults of different sizes, for example. Thus, the current dimensioning fault and its impact on the power system varies accordingly. Typically, the dimensioning fault is one of the following [19, pp.74-75]:

- The largest production unit connected to the system is disconnected abruptly.
- A power transmission line is tripped.
- A busbar fault at an electrical substation.
- An arbitrary major component is tripped, typically a power transformer.
- An HVDC interconnection is tripped. [39]

The operational security level of a power system is determined by division to Operational States. The System Operation Agreement lists five operational states [24]:

- The Normal State entails that power balance is maintained in the power system, and that frequency, voltages and transmissions are within the limits set for them. Additionally, the requirements for available reserve power capacity are met. Thus, the N-1 criterion is fulfilled.
- The Alert State is otherwise similar to normal state but the reserve requirements are not fulfilled. It is triggered when, for instance, fully activated Frequency Containment Reserves are not relieved by the Frequency Restoration Reserves within the time limits. A dimensioning fault during the Alert State would lead to triggering of the Disturbed State or the Emergency State.
- The Disturbed State entails that the power balance in the system is maintained, but either the frequency, voltage or transmission limits are exceeded. Additionally, return to Normal State would take more than fifteen minutes.
- The Emergency State entails that load-shedding or production-shedding is initiated in order to safeguard the system against blackouts. Furthermore, the grid could be divided into separated, islanded areas.
- The Network Collapse is the extreme operational state in which the whole power system or parts of it suffer from blackouts [19, pp.281-282].

Today, power systems are complex, geographically dispersed and require significant investments to build and maintain. There seldom are back-up systems for whole power systems, which makes recovering from disturbances, such as dimensioning incidents or severe power imbalance, critical. Hence the need for effective operational reserves: in order to retain operational security, the availability of a sufficient, geographically distributed volume of reserve capacity has to be assured at all times. [19, pp.271-272]

3.2 European guidelines for load-frequency control

Naturally, the Nordic transmission system operators' common objective is to establish a highly stable and reliable power system. However, this is not the only motivator for close cooperation as European level rules, called network codes, oblige the TSOs to collaborate on many fields. These codes are developed by ENTSO-E (European Network of Transmission System Operators for Electricity), an association that currently represents 42 electricity transmission system operators from 35 European countries. ENTSO-E was founded in 2009 to act as an association that enhances international TSO cooperation and enables further development of common European electricity markets, within the limits set by European energy and climate targets. [40]

The main tools for realizing the association's objectives are the network codes ENTSO-E prepares for the European Commission. A network code is a set of rules that is applied to one or more parts of the energy sector in the European Union. Once a code comes to effect, it becomes legally binding and this way equivalent to European Union's regulations. 10 codes have been issued so far and they can be divided into three categories according to what they are related to: the codes concerning grid connection, market related codes and the codes that cover operating of power systems. The Network Code on Load-Frequency Control and Reserves (NC LFCR), which is examined in this thesis, belongs to the last category along with network codes on Operational Security (NC OS), Operational Planning & Schedules (NC OPS) and Operational Procedures in an Emergency (NC EP). However, in order to simplify the application of all three codes, the codes LFCR, OS and OPS are merged together to form a single System Operation Guideline (NC SOG). [41] The NC LFCR will act as the basis for Part IV of the NC SOG [42].

The Network Code on Load-Frequency Control and Reserves acts as the basis for implementing frequency control processes in majority of Europe. The main objective of the code is to harmonize the different practices applied in ENTSO-E's member countries in three ways. First, the NC defines common terminology related to load-frequency control and reserves to be used by all member TSOs. Secondly, the code sets the minimum technical requirements that are to be taken into account when designing the LFC structures and reserves in a synchronous area. These requirements apply not only to Transmission System Operators but to all parties involved in arranging the operational reserves: the reserve connecting Distribution System Operators (DSOs) and reserve providers are also affected. Thirdly, the NC defines common criteria to be utilized in evaluating the frequency quality of a synchronized area and thus the performance of its load-frequency control. This allows comparing the results of frequency control both within a synchronous area and between synchronous areas. [39, pp.9]

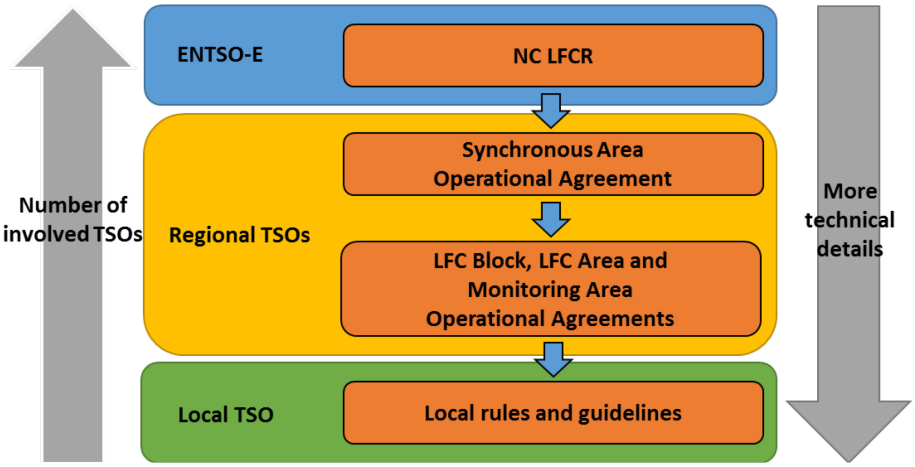

Figure 7: The hierarchy of rule setting documents.

The rules stated in the NC and its supporting documents are generic on purpose. Therefore, the NC itself contains requirements for creating more in-depth rule setting documents that are applied in regional levels, called Operational Agreements. Unlike the NC, these Operational Agreements are specific for single synchronous areas or parts of them only. [43, pp.17-20] The need for smaller scale agreements arises from the difficulty of including all the necessary values and operational procedures in the NC. For instance, the technical details of LFC implementation, assigning of TSO specific roles and LFC Block or LFC Area specific rules for sharing or exchanging of reserves are excluded. These have to be agreed upon on Synchronous Area or LFC Block level, typically, as harmonization at the European or synchronous area level might prove impossible. [39, pp.13-15] The hierarchy of areas within synchronous areas is introduced in section 3.41.

The minimum contents of operational agreements are predefined: for example, in the Synchronous Area Operational Agreement the utilized reserve types as well as their dimensioning principles have to be stated. The TSOs' common duties and possible special responsibilities, such as roles related to operation coordination, are also included. [43, pp.17-20] Depending on the internal hierarchy of a synchronous area, further need for smaller scale operational agreements may exist. In Figure 7 is illustrated the hierarchy formed by the different rule setting agreements and documents that concern load-frequency control in Europe. It is noteworthy that the technical detail of the documents increases towards the bottom of the figure but, on the other hand, the number of involved TSOs decreases at the same time. The Network Code on Load-Frequency Control and Reserves lies on the top, as it sets the minimum technical requirements and obliges all ENTSO-E's members. Below the NC are the Operational Agreements that involve a smaller number of TSOs operating in the same region. On the bottom are the detailed rules and guidelines set by the local TSO that direct the Distribution System Operators and reserve providers. It is to be noted, that document name System Operation Agreement (SOA) is used in the Nordic countries instead of Synchronous Area Operational Agreement. Furthermore, the terminologies used in the SOA and in the NC LFCR are partly contradictory. For instance, the NC's definition Northern Europe (NE) Synchronous Area corresponds to the definition Nordic Synchronous System used in the SOA. In this thesis, however, the terminology defined in the NC is used as it better corresponds to the Finnish TSO Fingrid's documents. The application of the Network Code, the SOA and the local rules in Finland and other Nordic countries are discussed in chapter 4 of this thesis.

The Network Code on Load-Frequency Control and Reserves contains legally binding rules that often lack explanations. Hence, the NC is supported with other documents that provide more insight into the code. The Supporting Document for the Network Code on Load-Frequency Control and Reserves contains plenty of background information and more accurate explanations for most of the requirements set in the NC [39, p.4], whereas a third document has been developed to explicitly explain the requirements set for FCR units with limited energy reservoir [44, p.3]. Contrary to the primary document, the supporting documents are not legally binding. However, consulting the supporting documents is essential in understanding and applying the network code [39, p.4].

In the next sections of the thesis the contents of the NC LFCR and its supporting documents are examined. Although studying the Continental European (CE) synchronous area is not in the particular focus of this thesis, covering it is included as it offers a more versatile and larger scale example of the network code application than the Northern Europe synchronous area.

3.3 Frequency quality

The nominal system frequency in each of the synchronous areas covered by ENTSO-E's network codes is 50 Hz [43, p.22]. Deviations from the nominal frequency directly indicate the current active power balance in the system. Effectively countering the imbalances with sufficient active power reserves is crucial regarding the operational security in the system. Thus, monitoring and evaluating the frequency quality, especially frequency deviations, is essential.

Typically, three indices are utilized when evaluating slow variations in the system frequency. First, a frequency deviation occurs when the real system frequency differs from the nominal system frequency. The size of the deviation is calculated by comparing the real system frequency to the nominal system frequency according to (1): [45, p.3]

$$\Delta f = f - f_r \tag{1}$$

where

Δf is the frequency deviation (Hz),

f is the real frequency in the system (Hz) and

f_r is the nominal system frequency (Hz).

Secondly, the relative frequency deviation $\varepsilon_f(\%)$ is calculated according to (2): [45, pp.3]

$$\varepsilon_f(\%) = \frac{f - f_r}{f_r} \cdot 100 \tag{2}$$

where

f is the real frequency in the system (Hz) and

f_r is the nominal system frequency (Hz).

Thirdly, the mean value of the system frequency over 10 seconds is calculated constantly. The mean values shall remain within a range set in the standard related to distribution system voltage supply. Limits for allowed frequency deviations in Finland are defined in the standard SFS-EN 50160. However, these limits are only applied to electricity distribution systems operated with a rated voltage of 150 kV or below. [46]

From the point of view of this thesis only the frequency deviations are interesting. The NC LFCR, however, lists various additional parameters for evaluating the frequency quality in a power system [43, pp.22-24]. The Frequency Quality Defining Parameters serve as the basis for reserve dimensioning. They define the necessary limits within which the system frequency is to be maintained during normal operation and after disturbances. It is to be noted, that the Frequency Quality Defining Parameters include not only frequency limits, but also time limits concerning persistence and clearing of frequency deviations. [39, pp.17-18]

The Frequency Quality Defining Parameters for the NE synchronous area given in the NC are listed in Table 3. For comparison, the corresponding values for the CE synchronous area are also provided. By examining the values related to frequency deviations, it is clearly visible that stricter limits are applied to the CE system. This is due to the considerable difference in scale. Even though the reference incident in the CE system is twice that of the NE system's, 3,000 MW in CE [39, p.110] and 1,400 MW in NE [24], the immediate consequences are less serious for the CE system. For example, the Maximum Instantaneous Frequency Deviation, that is the instant frequency drop caused by the reference incident, is deeper in the NE system. Furthermore, wider ranges for the Standard Frequency and the Maximum Steady-State Frequency Deviation are allowed in the NE synchronous area. On the other hand, the predefined time limits are exactly the same for both systems. The Alert State is triggered should the conditions for remaining in normal operational state remain violated for five minutes, and the timeframe for restoring the frequency back within the Standard Frequency Range is 15 minutes.

Table 3: The Frequency Quality Defining Parameters. [43, p.23]

Parameter	Synchronous area NE	Synchronous area CE
Standard Frequency Range	± 100 mHz	± 50 mHz
Maximum Instantaneous Frequency Deviation	1000 mHz	800 mHz
Maximum Steady-State Frequency Deviation	500 mHz	200 mHz
Time to Restore Frequency	15 minutes	15 minutes
Frequency Restoration Range	± 100 mHz	Not applicable
Alert State Trigger Time	5 minutes	5 minutes

Synchronous areas are designed to withstand the reference incident on the condition that the system frequency is close to the nominal value, that is, in the Standard Frequency Range. Reference incidents occurring while the frequency is not within the predefined range might lead to a severe disturbance in the system. Thus, the more time the system frequency stays outside of the Standard Frequency Range, the higher the risk of disturbances. [39, p.20]

In addition to the Frequency Quality Defining Parameters, the Network Code on Load-Frequency Control and Reserves defines the Frequency Quality Target Parameter for each synchronous area. This is the number of minutes per year the frequency in a synchronous area is allowed to stay outside of its Standard Frequency Range. Currently, the NC sets the Frequency Quality Target Parameter at 15,000 minutes per year for the Northern Europe and Continental Europe synchronous areas [43, p.23]. However, the TSOs operating in the NE synchronous area have agreed on setting the current target at 10,000 minutes per year [47]. For the CE synchronous area the value results from probabilistic risk analysis whereas for the NE synchronous area analysis of historical data is used [39, p.21]. Violating the yearly limit obliges the TSOs in charge of the synchronous area to take actions in addressing the causes to inadequate frequency quality [39, p.33].

Behavior of system frequency over longer time periods than minutes or hours is also a measure of frequency quality in a power system. Persisting over or underfrequency affect the speed of electric clocks driven by synchronous motors, making them show increasingly incorrect time. Thus, the Electrical Time Deviation reflecting the average frequency in the system is monitored. The Electrical Time Deviation is calculated according to (3): [19, p.363]

$$\Delta t = \int \left(\frac{f - f_N}{f_N} \right) dt \tag{3}$$

where

Δt is the Electrical Time Deviation (s),

f is the real frequency in the system (Hz) and

f_N is the nominal system frequency (Hz).

In order to limit the Electrical Time Deviation indicating the discrepancy between the electrical time and the astronomical time, the system frequency is aimed to be maintained at the nominal value. [19, p.363]

In spite of the best efforts made to maintain the nominal frequency, inevitably a time deviation develops. However, TSOs may limit the deviation within a predefined range by controlling the daily average frequency. For this purpose each synchronous area shall appoint one TSO to take the responsibility of monitoring the electrical time deviation and, whenever needed, coordinating and controlling the corrective measures [43, p.63]. In Europe, the Electrical Time Deviation is typically allowed to increase to no more than a couple of tens of seconds into either direction before corrective actions, that is intentionally maintaining over or underfrequency, are started. [39, p.94]

The TSOs of each synchronous area have the right to further define in the Synchronous Area Operational Agreement the default Frequency Quality Defining Parameters given in the NC. The modified values, however, must be based on careful assessment of historical behavior of the system frequency and the future outlook of the system. The future increase in generation from renewable energy sources, for instance, may be considered, as it replaces conventional, inertia providing generation. [39, pp.19-22]

3.4 Load-frequency control terminology

In order to understand the technical requirements set for the operational reserves, it is necessary to discuss the terminology related to Load-Frequency Control and reserves introduced in the NC LFCR. The local NE synchronous area is simply structured when it comes to operational reserve arrangements, whereas the CE synchronous area is far more complex and includes several hierarchical levels. Thus, the LFC arrangements within European synchronous areas are introduced in the beginning of this section. Next, fairly new concepts that are especially interesting from the perspective of this thesis are discussed. The definitions Reserve Providing Unit and Reserve Providing Group are of great importance as they facilitate and limit the aggregating of reserve power capacity from multiple sources. In addition to these, the reserve providing units with limited energy capacity, such as Battery Energy Storage Systems (BESS), are topical. They are best suited for FCR use specifically, hence, these are discussed in the Frequency Containment Process section. Finally, a brief overview of the Frequency Restoration and the Reserve Replacement Processes is taken.

3.4.1 Area hierarchy

The ENTSO-E's network codes cover several separate synchronous areas in Europe. Each of these areas are obliged to establish the necessary processes and structures to ensure the operational security. However, the operation of LFC processes, such as the operational reserves in particular, is divided between operational areas that not always correspond to whole synchronous areas but to smaller divisions instead [39, p.38].

