TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

EETU VÄÄNÄNEN

AGGREGATING LOADS FOR DEMAND RESPONSE IN INDUSTRIAL ENVIRONMENT

Master of Science Thesis

Examiner: professor Pertti Järventausta
Examiner and topic approved on 9 August 2017

ABSTRACT

EETU VÄÄNÄNEN: Aggregating Loads for Demand Response in Industrial Environment
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Keywords: aggregated demand response, industrial demand response, load aggregation, power reserve market

Objective of this thesis was to evaluate demand response potential of small loads in a paper mill. Target was to examine the capacity for frequency containment reserves and balancing power market operated by Fingrid. In addition, the emphasis of the thesis was on technology, in other words, the technical readiness of the paper mill for aggregated demand response product was evaluated. Important aspect of the thesis was extensibility to enable effortlessly identical examination in other similar factories.

Applied research took advantage of the tools provided by the company in question. Identification was performed at single motor level utilizing process knowledge. Lists of motors and frequency converter drives were used as base information. The most notable issues concerning the research were process constraints and limitations set by reserve market. Consumption information of the potential loads was examined with various methods; motors for balancing power market were measured with current clamps and frequency converter driven motors using automation systems. Next, limits for each converter drive were retrieved experimentally and true reserve power capacity was examined using historical information. Capacity for balancing power market was evaluated with bidding mechanism. Motors with frequency converters were analyzed with an Excel-tool. Reserve capacity was calculated with the tool for an example day in Jämsänkoski. Also, the available capacity for balancing power market was analyzed with sufficient accuracy.

Technical realization was evaluated by conversations with automation staff of the factory. Based on this, the thesis proposes few options for the realization. In practice, the implementations fulfill requirements for power metering in balancing power market and control measures needed for the frequency containment reserves.

Profitability in reserve market was evaluated using calculated and estimated capacities. Revenue was calculated with an earning model provided by Fingrid, and it is based on historical information of realized power sales. It is concluded that the available capacities are sufficient for decent payback period considering the investments needed for the technical implementation. In addition, the load aggregation for demand response is noted to be repeatable in other similar manufacturing plants using the methodology presented in this thesis.

TIIVISTELMÄ

EETU VÄÄNÄNEN: Kuormien aggregointi kysyntäjoustoon tehdasympäristössä
Tampereen teknillinen yliopisto
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Avainsanat: aggregoitu kysyntäjousto, kysyntäjousto teollisuudessa, kuormien aggregointi, reservimarkkina

Työn tavoitteena oli kartoittaa paperitehtaan kysyntäjoustopotentiaali pienten sähkökuormien osalta. Tavoitteina oli arvioida tehomäärä Fingridin taajuuden vakautusreserveille sekä säätösähkömarkkinoille. Tämän lisäksi työ painottui tekniikkaan, toisin sanoen työssä arvioitiin erityisesti paperitehtaan teknistä valmiutta aggregoidun kysyntäjoustotuotteen käyttöönottoon. Tärkeä osa työtä oli huomioida laajennettavuus, jotta saman selvityksen tekeminen muissa vastaavanlaisissa tehtaissa onnistuu vaivattomasti.

Käytännön tutkimuksessa käytettiin apuna ko. yrityksen antamia työkaluja. Kuormien selvittäminen tapahtui yksittäisten moottorien tasolla prosessituntemusta hyödyntäen. Lähtötietoina käytettiin listausta moottori- ja taajuusmuuttajakäytöistä. Huomioitavina asioina olivat päällimmäisinä prosessien rajoitteet sekä reservimarkkinoiden rajoitteet. Potentiaalisten kuormien kulutustiedot selvitettiin erilaisin menetelmin; säätösähkömarkkinoille soveltuvat kuormat mitattiin virtapihtimittarilla ja taajuusmuuttajalliset moottorit käyttäen automaatiojärjestelmää apuna. Tämän jälkeen haettiin kokeellisesti rajat kullekin taajuusmuuttajakäytölle sekä historiatietojen avulla arvioitiin todellisia reservikäyttöön soveltuvia tehoja. Säätösähkömarkkinoille soveltuvan kapasiteetin määrää arvioitiin tarjousmenetelmän avulla. Taajuusmuuttajallisten moottorien analysointi tapahtui Excel-työkalun avulla. Työkalulla saatiin laskettua reserviteho esimerkkipäivänä Jämsänkosken tehtaalta. Myös säätösähkömarkkinoille tarjottava kapasiteetti saatiin analysoitua riittävän tarkasti.

Teknistä toteutusta arvioitiin keskusteluilla tehtaan automaatiohenkilöstön kanssa. Työssä ehdotetaan tämän perusteella muutamaa vaihtoehtoa toteutukselle. Käytännössä toteutukset ratkaisevat säätösähkömarkkinoille vaadittavan tehon mittauksen aiheuttavat vaatimukset sekä taajuusohjattuihin reserveihin vaadittavat säätötoimenpiteet.

Laskettujen ja arvioitujen kapasiteettien avulla arvioitiin tuottavuutta reservimarkkinoilla. Tuotto laskettiin käyttäen apuna