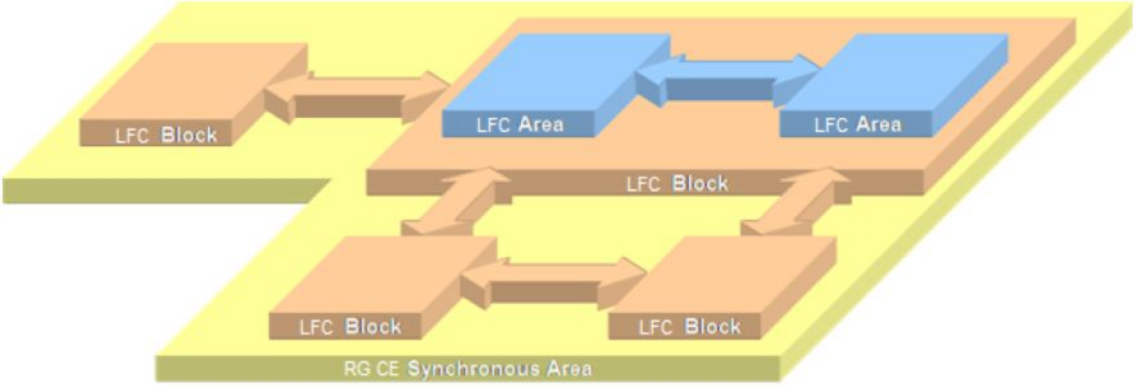

Figure 8: The division of load-frequency control structures within the Continental Europe (CE) synchronous area. [39, p.109]

As shown in Figure 8, the CE synchronous area, for instance, is divided into sublevels with a certain hierarchy. In principle, a synchronous area consists of one or several LFC Blocks which in turn include at least one LFC Area. The LFC Areas are in the same manner even further divided into Monitoring Areas and finally Scheduling Areas. The different operational area types are needed in order to define the Transmission System Operators' responsibilities in different areas and to limit the number of TSOs involved in smaller scale decision making. Consequently, fewer TSOs are operating in a LFC Area than in the LFC Block it is part of, and the LFC Area operational agreement includes more area specific rules than the corresponding agreement for the LFC Block. For example, the dimensioning of FCR is agreed upon on the synchronous area level by all the TSOs operating in the system, as the Frequency Containment Reserves are common for the whole synchronous area whereas the Frequency Restoration Reserves, on the other hand, are dimensioned on the LFC Block level by only those TSOs that operate in a certain block. [39, pp.38-41]

Another reason for dividing whole synchronous areas into smaller operational areas is to enable and effectively coordinate sharing and exchanging of reserves between Transmission System Operators. The NC LFCR states that TSOs are within certain limits allowed to share or exchange parts of their reserve maintaining obligations, namely Frequency Containment Reserves, Frequency Restoration Reserves or Replacement Reserves (RR), with other TSOs [43, pp.52-62]. Exchanging of reserve capacity entails that the TSO of area A agrees to maintain extra reserve capacity on behalf of the TSO of area B, thus allowing area B to connect less reserve capacity than what it is originally obliged to. This arrangement leads to the situation where the total reserve capacity in the system remains unchanged and both TSOs fulfill their obligations although the geographical distribution of the reserves is changed. Sharing of reserve capacity, on the other hand, denotes that the TSO of area A agrees to share a part of its reserve capacity with the TSO of area B. No additional reserve capacity is maintained in area A which means that the total reserve capacity in the system decreases. Hence, sharing of reserves is only allowed if both areas involved in the sharing rarely need the full reserve capacity simultaneously. It is to be noted, that several restrictions for sharing and exchanging of different reserve types are set in the NC. Moreover, the detailed rules are decreed in the operational agreements. [39, pp.75-77]

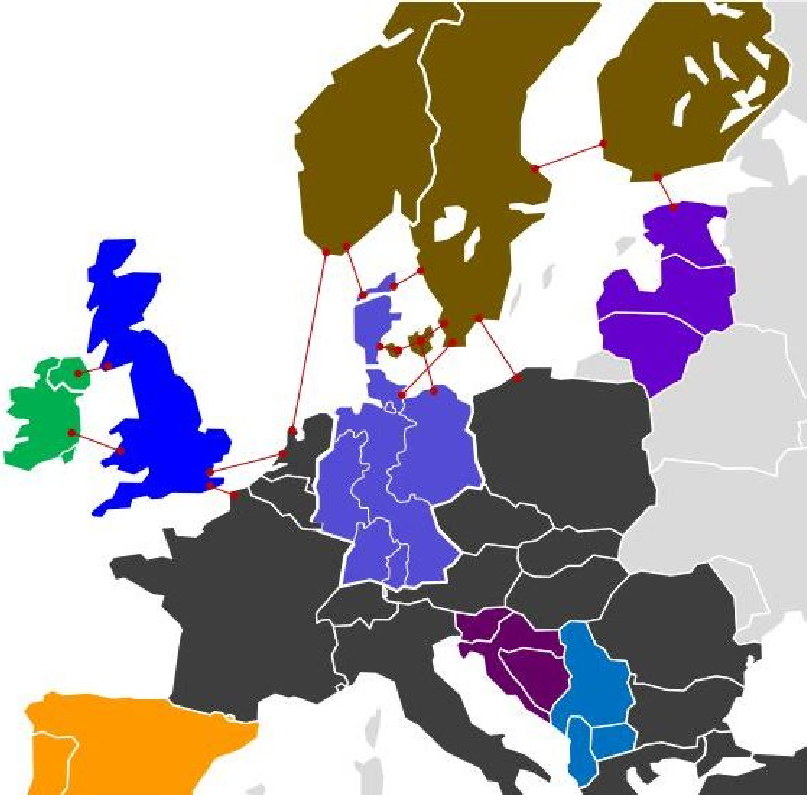

Figure 9: The five synchronous areas in Europe and their division into smaller operational areas. [39, p.42]

Figure 9 illustrates how the five European synchronous areas are geographically divided into LFC Blocks and LFC Areas. The Northern Europe, Great Britain and Ireland synchronous areas simply correspond to single LFC Blocks and single LFC Areas, as no further division into smaller operational areas is utilized [39, p.41]. The power networks in the Baltic countries are synchronized into the Belorussian and Russian grids, thus the Baltic TSOs collaborate with the other TSOs of the BRELL (Belorussia, Russia, Estonia, Latvia, Lithuania) grid [48]. The rest of the continental Europe, bordering Belorussia, Ukraine and Moldova, form the Continental Europe synchronous area. According to the principle shown in Figure 8, this vast synchronous area consists of interconnected smaller operational areas, which are clearly visible in Figure 9: the dark grey colored LFC Blocks correspond to single LFC Areas, whereas the more brightly colored LFC Blocks, such as the one formed by Germany and Western Denmark, include two or more LFC Areas [39, p.41].

3.4.2 Aggregation of reserve power capacity

Aggregated reserve power capacity has started to emerge in the Finnish ancillary service markets. The first industrial and domestic pilot projects finished with promising results [49, 50], and the first aggregation of decentralized household consumption entered the Finnish FCR-N market in March 2016 [5]. At present, however, the Finnish TSO Fingrid's grid codes regarding frequency controlled reserves do not recognize aggregating of reserve capacity, although it is not prohibited either [29]. Next, the two methods of implementing aggregation are introduced.

The NC LFCR allows aggregating FCR, FRR or RR capacity in its definitions for Reserve Providing Units and Reserve Providing Groups. An aggregation of power capacity may consist of Power Generating Modules, defined in the Network Code for Requirements for Grid Connection Applicable to all Generators (NC RfG), and Demand Units, defined in the Network Code on Demand Connection (NC DCC). A Power Generating Module is an electrical energy generating ensemble that is connected to the grid through single connection point [51]. According to the definition, a conventional power plant, a wind turbine or a photovoltaic solar power system, for instance, may act as a Power Generating Module. On the contrary, a Demand Unit is an indivisible set of electrical installations with an adjustable electricity demand [52], ranging from domestic boilers to largest industrial facilities, for example. Energy storages with the capability to generate and consume power, such as pumped-storage hydropower plants and Battery Energy Storage Systems (BESS), are considered either as Power Generating Modules or Demand Units depending on the mode of operation [39, p.64].

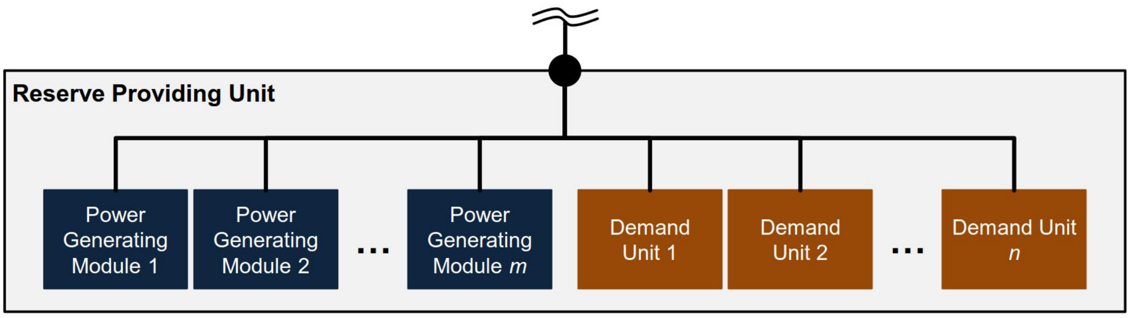

Figure 10: An example of Reserve Providing Unit [44]. A Reserve Providing Unit consists of Power Generating Modules and Demand Units connected to a common connection point.

In a Reserve Providing Unit a combination of Power Generating Modules and Demand Units may be included as long as they share a common connection point to the grid [43, p.12]. The principle is shown in Figure 10, in which a single Reserve Providing Unit is aggregated from *m* pieces of Power Generating Modules and *n* pieces of Demand Units. In the figure, the black dot linking all the units together represents the common connection point. By definition a single Power Generating Module or Demand Unit is also considered a Reserve Providing Unit. Furthermore, more concrete examples of possible formations of Reserve Providing Units are illustrated in Figure 11. It is essential to note, that although specific rules are set regarding single reserve capacity providing Power Generating Modules or Demand Units, according to the NC LFCR the individual subunits in a Reserve Providing Unit are not required to fulfill these requirements alone. That is, none of the subunits forming a Reserve Providing Unit are required to comply with the rules as long as the complete ensemble functions as required. [39, pp.64-67]

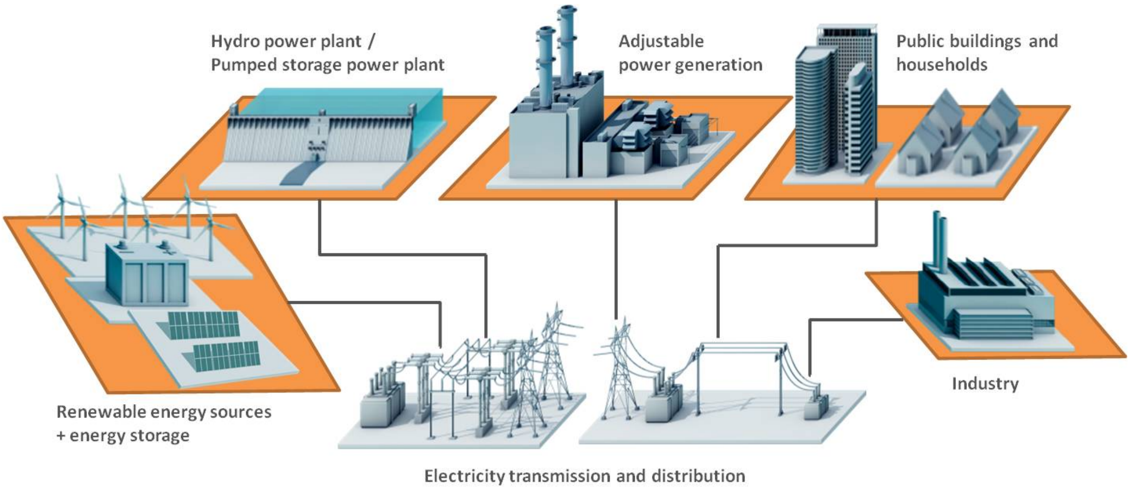

Figure 11: Example formations of Reserve Providing Units. Each orange area represents an individual Reserve Providing Unit connected to the electricity transmission and distribution system via a common connection point.

The definition of a Reserve Providing Group allows the aggregation of capacity in the same manner as it is allowed with Reserve Providing Units. The fundamental difference between a Reserve Providing Unit and a Reserve Providing Group, however, is how the individual units are connected to the grid. This difference is noticed when comparing Figure 10 to Figure 12: although both ensembles may consist of an arbitrary combination of Power Generating Modules and Demand Units, the definition of Reserve Providing Group includes no requirement for a common connection point. Thus, a Reserve Providing Group may be aggregated from subunits connected to any point in the grid and, consequently, a Reserve Providing Group may include one or several Reserve Providing Units that already consist of aggregated capacity. Again, no single subunit needs to fulfill the applied requirements alone, as long as the complete ensemble complies with the rules. [39, pp.64-67] The first commercial application of domestic demand response in the Finnish ancillary service markets fulfills the criteria of a Reserve Providing Group: a Finnish energy company Fortum Oyj aggregates water heating capacity from several households to participate in the up-regulation and down-regulation on the FCR-N market [5].

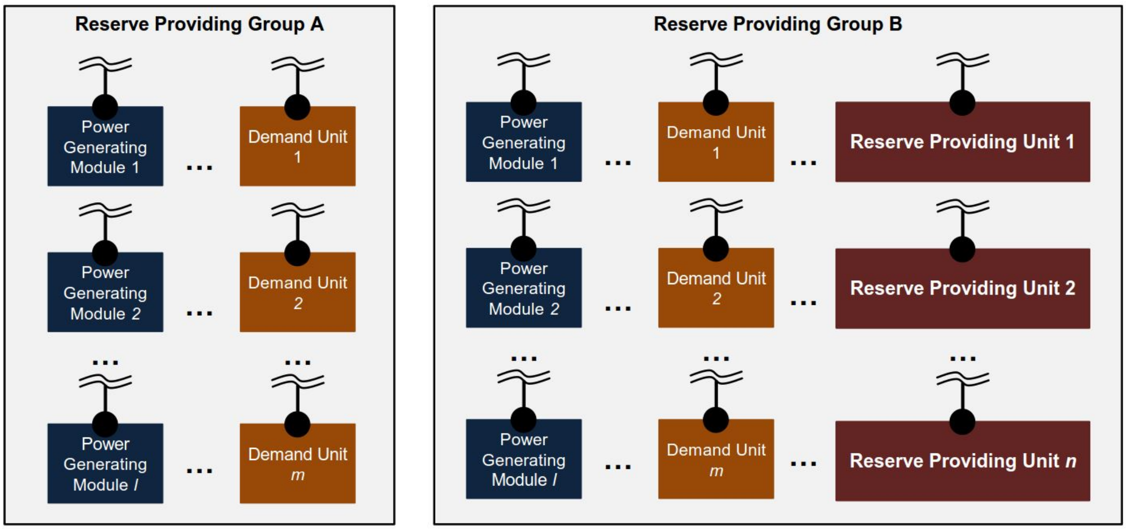

Figure 12: Two examples of Reserve Providing Groups [44]. Group A consists of an aggregation of Power Generating Modules and Demand Units, whereas Group B includes Reserve Providing Units in addition.

The minimum unit specific information, such as time-stamped active power data, that is exchanged between the reserve provider and the TSO is pre-defined. The same requirements apply to Reserve Providing Units and Reserve Providing Groups, although each TSO is entitled to set additional requirements regarding aggregated capacity. On the other hand, the reserve provider is allowed to aggregate the required data as long as none of the connected units exceeds the nominal power of 1.5 MW. However, the activation of individual units within a Reserve Providing Group or a Reserve Providing Unit shall always be separately verifiable. [43]

In order to distinguish the Reserve Providing Units from an arbitrary technical unit that provides FCR capacity, in the following chapters of this thesis the definition technical unit is used when denoting to the latter.

3.4.3 Frequency Containment Process

As defined in Article 33 of the NC LFCR, the objective of the Frequency Containment Process is to stabilize the synchronous area's system frequency by activating the Frequency Containment Reserves [43, p.32]. Preparing for stabilizing actions is necessary due to uncertainties in forecasting the total consumption and generation in the synchronous area and in order to maintain the operational security. The stabilizing effect is achieved by activating the FCR in proportion to the extent of the frequency deviation.

The contents of Frequency Containment Process, including the exact criteria for FCR dimensioning, are defined on the synchronous area level [39, p.13]. In general, the total FCR capacity maintained shall at least amount to the reference incident in the synchronous area or, alternatively, to the results of a probabilistic assessment. Additionally, the Frequency Quality Defining Parameters are to be considered in the estimations. The calculated FCR capacity shall ultimately suffice in any incident happening less frequently than once in twenty years. [43, p.41] The required total FCR capacity in the synchronous area and the risk of FCR exhaustion, that is, inadequacy of the reserves, shall be assessed annually or more often based on the information gathered on historical behavior of the system frequency. [43, p.27] Moreover, the unplanned unavailability of the largest FCR providing technical unit, corresponding to 5% of the total FCR capacity at most, shall be taken into account in the dimensioning process [43, p.45].

The TSO specific FCR obligations shall be assessed annually. The obligations are distributed according to the subsystem specific total yearly electrical energy consumptions, thus the largest subsystem usually provides the largest share of the reserve. [43, pp.41-42]. The TSOs operating in the same synchronous area are allowed to exchange parts of their FCR maintaining obligations either within the synchronous area or with TSOs from other synchronous areas via HVDC interconnectors. The maximum exchangeable share of the initial FCR obligation is decreed in the Operational Agreements, as the TSOs are obliged to procure at least a share of their obligations from their own subsystems in order to ensure a sufficient amount of reserve is available during possible islanded operation. On the contrary, sharing of FCR capacity within a synchronous area is prohibited as this would lead to explicitly violating the FCR dimensioning criteria and endangering the operational security. Furthermore, sharing of FCR between synchronous areas would lead to inevitable deficit of FCR capacity in either one of the involved synchronous areas. Sharing of FCR between synchronous areas is therefore prohibited. [43, pp.52-59]

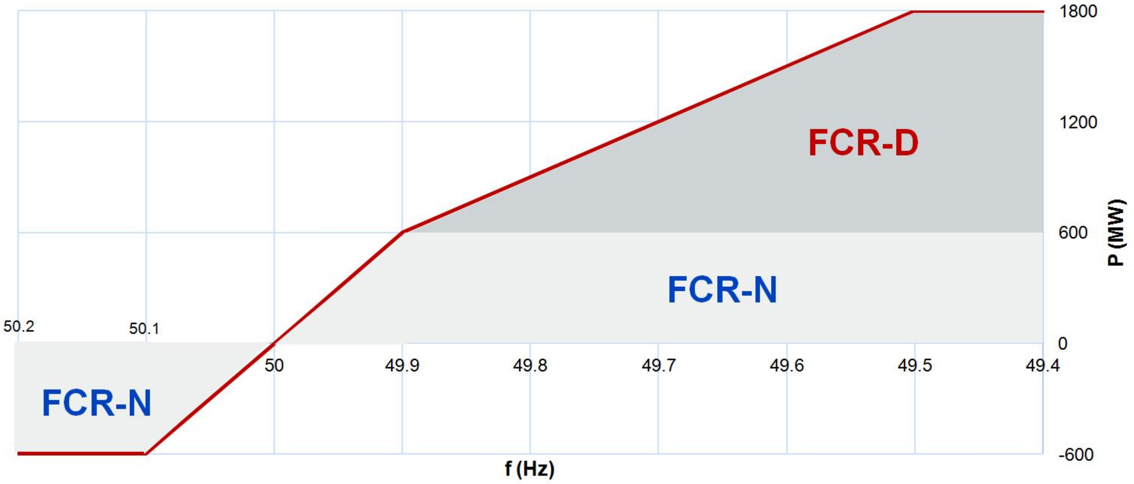

Figure 13: Combined activation of the two FCR responses applied in the NE synchronous area. [53]

As mentioned above, the Frequency Containment Reserves are activated in proportion to the severity of the frequency deviation. Ideally, this entails a completely linear activation of the total reserve capacity. In reality, however, not all technical units are capable of linearly controlling their active power output, hence the technical units participating in maintaining the FCR are allowed to employ stepped frequency responses as is the case with relay-connected load-shedding, for example. [43, p.43] Furthermore, the NC allows covering the FCR activation frequency range with more than one FCR response [39, p.42]. In the NE synchronous area, for instance, instead of one extensive response two differently activating FCR responses are utilized. First, the Frequency Containment Reserve in Normal operation is a bidirectional and symmetrical frequency response activated during frequency deviations occurring within the Standard Frequency Range. That is, the technical units participating in the FCR-N use are required to both up-regulate and down-regulate according to over or underfrequency in the grid, which is visible in Figure 13. The Frequency Containment Reserve in Disturbances, on the other hand, is a unidirectional frequency response activated during more severe frequency deviations. The FCR-D up-regulation, as seen in Figure 13, activates when the system frequency drops below the Standard Frequency Range. [24] It is noteworthy, that although the FCR-N response is symmetrical, the complete FCR response is asymmetrical due to the unidirectional activation characteristic of FCR-D.

In Finland, two Battery Energy Storage Systems have been recently installed [8, 54]. As the energy capacity of the batteries is restricted, utilizing BESSs as Frequency Containment Reserve is more complicated when compared to conventional power generation or load-shedding. Thus the NC LFCR introduces requirements related to the reserve utilization of technical units with limited energy reservoirs.

In the CE and NE synchronous areas, the technical units with limited energy reservoirs shall be capable of providing the full regulating capacity for at least thirty minutes and then restoring the energy reservoir within a time frame of two hours. Furthermore, should the frequency deviations during the thirty minute activation period remain below the full FCR activation frequency deviation, that is, the deviations do not reach the limits of the Standard Frequency Range, the units shall continue regulating until the energy reservoir is exhausted. [43, p.45]

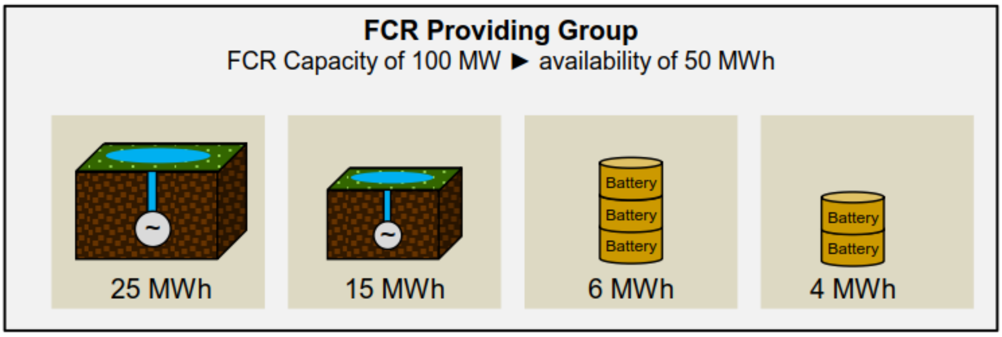

Figure 14: An aggregation of 100 MW of reserve capacity from technical units with limited energy reservoirs. According to the thirty minute activation requirement, the 100 MW active power output capacity entails a total energy reservoir of 50 MWh. [44]

An example of a FCR capacity aggregation is presented in Figure 14. In the figure, a combined energy reservoir of 50 MWh is aggregated from two BESSs and two pumped-storage hydropower plants. Provided that the units are capable of maintaining a total active power output of 100 MW, the thirty minute activation requirement entails that the total energy reservoir must be at least 50 MWh. Thus, in the example the requirement is fulfilled.

3.4.4 Frequency Restoration and Reserve Replacement Processes

In addition to the Frequency Containment Reserves, the NC LFCR recognizes two other reserve types. First, the Frequency Restoration Reserve is the secondary reserve type employed in the Frequency Restoration Process (FRP). Implementing the FRP is a collective responsibility of all the TSO operating in the same LFC Block, thus it is defined in the LFC Block Operational Agreement. The objective of FRP is to relieve the fully activated FCR resources and to restore the system frequency back within the Standard Frequency Range within the Time to Restore Frequency [43, p.32]. Contrary to the automatic activation of FCR, the activation of FRR resources is initiated by the TSOs operating in a LFC Area. [39, p.43]

The second additional reserve type is the Replacement Reserves utilized in the Reserve Replacement Process (RRP). Unlike the other reserves, implementing the

Replacement Reserves in a LFC Block is optional. Hence, in the NE synchronous area, for example, maintaining Replacement Reserves is not deemed necessary. Acting as the tertiary reserve type, the objective of the RRP is in turn to relieve the activated FRR resources, or to support the FRR activation. Not unlike the Frequency Restoration Reserves, the Replacement Reserves are also activated according to TSO instructions. [39, pp.43-44]

3.5 Operational reserves in the NE synchronous area

The Northern Europe synchronous area covers the whole Nordic power system except for Western Denmark, which belongs to the Continental European system through connections to Northern Germany. The synchronous area is further divided into the Finnish, Swedish, Norwegian and Eastern Danish subsystems, each with a respective Transmission System Operator holding the system responsibility for them. Thus, these TSOs are responsible for cooperating in implementing effective operational reserves and maintaining operational security in the whole synchronous area. [23, 24]

Due to the Nordic power system's special characteristics, such as the local generation structure and long transmission distances, the operational reserve arrangements differ from the arrangements in the CE synchronous area. Thus, the Nordic TSOs have agreed upon their own ways of implementation in the System Operation Agreement. As stated in section 3.4.1, the NE synchronous area comprises of one LFC Block and one LFC Area. However, due to congestion in power transmission between the countries, the synchronous area is divided into several Monitoring Areas, Finland forming one of them. [39, pp.106-112]

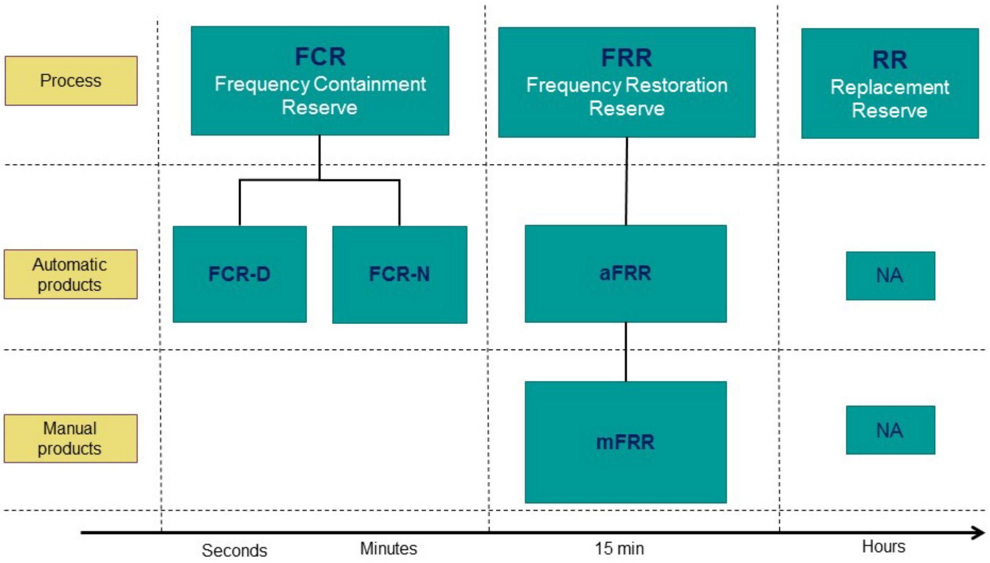

Figure 15: Reserve products currently utilized in the NE synchronous area. [25] The horizontal axis represents the activation time-scale for different reserve types.

The reserve products currently utilized in the NE synchronous area are illustrated in Figure 15. As mentioned before, no Replacement Reserves or automatic Frequency Restoration Reserve are procured at present. Also the implementation of two separate FCR responses is clearly visible in the figure. It is to be noted, that in the figure the denotation aFRR corresponds to FRR-A used in this thesis and the denotation mFRR to

FRR-M, respectively. Next, the main characteristics of different reserve products and their dimensioning are introduced.

3.5.1 Frequency Containment Reserve in Normal operation

The Frequency Containment Reserve in Normal operation is the first of the two separate FCR responses utilized in the NE synchronous area. This reserve type is automatically activated according to frequency variations within the Standard Frequency Range. As the Standard Frequency Range, namely 49.90 - 50.10 Hz is symmetrical around the nominal system frequency, the FCR-N response is also symmetrical, thus making it the only down-regulating reserve product currently utilized. [24]

Within the NE synchronous area, 600 MW of FCR-N capacity is constantly maintained. Procuring obligations are divided between the national subsystems, and the system-specific amounts are adjusted annually according to their total electricity consumptions in the previous year. That is to say, the operator of the subsystem with the highest total consumption has the greatest obligation. Exchanging of FCR capacity is allowed, as the TSOs may purchase FCR-N capacity from other subsystems or from other synchronous areas via HVDC interconnectors. However, in order to maintain the ability to fully operate under possible situation of islanded operation, each TSO is allowed to procure no more than third of its initial obligation from outside of its own subsystem. [10, 24]

3.5.2 Frequency Containment Reserve in Disturbances

The second FCR response utilized in the NE synchronous area is the Frequency Containment Reserve in Disturbances. As its name entails, the FCR-D resources are activated during frequency anomalies occurring in the grid. That is, this reserve type is automatically activated when the system frequency drops below the Standard Frequency Range, proportionally to the extent of the deviation. Hence, the FCR-D is fully activated when the system frequency reaches the negative Maximum Steady-State Frequency Deviation of 49.50 Hz. [24]

The total amount of maintained FCR-D capacity is determined by the prevailing dimensioning fault within the synchronous area, deducted by 200 MW due to self-regulation of loads. The exact amount varies due to changing operational conditions, thus it is revised on a weekly basis. At present, this equals to a maximum of 1,200 MW, according to the largest possible dimensioning fault. Not unlike the FCR-N capacity, the FCR-D obligations are also distributed between the subsystems, although the TSO-specific obligations are calculated differently. The amount of FCR-D a TSO is required to maintain is proportional to the dimensioning fault within the respective subsystem. That is to say, the TSO responsible for the subsystem with the direst dimensioning fault has the greatest obligation. Again, the TSOs are required to maintain a minimum of two thirds of their initial obligations within their own subsystem. [24]

3.5.3 Frequency Restoration Reserves

The Frequency Restoration Reserves in the NE synchronous area feature two reserve products, the manually and the automatically activated FRR [27]. However, maintaining of FRR-A is currently halted, thus only FRR-M is utilized at present [26]. Contrary to the automatic activation of the Frequency Containment Reserves, the TSOs request the activation of the FRR. [24]

The manual Frequency Restoration Reserve is utilized to maintain the power balance during normal operation and to relieve the fully activated FCR resources during disturbances. In contrast to the Frequency Containment Reserve products, the manual Frequency Restoration Reserves are subsystem-specific and dimensioned according to local requirements. Consequently, calculating the sufficient amount of FRR-M includes considering the prevailing dimensioning fault in the subsystem and the possible bottlenecks in electricity transmission between the neighboring subsystems. Similarly to Frequency Containment Reserves, procuring of the FRR-M from other subsystems is allowed to some extent, although this requires idle transmission capacity between the subsystems. [24] The objective of the automatic Frequency Restoration Reserve is to restore the system frequency back to the nominal value [27], thus supporting the FCR-N resources by relieving the activated resources.

4 Commissioning of Frequency Containment Reserves

In previous chapters of this thesis the basis for understanding the implementation of Frequency Containment Reserves was established. The ancillary service market places, the general reserve related European terminology and the Frequency Containment Process were discussed. The exact technical and procedural requirements applied in Finland, however, are finally studied in this chapter.

In the beginning of this chapter the whole verification process conducted before a technical unit may enter the FCR markets is reviewed. In section 4.2 the technical requirements set for units participating in the FCR use are examined, followed by an introduction to hardware equipment complying with the rules. Finally the commissioning process, including the pre-approved test curves utilized in the tests discussed in chapter 5, is presented in section 4.4.

4.1 Verification process

Requirements for commissioning a technical unit participating in the Frequency Containment Process in Finland are defined in the Finnish TSO Fingrid's rules. The fulfillment of rules is to be verified by regulating tests prior to commissioning. Successfully carrying out the tests is also a precondition for entering the Finnish ancillary service markets.

When a reserve provider plans to join the Finnish Frequency Containment Reserve markets with a technical unit, the verification process is always initiated by the reserve provider itself. Fingrid only approves or declines the unit based on the results of the process, and it holds the right to send its representative to observe and participate in the regulating tests. Hence, as a pre-qualification, the reserve provider is obliged to submit a pre-prepared commissioning plan and inform Fingrid of the test location and the test date two weeks in advance. [29]

The verification tests are performed in unit’s normal operating conditions, that is, when the unit is running as it is operated in everyday use. No special testing conditions are allowed to be activate in the control system, as the tests are supposed to simulate the unit’s performance in real incidents occurring in the grid. Should multiple controlling options exist, the tests are run with each option separately. [29]

Occasional changes in the requirements call for a reassessment of technical unit's compliance by repeating the verification tests. Additionally, a new set of tests is performed each time a unit undergoes significant changes that may affect participating in reserve use. For example, modifications to a unit’s hardware configuration or software changes in the control system may demand re-performing the verification process. Even if no changes to the general requirements or to the technical unit are introduced, Fingrid requires the tests to be performed at least once in every 10 years. [29] This requirement, however, contradicts the minimum reassessment interval of once in every five years stated in Article 44 of the NC LFCR [43] and in Article 155 of the NC SOG [42].

As mentioned above, the purpose of testing is to verify a technical unit's proper functioning in reserve use, that is, the desired activation of the reserve: the reserve capacity must activate and deactivate either linearly or according to chosen steps, and in the pre-defined time ranges. Another important parameter determined by the tests is the unit's maximum power capacity available to either one or both of the FCR market places. The capacity available to FCR-D up-regulating market is determined simply by metering the unit's capability to up-regulate its power in a given time. In order to take part in the FCR-N market, the unit must up and down-regulate symmetrically, that is, the same regulating power must be available to both directions. For example, should the unit's capability to up-regulate exceed its down-regulating capability, only the capacity corresponding to the unit's down-regulating capability complies with the market's rules. The extra up-regulating power capacity may be offered to the FCR-D market, however, as a unit is allowed to participate in both market places at the same time. [29] A complete summary of the parameters determined in the verification tests is presented in Table 4. The technical requirements related to these parameters are introduced in section 4.2.

Table 4: Parameters determined in the regulating tests. [29]

Parameter	FCR-N	FCR-D
Frequency control functioning, down-regulation	x	Not applicable
Frequency control functioning, up-regulation	x	x
Maximum capacity available to market, down-regulation	x	Not applicable
Maximum capacity available to market, up-regulation		x
Dead band in frequency regulation	x	x
Frequency response	x	x

The principle for performing the regulating tests is illustrated in Figure 16. The tests are performed by feeding a simulated frequency signal into the technical unit's controller while its frequency measurement is disconnected from the grid. Should this due to the system's characteristics prove impossible, another option is to temporarily modify the controller's set point values: raising the set point by 0.50 Hz, for example, corresponds to -0.50 Hz drop in the grid frequency and vice versa. The unit's frequency measurement and its response to the simulated signal, that is, the change in output power, are measured and logged in parallel. The fulfilling of the applicable criteria is determined based on the logged result data. [29]

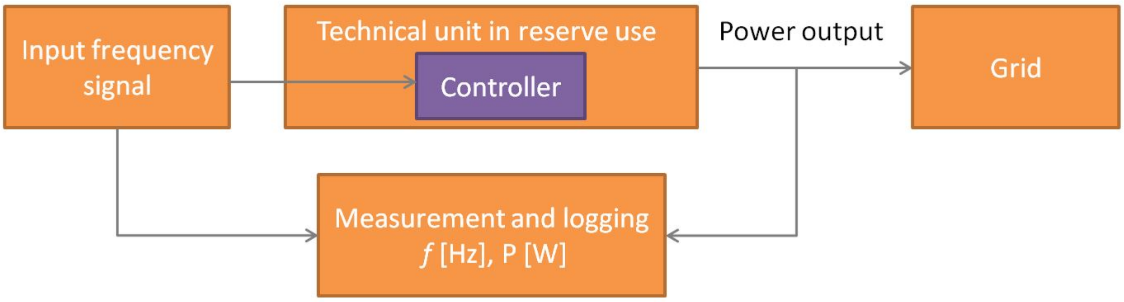

Figure 16: The principle for performing the regulating tests on a technical unit planned for FCR use.

After the regulating tests, the reserve provider delivers the complete result data along with curves plotted from the activation to Fingrid for evaluation. A description of the technical unit's controller and its settings, as well as a test protocol including other significant data, such as the test site temperature, are also submitted. Fingrid either approves the results or requires amendments. [29]

According to Fingrid's specialist Mikko Kuivaniemi, no standard procedures regarding initiating and performing the verification process exist. At present, the reserve provider contacts Fingrid's representatives and presents their free-form commissioning plan. Respectively, the data from regulating tests may be presented as the reserve provider sees fit, although the contents are pre-specified. Fingrid tends to be adaptable in these matters as long as the results of the verification process are acceptable. [55]

When it comes to aggregated reserve capacity, Kuivaniemi states that the situation is similar. No standard procedure exists but the reserve provider proposes how to perform the regulating tests. The current instructions do not cover how to verify the succeeding of aggregation in the first place: the reserve provider may choose to either test each technical unit separately or verify that the aggregation is successful, or both. However, performing regulating tests on each unit should ensure that the requirements are complied with. The implementation of the aggregator system itself is not of interest to Fingrid as long as the complete ensemble complies with the technical requirements, although submitting a description of the system’s functioning might prove beneficial. [55]

Due to raising number of technical units providing reserve capacity, it may prove impossible for Fingrid to attend all regulating tests in the future. Hence, new types of reserve capacity are of particular interest to Fingrid. For instance, offering a demand response implementation with a hypermarket's electrical systems to the ancillary service markets for the first time will probably attract Fingrid's attention. The next hypermarket case probably would not be looked into similarly. [55]

4.2 Technical requirements

The minimum technical requirements for Frequency Containment Reserves are established in Article 44 of the NC LFCR. The Transmission System Operators of a synchronous area may together define additional requirements in the Synchronous Area Operational Agreement on the condition that no conflicts with other network codes arise. Additionally, each TSO may further define rules to be applied in their parts of the synchronous area. [43]

At present, the rules applied to FCR capacity in Finland are set in the Finnish TSO Fingrid's application instruction [29]. The NC LFCR and the forthcoming NC SOG, however, already include several additional requirements that are yet to be included in the future revisions of Fingrid's application instruction. For comparison, the FCR related requirements gathered from the NC LFCR, the Nordic SOA and the application instruction are listed in Table 5.

Table 5: The FCR related requirements gathered from the rule setting documents. [24, 29, 43, 56]

Requirement	ENTSO-E NC LFCR		Nordic SOA		Application instruction	
	Value	Article	Value	Section	Value	Section
Minimum accuracy of frequency measurement	10 mHz	44.1			10 mHz	7.2.4
Maximum inherent Frequency Response Insensitivity (dead band)	10 mHz	44.1			FCR-N: 50 Hz ± 50 mHz	3.1
FCR Full Activation Frequency Deviation	50 Hz ± 500 mHz	44.1			50Hz + 100mHz 50Hz - 500mHz	3.1 3.2
FCR activation governor	Linear or stepped	44.6			FCR-N: linear[a] FCR-D: linear or stepped	3.1 3.2
Maximum power of aggregated units	1.5 MW	44.8			Not specified	
FCR activation persistence	As long as a frequency deviation persists	45.6				
FCR activation persistence, resources with limited energy reservoirs	As long as a frequency deviation persists unless energy reservoir exhausted	45.6			Not specified	
Minimum full activation time for resources with limited energy reservoirs	30 min	45.6			Not specified	
Maximum time to recover energy reservoir after exhaustion	120 min	45.6			Not specified	
FCR-N: full activation frequency deviation			50 Hz ± 100 mHz	App. 2, 4.1.1	According to SOA	
FCR-N: full capacity activation time, up-regulation and down-regulation			3 minutes	App. 2, 4.1.1	According to SOA	
FCR-D: full activation frequency deviation			49.50 Hz	App. 2, 4.1.2	According to SOA	
FCR-D: Up-regulation time, 50% of obligation[b]			5 sec	App. 2, 4.1.2	According to SOA	
FCR-D: Up-regulation time, 100% of obligation[b]	30 sec	44.1	30 sec	App. 2, 4.1.2	According to SOA	
Maximum FCR-N/D capacity of single Reserve Providing Unit/Group					70 MW	2
Total relay controlled load-shedding in FCR-D					100 MW	2
Activation time of relay controlled load-shedding, frequency ≤ 49,70 Hz					≤ 5 sec	3.2
Activation time of relay controlled load-shedding, frequency ≤ 49,60 Hz					≤ 3 sec	3.2
Activation time of relay controlled load-shedding, frequency ≤ 49,50 Hz					≤ 1 sec	3.2
Relay controlled load-shedding, reconnection allowed					$f \geq 49{,}90$ Hz for 3 minutes	3.2

a) in the 2017 version of the application instruction a stepped FCR-N response is introduced

b) in the event of an instant -500 mHz frequency drop

As Table 5 shows, the legally binding Nordic SOA is applied directly whereas part of the requirements from NC LFCR contradict the current practice in Finland. First of all, the requirements applied for FCR Full Activation Frequency Deviation differ due to utilization of two separate FCR responses in the NE synchronous area, both with their own activation characteristics. For example, when the frequency is returned to the Standard Frequency Range, namely to 49.90 Hz, the FCR-D capacity is no longer required to remain activated, whereas the FCR-N response continues fully activated. Hence the full activation frequency deviation is defined for both FCR responses separately. This division is clearly visible in Figure 13. In addition, the combined response from FCR-N and FCR-D is not symmetrical: full FCR up-regulating capacity is activated when the system frequency drops to 49.50 Hz, whereas the full down-regulating capacity is activated already as soon as the system frequency raises to 50.10 Hz. [29]

Secondly, the FCR activation persistence requirement depends on the chosen activation characteristic. Not all reserve capacity activates linearly in proportion to the frequency deviation from the nominal system frequency. In FCR-D use, reconnecting the relay-connected loads is allowed when the system frequency has returned to the Standard Frequency Range and remained above it for three minutes [29]. Furthermore, no explicit rules concerning the activation persistence of technical units with limited energy reservoirs exist at present. In principle, the unit must be able to continue activation through the whole one hour market period, should the frequency deviation persist. An availability requirement of 30 minutes is currently applied, however. [55]

Third, as mentioned before, the current version of Fingrid's application instruction recognizes neither aggregating of reserve capacity nor units with limited energy reservoirs. Bringing such capacity to the FCR markets is assessed case by case, as no clear instructions exist regarding the allowed energy reservoir recovery time, for example. Presently, the unofficial requirement is thirty minutes of regulation in any direction after which a two hour recovery is allowed. [55]

4.2.1 Activation

The first of the two FCR response levels implemented in the NE synchronous area is the Frequency Containment Reserve in Normal operation. The FCR-N is a bidirectional, symmetrical response activated linearly within the Standard Frequency Range. The full down-regulating capacity is activated at the upper limit of the Standard Frequency Range and the full up-regulating capacity at the lower limit, respectively. The full regulating power shall be available no later than in three minutes following a stepwise ±0.10 Hz frequency change. Should the system frequency rise above or fall below the Standard Frequency Range, the FCR-N response remains completely activated until the frequency deviation is cleared.

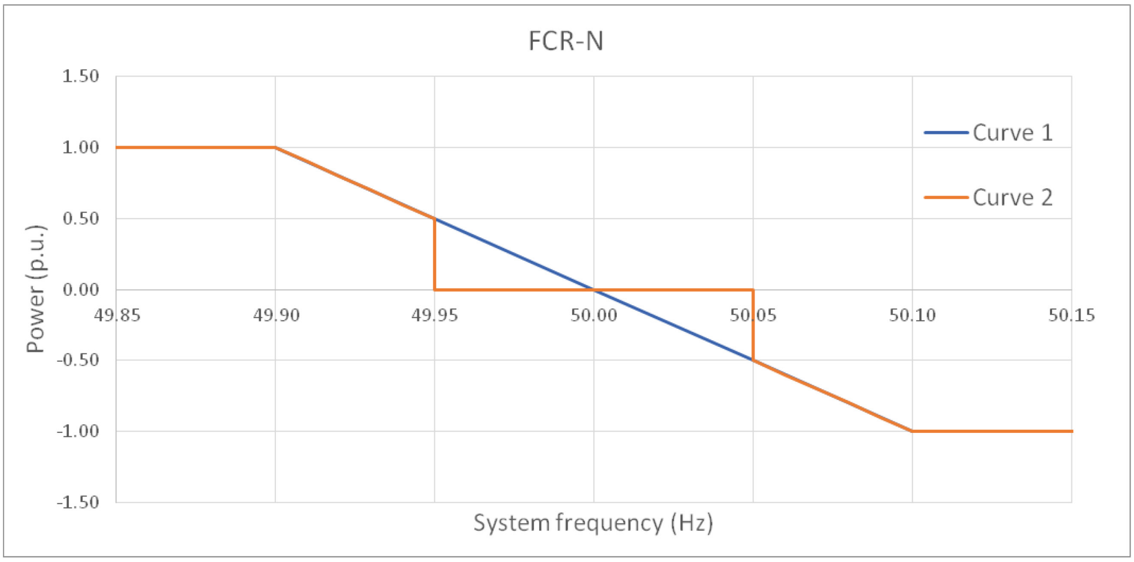

Figure 17: Ideal control curves for FCR-N activation with the maximum allowed dead band and without a dead band. Positive power denotes up-regulation and negative power denotes down-regulation.

Figure 17 illustrates the ideal control curves for FCR-N activation. Curve 1 represents the completely linear activation characteristic: a technical unit following Curve 1 regulates strictly in proportion to the frequency deviation throughout the whole Standard Frequency Range of 49.90-50.10 Hz. That is, the unit starts regulating right at the moment when a measurable frequency deviation appears, with regulating power proportional to the size of the deviation. Curve 2, on the other hand, represents the completely linear activation characteristic applied with the maximum allowed dead band of ±50 mHz. That is, only frequency deviations larger than the dead band commence the regulation. Thus, when the system frequency remains within the range of 49.95-50.05 Hz, no up or down-regulation is active. As the dead band is exceeded, up or down-regulation begins following Curve 1. The maximum allowed dead band includes both inherent frequency measurement insensitivities and possible intentional insensitivities implemented in the frequency control.

The Frequency Containment Reserve in Disturbances acts as the second level of FCR response. It is a unidirectional response activated when the system frequency falls below the Standard Frequency Range, thus, the whole FCR-D capacity is dedicated solely to up-regulation. The FCR-D capacity is activated either linearly in proportion to the extent of the frequency deviation or, in the case of relay-connected load-shedding, according to pre-defined steps. The linear up-regulation begins at the lower limit of the Standard Frequency Range (49.90 Hz) reaching full regulating power at the Maximum Steady-State Frequency Deviation (49.50 Hz). Following a stepwise -0.50 Hz frequency change, half of the up-regulating capacity shall be available in five seconds, and the full capacity shall be activated in thirty seconds. The regulation shall continue even if the system frequency drops below the Maximum Steady-State Frequency Deviation.

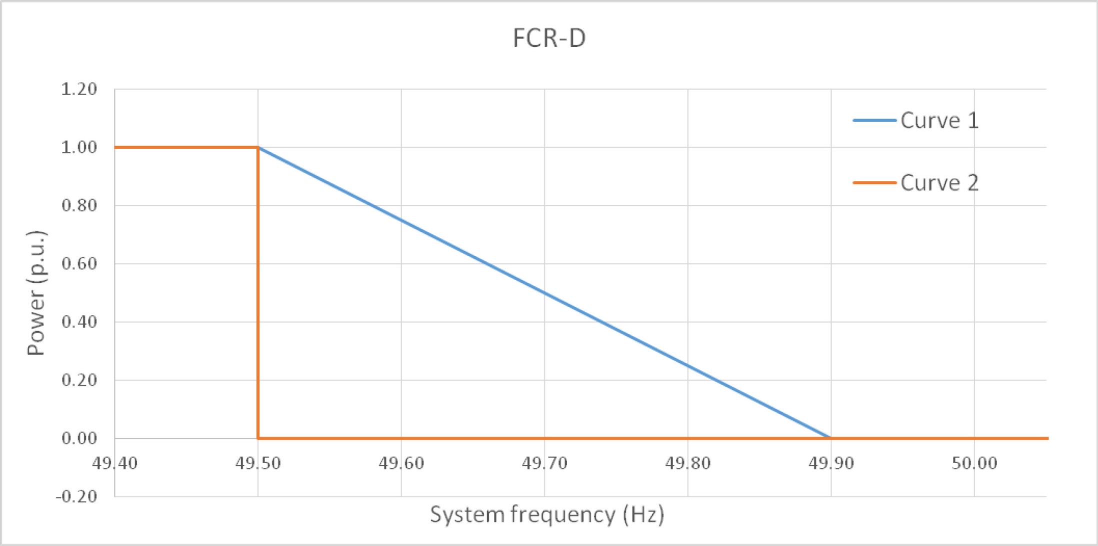

Figure 18: Ideal control curves for linear and stepwise FCR-D activation.

In Figure 18, Curve 1 represents the ideal linear activation characteristic: the up-regulating starts as soon as the system frequency falls below 49.90 Hz, increasing in proportion to the frequency deviation until reaching the full regulating power at 49.50 Hz. Curve 2 illustrates the required response to a stepwise -0.50 Hz change in the system frequency. It also represents one of the pre-defined disconnection steps for relay-connected load-shedding: when the system frequency falls below the chosen limit, the load shall disconnect in the respective time frame. The additional disconnection options are listed in Table 6. Technical units following linear activation curve may stop regulating as soon as the system frequency returns to the Standard Frequency Range. The reconnecting of relay-connected loads, however, is allowed when the system frequency has remained above 49.90 Hz for three minutes.

Table 6: The pre-defined disconnection steps and time frames for relay-connected load-shedding. [29]

Disconnection option	System frequency (Hz)	Required disconnection time
1	≤ 49.70	Max 5 seconds
2	≤ 49.60	Max 3 seconds
3	≤ 49.50	Max 1 second

It is important to notice that the ±50 mHz dead band in FCR-N regulation already includes the maximum allowed measuring inaccuracy of ±10 mHz. Although no such intentional dead band is allowed in linear FCR-D regulation, the same measuring accuracy requirement is applied. Another noteworthy detail in Fingrid's application instruction is the requirement for almost linear activation [29]. This allows participating in the linear regulation by implementing a control characteristic that imitates completely linear activation with a number of narrow steps. Thus, the requirement facilitates the access of aggregated reserve capacity to the FCR markets: for example, a frequency control implementation with a set of illuminators not suitable for individual linear control may participate in either linear or stepped FCR-D regulation.

4.2.2 Data exchange

The data exchange between the reserve provider and Fingrid consists of both real-time and history data. This data is used for invoicing purposes and, most importantly, to verify the correct activation of the ordered reserve capacity. [29]

In order to monitor the total reserve capacity activated at a given moment, the reserve provider shall provide Fingrid with the real-time unit-specific data of maintained FCR-N and FCR-D capacity. The data shall be delivered at least once in every three minutes. Verification of activation after disturbances, on the other hand, is based on the unit-specific active power history data. The unit's active power output or input, depending on the regulating direction, shall be logged with one second resolution. The reserve provider is obliged to store the history data for at least four days, during which Fingrid holds the rights to request the data. In addition, the reserve provider shall provide Fingrid with unit-specific hourly average power and hourly maximum power data for invoicing. [29]

According to Fingrid's Kuivaniemi, for aggregated reserve capacity the above mentioned data shall be merged into a single data entry to be delivered. That is, no unit-specific data from an aggregated ensemble is required nor desired. Additionally, in the future a real-time information on the battery's State Of Charge (SOC) value or the available full activation time might be requested when utilizing technical units with limited energy reservoirs. [55]

4.2.3 Equipment

In order fulfill the technical requirements, a technical unit is equipped with a control system capable of frequency control. Only a few direct requirements for the control equipment are set in either the Network Codes, the Nordic SOA or in Fingrid's application instruction. Moreover, these requirements are directed at the performance of the control equipment, thus allowing the reserve provider to implement the frequency control by numerous different hardware combinations.

Naturally, a free form controller, such as an industrial Programmable Logic Controller (PLC), is needed. The controller must be capable of reading the frequency measurement, processing the frequency control logic and logging the required data in rapid cycles in order to ensure the timely functioning of the regulation and to maintain the required logging resolution. A storage medium for storing the pre-defined activation data for at least four days shall be included in the controller. Arranging online access to the data log is beneficial, as this eliminates the need for service personnel, for example, to access the installation site each time the logs are requested. Additionally, a local frequency measurement system measuring the grid's system frequency is mandatory. As denoted in Table 5, an accuracy requirement of 10 mHz or better is applied.

Similar requirements are applied to the test equipment utilized in the regulating tests. The resolution requirement for active power and frequency sampling, however, is stricter, as logging shall be performed in 0.2 second intervals in order to ensure sufficient accuracy in determining the reserve capacity and in verifying the correct activation. Additionally, the total error in the measurement shall not exceed 10%. [29]

4.3 The commissioning process

The application instruction contains the standard commissioning processes suitable for conventional power plant machinery and relay-connected load-shedding. However, verification processes suitable for more modern resources, such as Battery Energy Storage Systems and less powerful technical units included in an aggregation of reserve capacity, are needed. Additionally, due to possibly large number of individual resources, the process should be as simple as possible. In this section such a verification process is defined and the necessary regulating test signals are presented. A commissioning report template for Siemens Osakeyhtiö will be prepared based on the process and the test signals.

In Figure 19, the complete commissioning process performed prior to market utilization is divided into separate phases. First, as a pre-qualification, the reserve provider submits the commissioning plan for Fingrid's approval. The contents of the plan are looked into in section 4.3.1. Next, the regulating tests introduced in section 4.4 are performed on the technical unit intended for FCR market utilization. According to results acquired from the regulating tests, Fingrid either approves the unit as ready for market utilization or requires amendments. With pre-approved regulating test signals, the amendments most probably entail modifications to the technical unit itself unless a mistake in analyzing the results occurred.

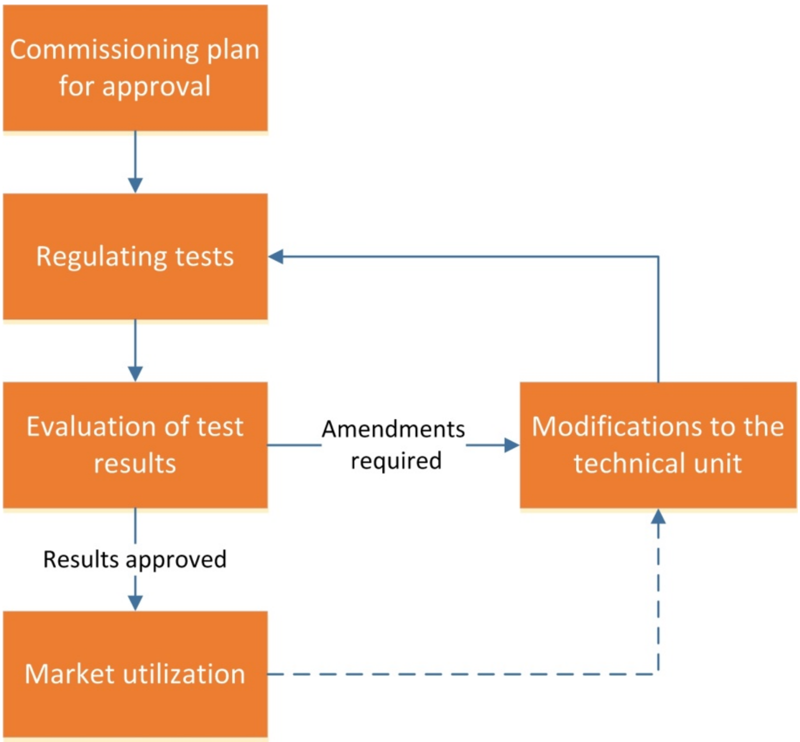

Figure 19: The principle of commissioning process for a technical unit intended for FCR market use.

The market utilization on either hourly or yearly markets, of course, is only allowed provided that the reserve provider has made the appropriate contracts with Fingrid. The FCR market places and respective contracts are introduces in chapter 2 of this thesis. Should modifications to the technical unit occur during its market use, the regulating tests are re-performed. In Figure 19, this is denoted with the dashed line.

4.3.1 Pre-qualification

No clear rules exist regarding the pre-qualification data submitted for Fingrid's approval prior to performing the regulating tests. Only the minimum contents are listed in the application instruction and until now a free-form documentation including the required information has sufficed [55]. Thus, in order to facilitate a straightforward and simple commissioning process, a pre-prepared template including all the necessary data is needed.

The process illustrated in Figure 19 is only applicable to individual technical units or Reserve Providing Units. That is, a phase for verifying the correct functioning of aggregation is excluded, as it is presently not required [55]. However, it might sometimes prove beneficial to verify the succeeding of aggregation, as the reserve provider is responsible for the availability of the reserve capacity sold to the market.

According to the application instruction, in the pre-qualification phase descriptions of the following systems and parameters shall be provided [29]:

- The implemented frequency measurement system and its accuracy.
- Intentional dead bands and possible filters in the frequency measurement.
- Functioning of the frequency-control system.

- In case of conventional power generation, the general information on the power plant's generator and turbine including applicable time constants.

Although not required by the current rules, a short description of the functioning of the aggregator system shall be provided when commissioning reserve capacity that is part of an aggregation. Additionally, possible limitations of the technical units energy reservoir are to be specified in the pre-qualification: when commissioning a BESS, for example, the size of the energy storage as well as the calculated maximum reserve power capacity shall be stated.

4.4 Regulating tests

Contrary to vague instructions concerning the pre-qualification process, the principles for performing the minimum regulating tests are stated in the application instruction. However, no actual test signals are presented. Furthermore, the tests described in the application instruction are intended for conventional power generation and relay-connected load-shedding, thus performing the regulating tests accordingly is not sensible in all cases. For instance, verifying the designed functioning of a densely stepped frequency-control imitating completely linear control requires another approach for testing. Hence the need for defining a new set of regulating test signals.

An additional goal in defining the new regulating test signals was to speed up the commissioning process by minimizing both the number of required tests and the time they take to run. In addition, the new test signals should be as close to universally applicable as possible, that is, independent of the type of the technical unit. In order to even further simplify the commissioning of new FCR resources, the signals were discussed and pre-approved with Fingrid's Kuivaniemi. In chapter 5 of this thesis, actual regulating tests are run with these signals and the acquired results are analyzed.

Originally seven individual test sequences were drafted. However, it was soon acknowledged that with minimal modifications to the original test sequence, the test later referred to as Test 4 was sufficient for verifying the correct functioning of both linear FCR-D up-regulation and stepped load-shedding. The total number of tests was further reduced by two tests after the consultation with Fingrid's representative. Due to current practice and lack of instructions, testing the up and down-regulating capacity of technical units with limited energy reservoirs by running full 30 minute long test sequences was not deemed necessary. The sufficiency of the energy reservoir shall be proven by calculations. [55] Finally a total of four test signals were selected. Tests 1 and 2 are applied to units intended for FCR-N market use, and tests 3 and 4 to units intended for FCR-D use, respectively. Next, the final regulating test signals are presented and analyzed.

4.4.1 Test 1, FCR-N capacity

The purpose of Test 1 is to determine the maximum active power capacity a technical unit may offer to the FCR-N market. The input frequency signal utilized in Test 1 is shown in Figure 20. The test signal is formulated according to the description in the application instruction.

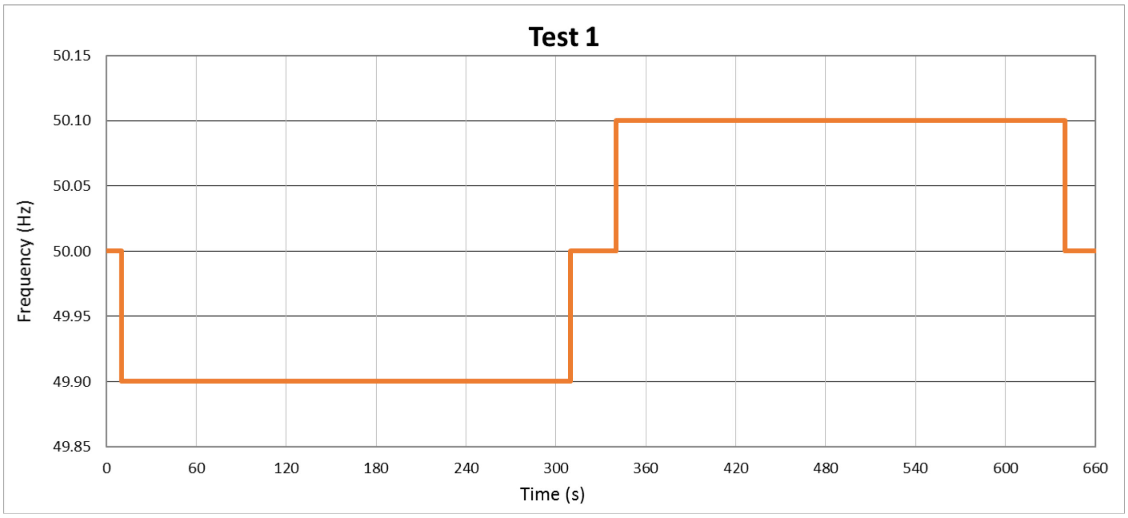

Figure 20: The regulating test signal for determining the technical unit's active power capacity available to FCR-N market.

Table 7: A list of test phases, time periods and input signal frequencies in Test 1.

Test phase	Period (s)	Input frequency (Hz)	Explanation
1	[0; 10]	50.00	Initial nominal system frequency.
2	[10; 310]	49.90	Full up-regulating capacity activated.
3	[310; 340]	50.00	Recovery phase. Nominal system frequency.
4	[340; 640]	50.10	Full down-regulating capacity activated.
5	[640; 660]	50.00	Recovery phase. Nominal system frequency.

Test 1 is divided into five consecutive phases as listed in Table 7. In phase 1, initial nominal system frequency is fed into the technical unit's controller. In phase 2, a stepped frequency drop to the full up-regulating activation frequency of 49.90 Hz is produced. Low input frequency is maintained for five minutes during which the unit's up-regulating output power is monitored. Phase 3 is a thirty second long recovery phase between the up and down-regulating phases. In phase 4, the technical unit's down-regulating is monitored while feeding its controller the full down-regulating activation frequency of 50.10 Hz for five minutes. Phase 5 is the final recovery phase after which the test is finished.

The five minute duration of test phases 2 and 4 is decreed in the application instruction. The maximum regulating capacity, however, is determined three minutes after the beginning of the phase, according to the FCR-N activation time requirement in Table 5. Thus, the possible additional active power change achieved during the latter two minutes will be rejected, as the extra duration is intended for verifying a continuous activation. Due to the bidirectional and symmetrical regulating characteristic, the regulating capacity available to the market corresponds to the least of the up and down-regulating capacity achieved in the test.

Moreover, the required recovery time between the up and down-regulating phases depends on the technical unit, thus revising the duration of phase 3 is sometimes necessary. However, for units capable of very fast regulation, such as Battery Energy

Storage Systems, even shorter duration than thirty seconds is often sufficient. The same applies to the final recovery phase at the end of the test sequence.

4.4.2 Test 2, FCR-N activation

The primary purpose of Test 2 is to verify the correct functioning of the frequency control. Additionally the dead band in the frequency control is determined. The input frequency signal utilized in Test 2 is not a standard test signal described in the application instruction but especially formulated in this thesis. This type of activation test is not specifically required by Fingrid, although close to similar tests are often performed [55]. The input frequency signal is presented in Figure 21.

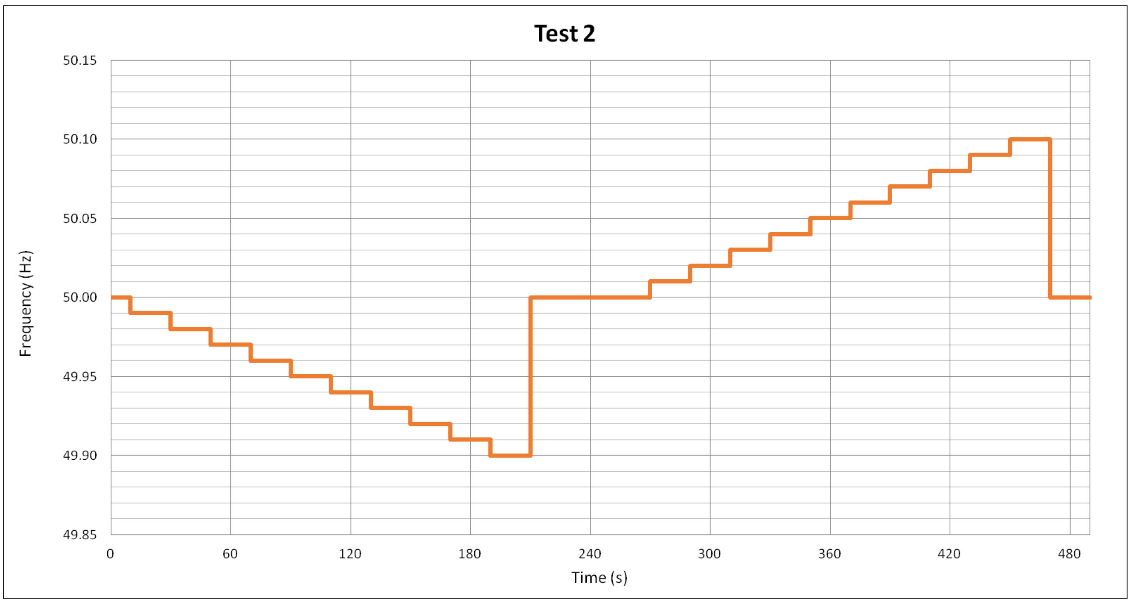

Figure 21: The regulating test signal for verifying the correct FCR-N activation.

Table 8: A list of test phases, time periods and input signal frequencies in Test 2.

Test phase	Period (s)	Input frequency (Hz)	Explanation
1	[0; 10]	50.00	Initial nominal system frequency.
2	[10; 90]	49.99 ... 49.95	Frequency decreases gradually within the maximum allowed dead band of 50 mHz.
3	[90; 190]	49.95 ... 49.90	Frequency decreases gradually until reaching full up-regulating frequency deviation.
4	[190; 210]	49.90	Full up-regulating capacity activated.
5	[210; 270]	50.00	Recovery phase. Nominal system frequency.
6	[270; 350]	50.01 ... 50.05	Frequency increases gradually within the maximum allowed dead band of 50 mHz.
7	[350; 450]	50.05 ... 50.10	Frequency increases gradually until reaching full down-regulating frequency deviation.
8	[450; 470]	50.10	Full down-regulating capacity activated.
9	[470; 490]	50.00	Recovery phase. Nominal system frequency.

Test 2 is comprised of 9 consecutive phases, as shown in Table 8. Similarly to Test 1, Test 2 also begins with a short nominal system frequency phase. In phase 2, the input frequency is gradually decreased within the maximum allowable dead band in twenty second long steps, thus no up-regulating is required to commence yet. In phase 3, the gradual frequency decrease is continued outside the maximum dead band until the full up-regulating frequency deviation of -0.10 Hz is reached. During phase 4, the 49.90 Hz frequency is maintained so that the total time below the nominal system frequency certainly exceeds three minutes. Phase 5 is a recovery phase between the up-regulating and the down-regulating phases. During phase 6, the input frequency is increased gradually within the maximum allowed dead band in twenty second long steps. Again, no regulating is required to commence within the dead band. In phase 7, gradually increasing the frequency continues until the full down-regulating activation frequency of 50.10 Hz is reached. Phase 8 ensures that the total time above the nominal system frequency exceeds three minutes. Phase 9 is the final recovery phase after which the test sequence is finished.

Noteworthy in Test 2 are the combinations of up-regulating phases 2 and 3 as well as the down-regulating phases 6 and 7. These combined phases imitate the almost linear control by applying several densely distributed moderate frequency changes. The twenty second division between the stepped frequency changes ought to be long enough for most resources to follow and allows them to regulate somewhat linearly. For very fast regulating resources the steps could also be more densely distributed, thus minimizing the duration of the test, whereas slower resources might require wider steps. However, the twenty second division is a compromise between more universal applicability and shorter performing time. Another detail to notice is that should the technical unit be able to ramp up to its full regulating capacity during phases 4 and 8, this automatically proves the unit's capability to up and down-regulate its power in the required time frame of three minutes.

The dead band in the technical unit's up-regulation is determined during test phases 2 and 3: the up-regulating shall begin right after the frequency falls below 49.95 Hz. Respectively, the dead band in down-regulation is determined in test phases 6 and 7, as the unit shall start regulating during these phases. The duration of the recovery phase in the middle of the test run is set to one minute in this test. However, the required recovery time is again unit specific and modifying the setting will give a chance to minimize the run time of the test.

4.4.3 Test 3, FCR-D capacity

The purpose of Test 3 is to determine a technical unit's maximum reserve capacity in compliance to the FCR-D market rules. The input frequency signal utilized in this test is shown in Figure 22. Due to unidirectional FCR-D response, the test is simply a step response test carried out according to description in the application instruction.

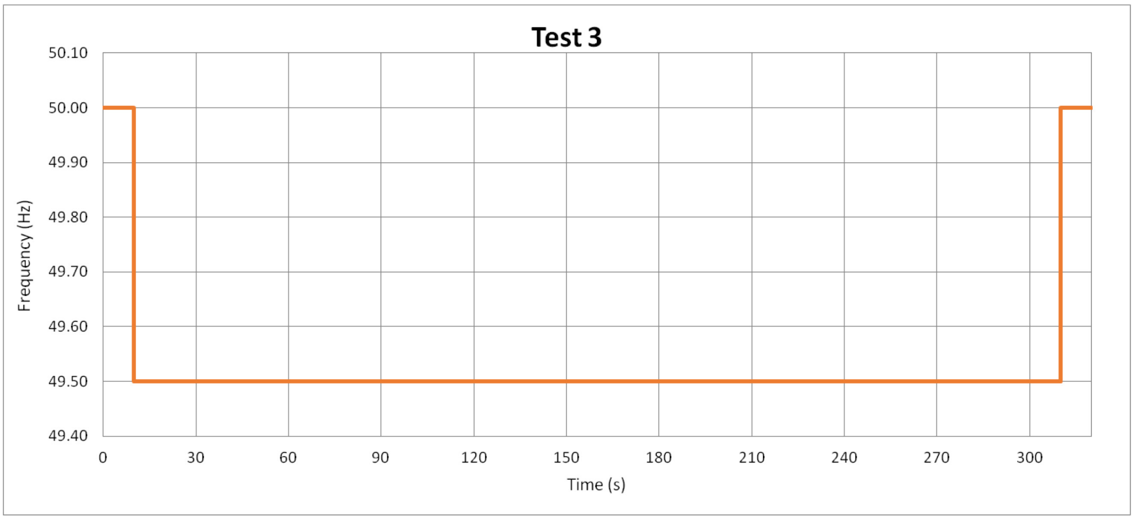

Figure 22: The regulating test curve for determining the capacity available to the FCR-D markets.

Table 9: A list of test phases, time periods and input signal frequencies in Test 3.

Test phase	Period (s)	Input frequency (Hz)	Explanation
1	[0; 10]	50.00	Initial nominal system frequency.
2	[10; 310]	49.50	Full up-regulating capacity activated.
3	[310; 320]	50.00	Recovery phase. Nominal system frequency.

Test 3 includes only three phases, as listed in Table 9. In phase 1 the nominal system frequency is fed into the technical unit's controller. Phase 2 is a five minute long period while the input frequency is set to 49.50 Hz, corresponding to the FCR-D full activation frequency deviation of -0.50 Hz. Phase 3 denotes recovery while the input frequency is returned to the nominal value.

Essentially, Test 3 is a simpler variant of Test 1, as no down-regulating capacity is determined for resources participating in the FCR-D use. For power generating units, the maximum up-regulating capacity available to the FCR-D market is the lesser of either the power change achieved in thirty seconds or twice the power change achieved in five seconds. In case of relay-connected load-shedding, the maximum reserve capacity is the active power change achieved within the chosen disconnection time frame, see Table 6. Despite the requirements for short activation times, the test duration is set to five minutes in order to verify the continuous activation.

4.4.4 Test 4, FCR-D activation

The purpose of Test 4 is to verify the correct activation of up-regulation in FCR-D market use. The test is applicable to power generating units capable of linear or almost linear regulation as well as to relay-connected load-shedding resources. Additionally, the correct reconnecting of loads and the dead band in unit's frequency control is verified. The input test signal is presented in Figure 23.

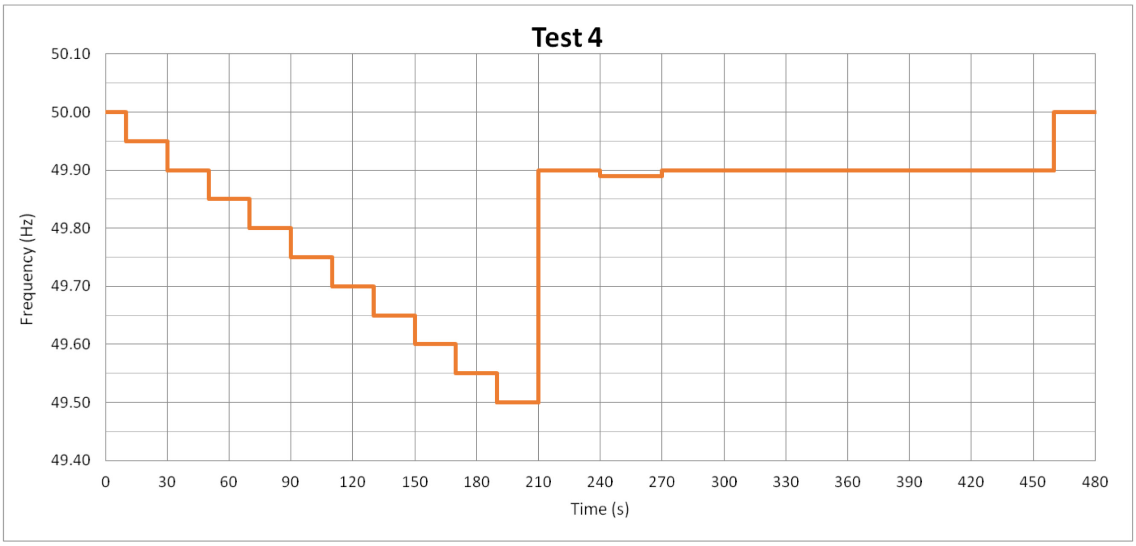

Figure 23: The regulating test signal for verifying the correct FCR-D activation.

Table 10: A list of test phases, time periods and input signal frequencies in Test 4.

Test phase	Period (s)	Input frequency (Hz)	Explanation
1	[0; 10]	50.00	Initial nominal system frequency.
2	[10; 190]	50.00 ... 49.50	Frequency decreases gradually until reaching full up-regulating frequency deviation.
3	[190; 210]	49.50	Full up-regulating capacity activated.
4	[210; 240]	49.90	Moderate frequency deviation persists.
5	[240; 270]	49.89	Stepped 10 mHz frequency drop.
6	[270; 460]	49.90	Moderate frequency deviation persists.
7	[460; 480]	50.00	Recovery phase. Nominal system frequency.

Test 4 consists of seven consecutive phases. Again, the test begins with a short initializing phase. During phase 2, the input frequency is gradually decreased in twenty second long steps until the full FCR-D activation frequency of 49.50 Hz is reached. The full up-regulating capacity is activated until the end of phase 3. During phases 4 to 6, a moderate frequency deviation of 49.90 Hz persists except for a thirty second long period in the middle when a slight drop in the input frequency occurs. Phase 7 is the recovery phase after which the test sequence is finished.

The linear or almost linear activation of up-regulation is tested in phase 2, as the input frequency is decreased by 0.05 Hz every twenty seconds. The timely functioning of relay-connected load-shedding is also verified during the same test phase, as load disconnection should occur according to Table 6. Regardless of the resource type or the chosen activation characteristic, the full up-regulating capacity should be activated during test phase 3. In the beginning of phase 4, the input frequency returns to the lower limit of the Standard Frequency Range, thus allowing the technical units capable of linear or almost linear control to cease regulating. Reconnecting the relay-connected loads, however, is only allowed after the test frequency has remained at 49.90 Hz for three consecutive minutes, that is, not until the end of test phase 6. This is due to the thirty second long slight frequency drop in phase 5, which resets the three minute reconnection timer.

The maximum allowed dead band in FCR-D use corresponds to the minimum accuracy requirement set for the technical unit's frequency measurement, see Table 5. Hence, the units participating in the linear regulation begin their regulating right after the frequency declines below 49.90 Hz, whereas the load-shedding should commence right after the test frequency falls below the chosen disconnection threshold.

Obviously, when performing the test on technical units capable of linear or almost linear regulation, during the latter half of the test run only the dead band is tested in phase 5. The main purpose of the latter half is to test the correct functioning of load reconnection, which is verified during phases 4 to 6. The objective was to restrict the number of required tests, however, thus only one universal test was formulated. Furthermore, when it comes to BESS, for example, the density of the stepped frequency changes as well as the recovery phase at the end of the test sequence could be modified in order to minimize the running time.

4.4.5 Further considerations

According to Fingrid's application instruction, the reserve power capacity a technical unit is capable of producing is determined at an accuracy of 0.1 MW [29]. When performing the regulating tests on less powerful resources that are part of a reserve power aggregation, however, the aforementioned accuracy is inadequate. Additionally, a power generating unit's different controller settings have to be considered when performing the capacity determining regulating tests. Should more than one setting exist, the tests are required to be performed with each setting and thus the maximum capacity is separately determined for each setting. [29]

As already mentioned in the test signal analyses, several of the currently applied requirements do not recognize the fast regulating capability of modern resources, such as BESS or other technical units connected via power electronics. For example, the three minute activation requirement applied to units participating in the FCR-N market is clearly intended for conventional power generation and does not take advantage of fast regulation, and the same applies to virtually all of the present activation time requirements. However, better utilizing the fast ramping reserve capacity could prove beneficial from the point of view of the whole power system: as the full active power capacity is available sooner, during the activation period more energy is supplied into the grid when compared to units that regulate more slowly [6]. Consequently, introduction of an ancillary service product exploiting the resources capable of fast regulation is seen in the future [55].

5 Regulating tests

In the previous chapter, the technical requirements for individual units participating in the Frequency Containment Reserves were introduced and the necessary regulating tests for verifying the compliance with the requirements were formulated. In this chapter, the regulating tests are performed on a Siemens SieStorage Battery Energy Storage System and the acquired test results are analyzed.

5.1 Test setup

The regulating tests were performed on Siemens SieStorage Battery Energy Storage System installed in Viikki Environment House located in Helsinki, Finland. The BESS is primarily intended for optimizing the electrical energy consumption of the building which is equipped with energy saving technology, such as solar panels [57]. The test BESS is illustrated in Figure 24.

Figure 24: The Siemens SieStorage BESS in Viikki Environment House in Helsinki.

The BESS is equipped with modern lithium-ion batteries with a total energy capacity of 45 kWh and its nominal active power output is 90 kW. In theory, the energy capacity and power output values entail a C-rating of 2C, as the BESS is able to supply its nominal power for 0.5 hours. However, in reality roughly two thirds of the energy capacity is available for utilization due to limits set for upper and lower allowed State Of

Charge (SOC). The limits are set in order to preserve the battery from premature degradation and they are acknowledged in calculating the active power output settings utilized in the tests.

The principle of the frequency control system implemented with the SieStorage is presented in Figure 25. The system frequency in the grid is measured with an accuracy of 1.0 mHz by the SieStorage's integrated frequency measurement. The frequency measurement is transferred via an industrial field bus into the Siemens S7-1200 -series industrial PLC which processes the frequency control logic, transmits the control signal to the BESS controller and receives the real-time active power and SOC data for logging. Communication between the PLC and the BESS controller is transferred via an industrial field bus. The logs stored in the PLC are remotely accessible through a Virtual Private Network (VPN).

Figure 25: The principle of frequency control implementation.

As the energy reservoir of a BESS is limited, the active power output capacity available to the FCR markets within the current thirty minute regulating requirement is estimated mathematically. The theoretical maximum capacity is estimated from (4):

$$P_{cap} = \frac{BAC \times E_{tot}}{t_{use}} \tag{4}$$

where

P_{cap} is the active power capacity available to the regulation (kW),

BAC is the Battery Available Capacity (%),

E_{tot} is the total energy capacity of the battery (kWh) and

t_{use} is the time in regulation use (h).

It is to be noted, that the available battery capacity corresponds to the SOC zone available for utilization. Estimating the maximum active power capacity available to the unidirectional FCR-D regulation is straightforward, as the whole energy capacity within the SOC limits is available. On the other hand, when estimating the corresponding maximum capacity to the FCR-N market, the bidirectional and symmetrical regulating characteristic has to be acknowledged: for FCR-N use, the initial SOC in the beginning of market use should be approximately in the middle of the available SOC zone, as maintaining equal regulating capacity to both directions is required. This denotes that the FCR-N capacity from the same BESS is approximately half the capacity available to the FCR-D use.

For the test BESS, the calculated estimates for the maximum active power output capacities as well as the raw data used are listed in Table 11. The tests were run with a power output setting of 30.0 kW in both up and down-regulation. This setting, however, slightly contradicts the obtained estimate of 29.25 kW for the maximum FCR-N active power output capacity.

Table 11: The raw data used in calculating the maximum active power capacities available to the FCR-N and FCR-D markets as well as the obtained values.

Parameter	Value
Battery Available Capacity (BAC)	65 %
Total energy capacity of the battery (E_{tot})	45 kWh
Minimum time in regulation use (t_{use})	0.5 h
Maximum capacity available to the FCR-D market ($P_{cap,D}$)	58.50 kW
Maximum capacity available to the FCR-N market ($P_{cap,N}$)	29.25 kW

According to the recommendations given in Janne Huvilinna's Master's thesis from 2015, while running the FCR-N tests, the maximum allowed dead band of ±50 mHz in frequency control is applied. First of all, this is due to avoiding of premature battery degradation, as the number of discharge cycles is higher when no dead band or a narrower dead band is applied. Additionally, a higher market availability is reached by utilizing the broader dead band. [6] However, consecutive stepped power output changes cause extra wear on the BESS hardware, especially on the power electronics and the battery. Another noteworthy detail is that during the test runs, the BESS was utilized as a linearly controllable Power Generating Module in up-regulation and as a linearly controllable Demand Unit in down-regulation. Thus testing the correct functioning of load-shedding options presented in Table 6 was not performed.

5.2 Test results and analysis

The regulating tests were run according to the test curves formulated in chapter 4. The following should be taken into account when studying the results presented in Figures 26-35:

- Defined by the control software in the BESS, negative power output denotes active power output into the grid, that is, the battery is discharging. Positive power output, in turn, denotes that the battery is charging.

- The sampling of data is executed in 200 ms intervals, according to Fingrid's requirements.

- The battery's State Of Charge is logged with an accuracy of 0.5%.

5.2.1 Regulating Test 1

The first regulating test was run using the test signal 1 presented in Figure 20 which is normally utilized in determining the technical unit's maximum reserve power capacity on the FCR-N market. The test record is presented in Table 12.

Table 12: Test record of Test 1.

Record	Value
Control logic software version:	0.6 (27.9.2016)
Test site temprerature:	24 °c
Power setting, up-regulation (discharge):	-30.0 kW
Power setting, down-regulation (charge):	30.0 kW
Test started:	08.55
SOC at the start of the test run:	57.0 %
Test finished:	09.06
SOC at the end of the test run:	56.0%

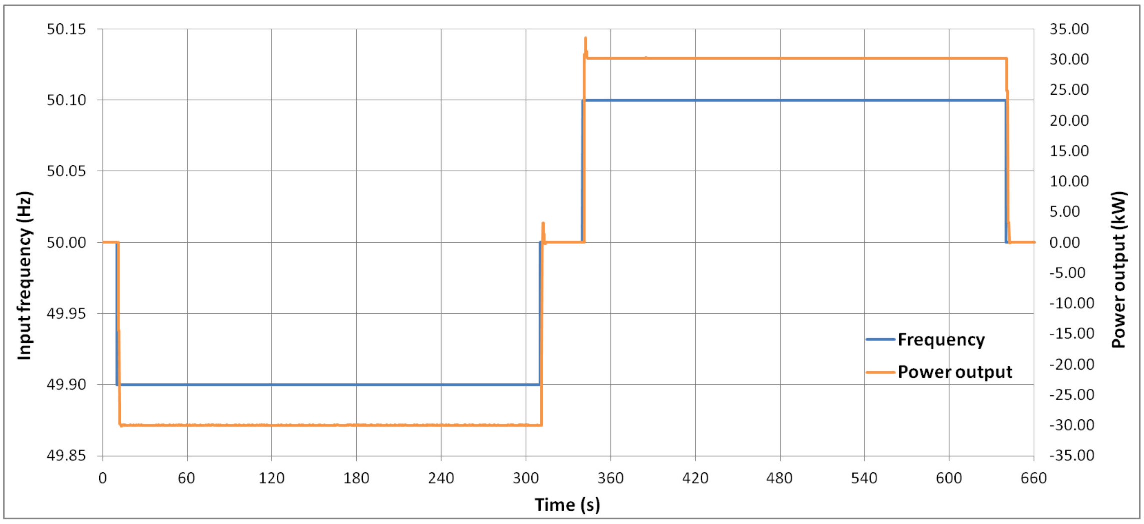

Figure 26: The input frequency signal and the measured power output of the BESS in Test 1.

In Figure 26, the input frequency signal and the measured power output of the BESS are plotted. The regulation from idle to full up-regulation in the beginning of the test run and from full down-regulation to idle in the end of the test run is executed in slightly more than two seconds in response to the change in the input frequency signal. Correspondingly, in the middle of the test run the regulation from full up-regulation to idle and from idle to full down-regulation takes slightly more than two seconds, although the steady state takes about a second more to reach due to modest overshoot in regulating, which is clearly visible in the figure. As overshooting in up-regulating is not so well manifested in this test, the overshooting will be discussed in the next section. However, the tendency to overshoot is characteristic for the test BESS and is not related to the test sequence itself.

The exact time taken in either up or down-regulating can't be determined due to the inadequate logging resolution. However, the three minute time requirement set for the full output power change is clearly fulfilled in both up and down-regulation. It is to be noted, that the regulating capacity available to the FCR-N market is normally determined three minutes after the beginning of the up or down-regulation. This is not applied for Battery Energy Storage Systems, as the regulating power must be calculated and set prior to the test.

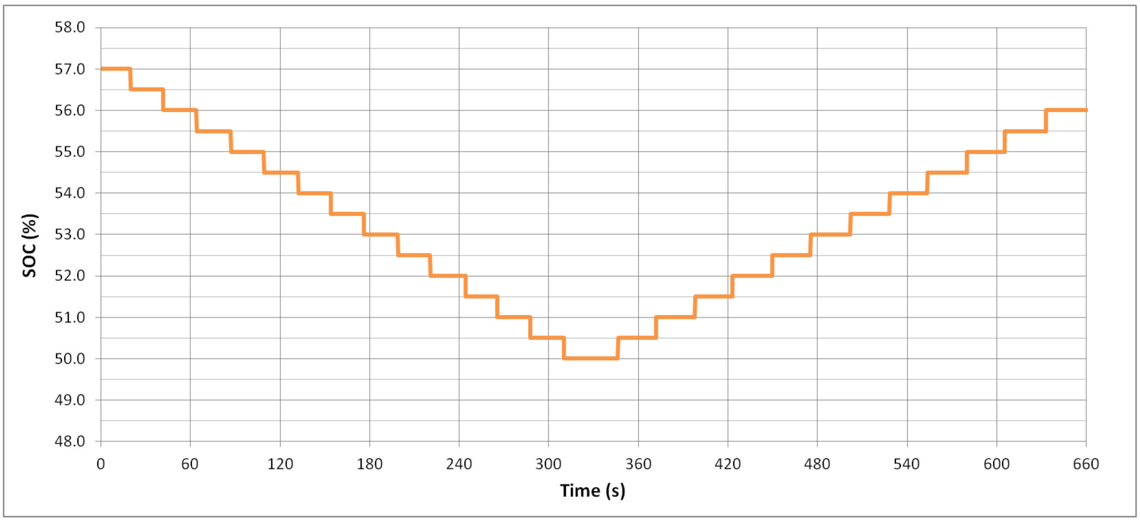

Figure 27: The battery State Of Charge during Test 1.

The behavior of the battery's SOC during Test 1 is illustrated in Figure 27. The bidirectional regulation characteristic of FCR-N is easily recognized as the battery is discharging and charging during the test run. As is shown in the figure, the decrements and increments of the SOC value occur at fairly constant intervals, which is due to the constant output power applied during the up and down-regulating phases of the test. Examining the data log reveals that in the up-regulating phase the 0.5% decrements in the SOC occur at an average interval of 22 seconds. At this rate, continuous up-regulation for the whole thirty minute time requirement denotes approximately 40.5 percentage point decrease in the SOC. Correspondingly, the increments occur at 26 second intervals in average, which denotes to an approximate 34.5 percentage point increase in the SOC. Thus, it is noticed that in FCR-N use the ±30.0 kW output setting would require a BAC value of roughly 75.0% as the full regulating capacity should be available for thirty minutes to any of the two directions.

Another noteworthy detail registered from the Figure 27 is that despite the equally long durations of the up and down-regulating phases, the final SOC value is below the initial SOC: during the test run approximately one percent of the battery's energy capacity is lost, as the SOC value drops faster than it rises. This is due to losses in the power converter, the battery and other circuits. Additionally the cooling system increases the total losses in the system.

5.2.2 Regulating Test 2

The second regulating test was run according to the test signal presented in Figure 21. The purpose of Test 2 was to verify the correct functioning of the FCR-N frequency control. The test record is presented in Table 13.

Table 13: Test record of Test 2.

Record	Value
Control logic software version:	0.7 (28.9.2016)
Test site temprerature:	24 °C
Power setting, up-regulation (discharge):	-30.0 kW
Power setting, down-regulation (charge):	30.0 kW
Test started:	08.48
SOC at the start of the test run:	46.0%
Test finished:	08.56
SOC at the end of the test run:	45.5%

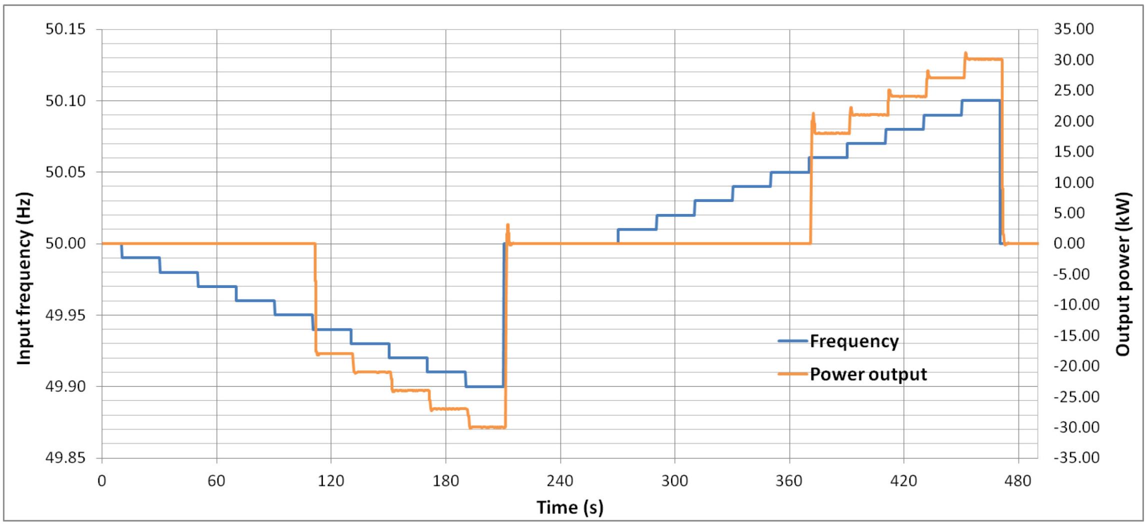

Figure 28: The input frequency signal and the measured power output of the BESS in Test 2.

The input frequency signal and the measured output power logged during Test 2 are plotted in Figure 28. The applied dead band of ±50 mHz is clearly visible in the figure: the up-regulation commences right after the input frequency drops to 49.94 Hz and, respectively, the down-regulation starts right after the input frequency rises to 50.06 Hz. Thus, the maximum allowed dead band is not breached and the frequency control functions according to Fingrid's requirements. The impact of applying the maximum allowed dead band in the frequency control is also noticed: a steep stepped change in the active power output occurs after the dead band is exceeded. 60% of the BESS's full regulating power is activated at once, as the control logic starts to follow the linear control characteristic presented in Figure 17.

Up-regulating to the power output set point calculated by the PLC takes between 2.6 and 3.6 seconds after the change in the input frequency signal, including the time taken to reach the steady state after the overshoot in regulation. The full up-regulating power is activated during the twenty second long maximum frequency deviation, thus the requirement for full activation within three minutes is clearly fulfilled. The steady state in down-regulating after the frequency change is reached in 3.0 to 3.8 seconds. Again, the overshoot causes additional delays in reaching the steady state active power output. During the maximum frequency deviation the full down-regulating power output is reached, which entails that the three minute activation requirement is fulfilled in down-regulation also.

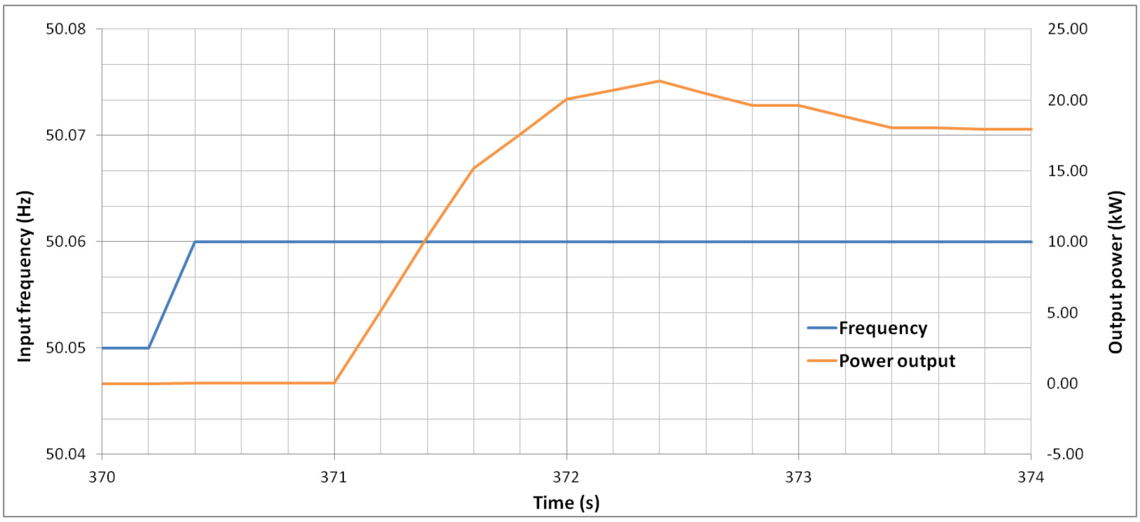

Figure 29: A detail of the overshoot in down-regulating from idle to 60% of the maximum down-regulating power during Test 2.

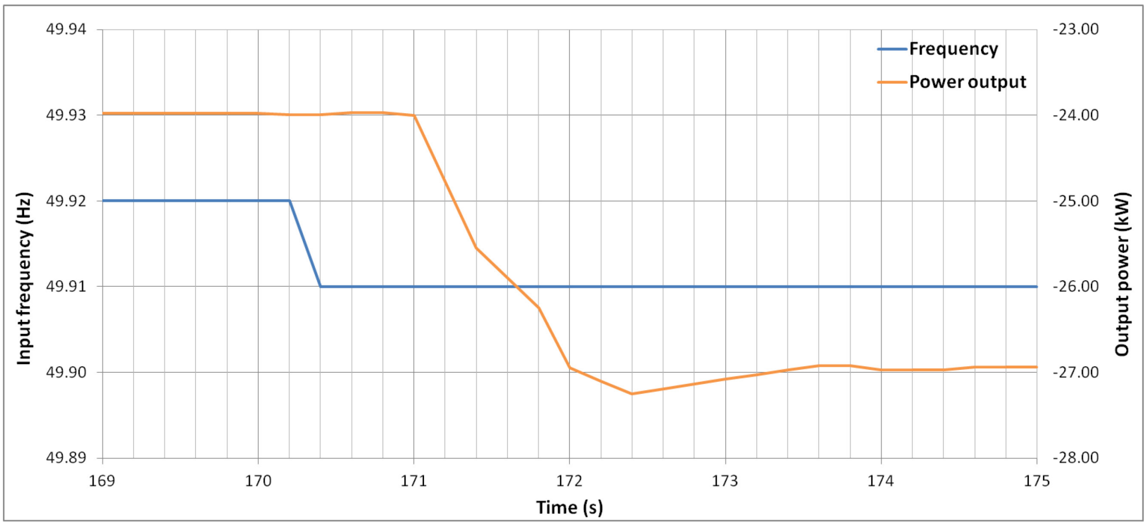

Figure 30: A detail of the overshoot in up-regulating from 80% to 90% of the maximum up-regulating power during Test 2.

Details of the overshoot in down-regulating and in up-regulating are presented in Figures 29 and 30. While examining the active power changes in the data log, successive data records with the same active power value were observed. Plotting detail figures with these records would lead to curves that suggest that the changes in the test BESS's active power output are stepped instead of linear. However, as the BESS is capable of adjusting its active power output faster than in the 0.2 second sampling intervals utilized in logging, it can be assumed that the duplicated or triplicated values appeared primarily due to the cyclical execution of both the data logging and the control logic and secondarily due to time lag in the data transmission between the PLC and the SieStorage controller. Hence, in order to achieve more realistic curves, the recurring active power values were eliminated by interpolating: the intermediate values were replaced with mean values.

In Figure 29 the greatest overshoot in down-regulating during the test run is illustrated and, respectively, in Figure 30 is shown the corresponding overshoot in up-regulation. As is clearly visible in the detail figures, the overshoot occurs in the direction of the regulation, that is, the BESS's active power output momentarily exceeds the calculated set point value. As is also noticed in Figures 26 and 28, this is more strongly manifested in down-regulation: in Figure 29 the set point of 18.0 kW is exceeded by 3.33 kW, whereas in Figure 30 the power output reaches -27.25 kW prior to settling slightly above the set point of -27.0 kW. In both details, the steady state is reached in roughly 1.0 second, thus the continuity of the regulation is not threatened by the overshooting. Additionally, the time delay in reaction to the change in the input frequency signal is visible in the details: in the detail figures, initiating the change in power output takes around 0.6 seconds, although studying the data log reveals that the reaction times vary, and in some cases twice the time is taken. It is to be noted, that determining the reaction times by examining the data log is inaccurate due to the 200 ms sampling intervals. However, compared to conventional power generation, the delays are brief and the total up and down-regulating times are considerably shorter.

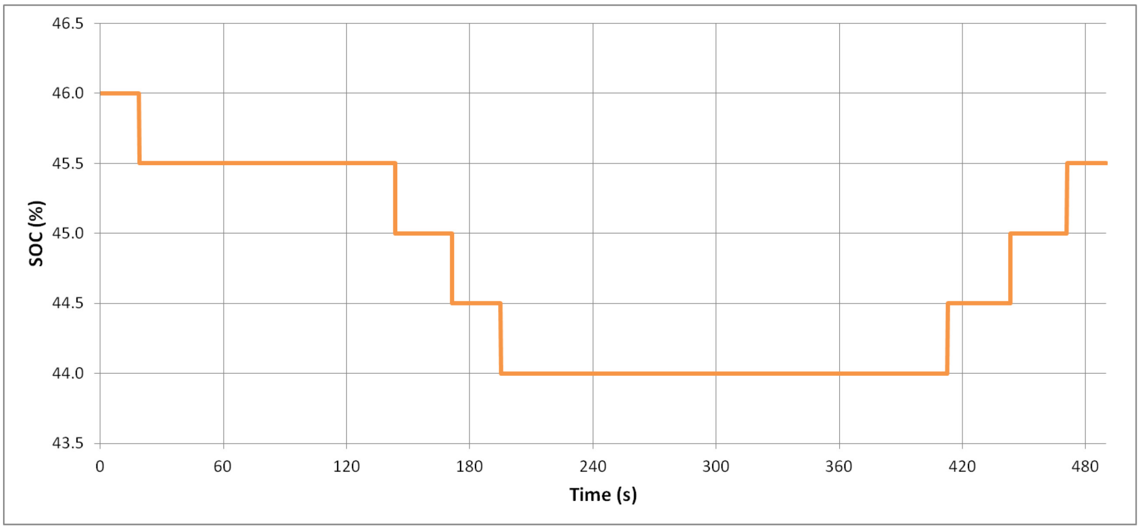

Figure 31: The battery State Of Charge during Test 2.

Figure 31 illustrates the behavior of the battery's SOC during the test run. The first observation is that despite no regulation has yet began, the SOC drops nineteen seconds after the beginning of the test run. This is due to the manner the BESS's Battery Management System (BMS) calculates the SOC value. Other noteworthy details in Figure 31 are the unequally long periods the SOC stays on single steps. This is due to more intense regulating in the latter stages of both the up and down-regulating phases. Again, despite the equally long and symmetrical up and down-regulating phases, the final SOC is below the initial value.

5.2.3 Regulating Test 3

The regulating test 3 was run according to the test frequency signal presented in Figure 23. The test is normally utilized in determining the technical unit's maximum reserve power capacity suitable for the FCR-D market. The test record is presented in Table 14.

Table 14: Test record of Test 3.

Record	Value
Control logic software version:	0.6 (27.9.2016)
Test site temprerature:	24 °c
Power setting, up-regulation (discharge):	-30.0 kW
Power setting, down-regulation (charge):	Not applicable
Test started:	09.15
SOC at the start of the test run:	55.5%
Test finished:	09.20
SOC at the end of the test run:	49.0%

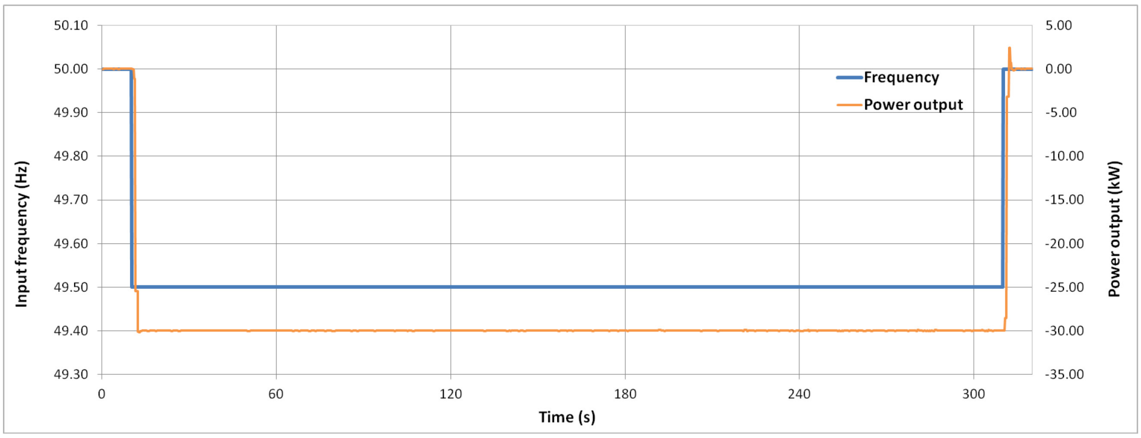

Figure 32: The input frequency signal and the measured power output of the BESS in Test 3.

In Figure 32 the input frequency signal and the measured power output of the test BESS during regulating Test 3 are plotted. The purpose of the test is to determine the maximum active power capacity a technical unit may offer to the FCR-D market, however, as with Test 1, the power output of a BESS must be calculated and set prior to performing the test. Thus, no power output is necessary to be determined either five or thirty seconds after the beginning of the up-regulation, as the application instruction would require. Furthermore, examining the curves shows that the BESS's power output responds correctly to the input frequency signal.

The notable details in Figure 32 are the brief discontinuities in the otherwise linear up and down ramping phases right at the beginning and at the end of the regulation, and the overshoot in regulation as the BESS returns to idle state at the end of the test run. The discontinuities cause slight delays in reaching the power output set points. By examining the data log, it is noticed that after the change in the input frequency signal, the steady state in the beginning of the up-regulation is reached in approximately five seconds, during which a 1.0 second long period of output power value -25.47 kW is recorded. This might be due to the reasons discussed earlier with the Figures 29 and 30, although now the power output values recur several times. Thus, it seems that the ramping process might halt for a short period of time.

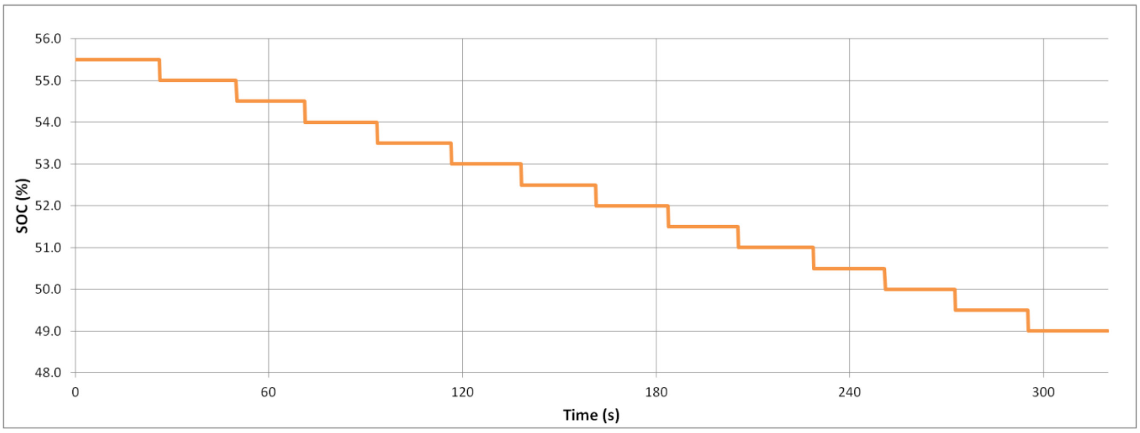

Figure 33: The battery State Of Charge during Test 3.

Figure 33 illustrates the behavior of the battery's SOC during the test run. As Test 3 is utilized for determining the FCR-D capacity, no down-regulation and thus charging of the battery occurs. The SOC drops at average intervals of 22.4 seconds, which is expected due to the applied constant up-regulating power. At this rate, approximately 40.5% of the battery's energy capacity would be spent during the required thirty minute long activation period. In respect to the lowest allowed SOC value of 25%, it can be stated that the initial SOC of 55.5% is not sufficient for a thirty minute long activation, as the SOC would drop to approximately 15.0%.

5.2.4 Regulating Test 4

The fourth regulating test was run in order to verify the correct functioning of the frequency control in FCR-D use. The test frequency signal presented in Figure 23 was utilized. The BESS was running in linear control mode, thus no disconnection according to the load-shedding steps were tested. The test record for regulating test 4 is presented in Table 15.

Table 15: Test record of Test 4.

Record	Value
Control logic software version:	0.6 (27.9.2016)
Test site temprerature:	24 °c
Power setting, up-regulation (discharge):	-30.0 kW
Power setting, down-regulation (charge):	Not applicable
Test started:	09.20
SOC at the start of the test run:	49.0%
Test finished:	09.28
SOC at the end of the test run:	46.5%

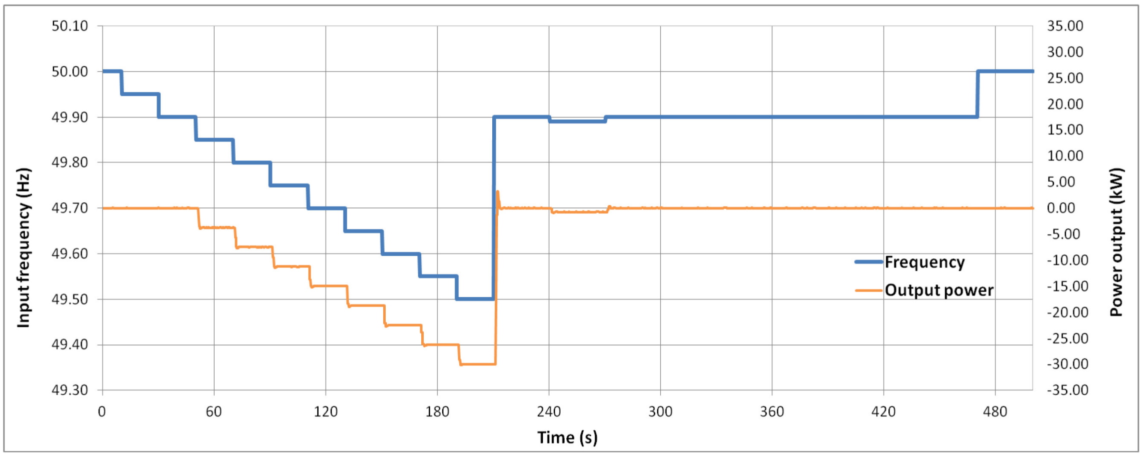

Figure 34: The input frequency signal and the measured power output of the BESS in Test 4.

In Figure 34, the input frequency signal and the measured power output of the BESS during the Test 4 are plotted. The up-regulation activates right after the input frequency falls below 49.90 Hz, which is the upper limit of the FCR-D regulation. During the phase of stepped frequency changes the BESS's active power output response functions correctly, although slight overshoot in the up-regulating is observed. Stronger overshoot is visible at the end of up-regulation when the input frequency returns to 49.90 Hz. During the thirty second long period while a modest -0.01 Hz frequency change is applied, the frequency control reacts and a change in the BESS's active power output is seen, thus the requirement for the minimum measuring accuracy of ±10 mHz is fulfilled.

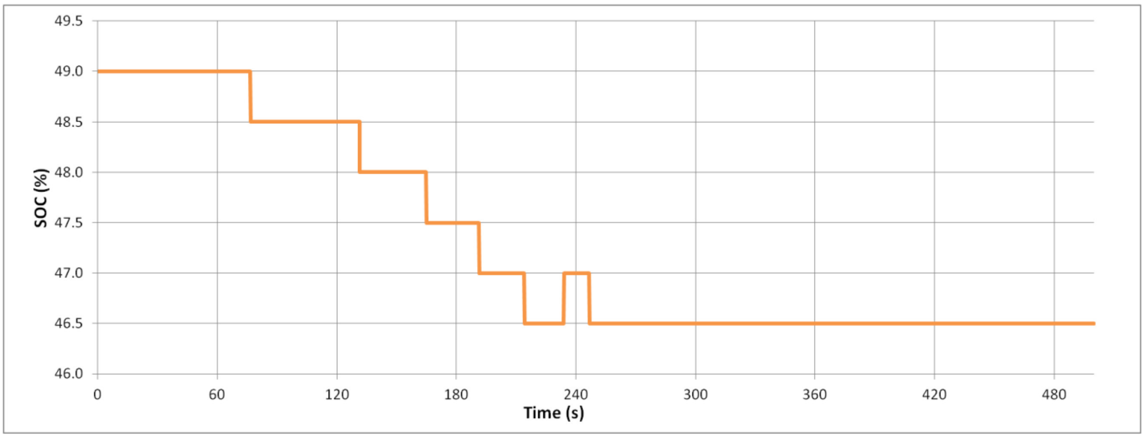

Figure 35: The battery State Of Charge during Test 3.

The behavior of the battery's SOC during Test 4 is illustrated in Figure 35. Examining the figure presents two observations. First, the time spent on a separate SOC percentage level decreases the further the test advances. This denotes that the SOC is decreasing at an accelerating rate, which is expected due to the increasing up-regulating power. Second, the temporary increase in the SOC level in the middle part of the test run is again caused by the functioning of the BMS.

5.2.5 Observations

The most important cause to measuring inaccuracies in the regulating tests described in this chapter is the limited sampling rate of 200 ms. The 200 ms intervals between the data records are too long for capturing the precise behavior of the test BESS, as the BESS is capable of adjusting its power output faster. However, as Fingrid's minimum requirements are fulfilled, no necessary changes to the measuring and logging are foreseen. Furthermore, as discussed earlier, delays due to the data processing cycles and communication between the PLC and the SieStorage controller occur. The combined effect of these delays is unknown, and they cause further measuring inaccuracies.

Although the above mentioned measuring inaccuracies prevent exactly determining the minimum and maximum times taken to up or down-regulate, the results acquired present worst cases. Thus, as the correct functioning of the frequency control was observed and the full regulating capacity was activated in a timely manner, it can be stated that the test BESS fulfills the requirements and is ready for FCR market use, although only as a part of an aggregation.

Analyzing the results from tests 1 and 3 showed the importance of carefully assessing the reserve power capacity offered to the FCR markets, as the chosen power output setting proved too high regarding the thirty minute activation requirement. In continuous full activation, the battery's energy capacity would prove inadequate, at least in respect to the battery's initial State Of Charge in the tests. Furthermore, when planning the reserve use of a Battery Energy Storage System, it has to be noticed that during BESS's normal use its SOC does not necessarily stay constantly at the optimal level regarding the FCR-N or FCR-D market use. That is, the active power capacity available to the chosen market place varies according to the BESS's normal utilization scenarios. The test BESS, for example, will be utilized in optimizing the electrical energy consumption of the environmental house which has to be considered, especially when planning bidirectional FCR-N use.

6 Conclusions

In the final chapter, the regulating tests performed on a Battery Energy Storage System are summarized and the acquired results are reviewed. Based on the results, the fulfillment of the primary goal set for this thesis is discussed. Additionally, an alternative activation characteristic for technical units applying broad dead band in FCR-N use is proposed. Finally, an outlook to the future evolution of the FCR requirements in Finland is taken.

6.1 Regulating tests on a Battery Energy Storage System

The main objective of this thesis was to investigate the current rules and requirements applied to the Frequency Containment Reserves in Finland, and to define the necessary verification processes performed when commissioning FCR resources. This included outlining a simple commissioning process and formulating the regulating tests utilized in verifying the correct functioning of frequency control.

The only tests explicitly presented in the Finnish TSO Fingrid's application instruction are the tests utilized in determining a technical unit's active power capacity available to the FCR market places. These simple step response tests are performed separately to units intended for utilization on both FCR-N and FCR-D markets, as the test signal frequencies are reserve product specific and, due to its bidirectional activation characteristic, also the down-regulating capacity of FCR-N regulation is verified. In addition to the explicitly presented tests, tests for assessing the technical unit's compliance with the other requirements stated in the application instruction are performed. Hence, in chapter 4 of this thesis, four regulating tests were defined and pre-approved by Fingrid's representative. The main goal in formulating the test sequences was to achieve universal applicability among a wide range of different technical units intended for use in the FCR markets, thus facilitating a swift and straightforward commissioning process. Furthermore, the total number of tests was to be minimized.

In chapter 5, the regulating tests defined earlier were performed on a Siemens SieStorage Battery Energy Storage System. Performing the FCR-N related tests on a BESS was highly reasonable due to its excellent applicability to the FCR-N regulation [6]. The suitability to FCR-D markets, however, is more arguable [6], thus the FCR-D related tests were only performed in order to test the applicability of the test sequences. Analyzing the acquired test results yielded three general findings. First, each of the four tests were successfully performed and the BESS's frequency control followed the input frequency signal correctly, thus the BESS passed each of the tests. After Fingrid's result evaluation process it can be expected that the BESS will be approved for FCR market use, although only as a part of an aggregation due to the inadequate maximum power output capacity, of course. Additionally, the regulating test sequences are expected to receive the final approval after Fingrid's evaluation, allowing their future utilization. Second, the hardware utilized in monitoring and measuring suffered slightly from different delays, which caused inaccuracies in result data processing. The third finding was related to the Battery Energy Storage System's regulating characteristics, especially to its controller and its power converter. Further analysis of the hardware related findings was excluded from this thesis. Next, the regulating tests and the acquired results are briefly reviewed.

The purpose of Test 1 is simply to determine the maximum reserve capacity a technical unit may offer to the FCR-N market. It is based on the explicit description presented in the application instruction. No surprising results were acquired from the test run, as, from the point of view of the regulation, the BESS's frequency control performed right as expected: the regulating power was activated well within the time limits and the output power in up and down-regulation corresponded to each other. The tendency to briefly overshoot in regulating, especially when reducing the output power, was registered when studying the plotted output power. This, however, was not related to the test sequence itself but is characteristic for this BESS.

Test 2 is the second regulating test related to FCR-N use. It is more complicated when compared to Test 1, as Test 2 tests the correct functioning of the linear or the almost linear regulation, naturally to both directions. Analyzing the test run yielded no peculiarities related to the functioning of the regulation, although the effect of the applied maximum allowed dead band of ±50 mHz is noteworthy, and clearly visible in the plotted output power. The BESS's tendency to overshoot more strongly when down-regulating manifested itself even more clearly.

In essence, Test 3 is a simpler version of Test 1, however, only this time the technical unit's active power capacity available to the FCR-D market is determined. Due to different market, in this test the input frequency utilized in the step response initializing the up-regulation corresponds to the Maximum Steady-State Frequency Deviation. Additionally the down-regulating phase is excluded, as only unidirectional regulation is applied in FCR-D use. Again, the analysis of the acquired results brought up no concerns, as the BESS was able to initiate and maintain the up-regulation expectedly.

Test 4 is the second regulating test applied to technical unit's intended to FCR-D use. It tests both the linear or almost linear up-regulation and the timely disconnection of relay-connected load-shedding. Additionally, the correct functioning of load reconnection is verified, however, it is to be noted that during the test run the BESS acted as a linearly controllable Power Generating Module. The dead band in frequency measurement proved lower than the maximum allowed, which was manifested by the initiation of the up-regulation according to the -0.01 Hz frequency change fed into the controller in the latter phases of the test run. Apart from the tendency to overshoot in regulation, no other particular remarks were made in the result analysis.

As mentioned, the four regulating tests defined in this thesis were approved by Fingrid and analyzing the acquired results proved that the tests are suitable for utilization as official regulating tests. Thus, in this respect, it can be stated that the goals set for this thesis were reached. Moreover, the regulating tests 2 and 4 already comply with Fingrid's future rules, as the functioning of the coming linearly stepped activation characteristics should be verifiable by the tests [55, 58]. Slight modifications, however, are foreseen now that the application instruction for year 2017 is published.

As Battery Energy Storage Systems are typically capable of rapidly ramping up the nominal power output, it is not reasonable to determine the active power output capacity by regulating tests. On the contrary, the active power output available to the application, to FCR use for instance, shall be calculated and, if required, verified by running longer duration tests. As such tests are not presently required in Finland [55], the fulfillment of the availability requirements may also be determined by analyzing the behavior of the battery's State Of Charge during the shorter duration regulating test runs. Hence, excluding Test 1 and Test 3 from the commissioning process applied to BESSs might prove reasonable in the future. Should the continuous activation of the unit not be properly verified by running the tests 2 or 4 in their current forms, the duration of the tests is easily extended if required by Fingrid.

Due to findings in results gained from regulating test 2, an alternative activation characteristic is proposed. Currently, the technical units applying a dead band in FCR-N regulation are required to regulate according to the completely linear control curve after the system frequency shifts outside the dead band. However, for technical units capable of fast regulation, such as BESS, this entails that a considerable share of the unit's total regulating power capacity is activated at once. Typically the activation occurs in a time frame of seconds, which is shown in regulating test 2 performed in this thesis.

The forceful activation has the following consequences. First, should a significant share of the total FCR-N capacity comprise of units capable of fast regulation, as soon as the units begin regulating the system frequency is returned within the dead band. Without requirements to maintain the activated power output for a period of time, the units discontinue regulating at the same time, thus forcing the system frequency back outside the dead band. Such behavior affects the frequency quality in the whole synchronous area. Second, the constant up and down-regulating due to the aforementioned behavior of the system frequency causes excessive stress and wear on the hardware of the technical units providing the FCR-N capacity.

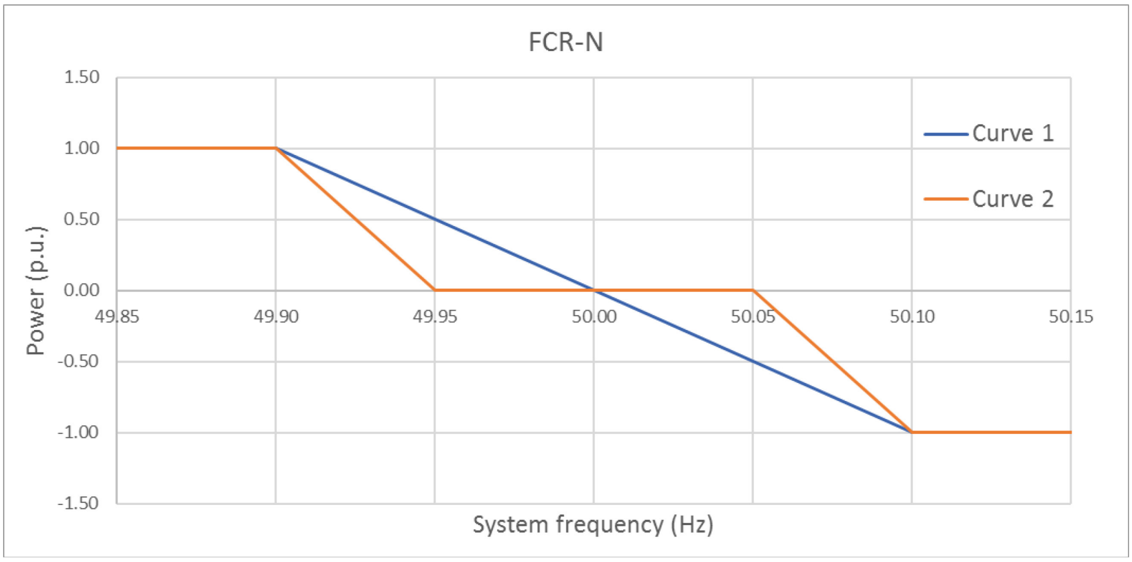

Figure 36: The completely linear FCR-N activation characteristic and the proposed characteristic for units capable of fast regulation.

The unwanted behavior could be tackled by revising the requirements. For example, allowing the rapidly regulating units to activate according to Curve 2 in Figure 36 would cause less wear on the technical units and the system frequency's oscillations around the maximum allowed dead band could be prevented.

6.2 The FCR requirements in the future

In addition to examining the currently applied FCR rules, another goal of this thesis was to look into how the requirements are expected to evolve in the near future. That is why the Finnish TSO Fingrid’s specialist Mikko Kuivaniemi, who is responsible for the technical implementation of frequency controlled reserves, was consulted with.

Due to present hype around Demand Response and smart grids, especially the technical requirements related to two fairly modern reserve concepts were interesting from the point of view of this thesis. First of all, the first aggregated reserve resources have entered the Finnish ancillary service markets. However, aggregating of reserve capacity is not currently recognized in Fingrid's application instruction. According to Kuivaniemi, the recently published application instruction for year 2017 did not bring immediate changes to the situation. This is due to unfinished drafting of applicable market rules: a clear understanding of the FCR markets' response to the revised rules is a precondition for eventually formulating the technical requirements. [55] For example, the topical question of facilitating the operation of third party aggregators, that is, companies that procure the capacity from external resources and then sell it to the reserve markets, is under investigation [7]. However, it can be stated that no technical requirements specific for aggregation only are foreseen [55].

Secondly, no official rules regarding the market utilization of technical units with limited energy reservoirs, such as the BESS presented in chapter 5 of this thesis, exist. The NC LFCR and the coming System Operation Guideline include requirements regarding such units. However, the Nordic TSOs have not yet reached a consensus on how these ENTSO-E's rules should be implemented. For example, the requirements regarding the activation and restoration times are still under consideration. [55] Furthermore, the fast regulating capability of Battery Energy Storage Systems was manifested in the tests performed in this thesis. According to Kuivaniemi, a faster ancillary service product suitable for BESSs and relay-connected load-shedding might be introduced in the future [55].

The discussion with Kuivaniemi also brought out the on-going Nordic project for defining the whole Frequency Containment Process in the NE synchronous area anew. This entails harmonizing the technical requirements set for FCR providing resources, for example. The motivators for the project are the endeavors to attenuate the oscillations characteristic for the synchronous area, as well as to prepare for the future changes in the power system, such as the rising share of renewable electricity production. [4]

Due to the harmonization and modernization of the technical requirements, the verification of compliance with the requirements is facing fundamental changes in the future. Along with the new requirements a shift to new testing methods will occur: in addition to testing the capacity and the performance of a technical unit, totally new stability requirements are to be fulfilled and regulating tests performed with sine waves are introduced. [55]

Moreover, changes regarding relay-connected load-shedding are foreseen, as a new linearly stepped activation characteristic is coming along with the System Operation Guideline [58]. Furthermore, utilizing a single disconnection option, as listed in Table 6, is probably prohibited [55]. In addition to changes in technical requirements, the SOG will introduce changes in the TSO responsibilities [58].

The most important FCR market related changes in the future are the introduction of FCR-D down-regulation market place and the impacts of the new technical requirements on the current market: faster FCR-N regulation is required in the future, which is assumed to cause difficulties to hydropower generation. The Finnish power plants typically utilize a Kaplan type turbine, which will suffer from the change. [4]

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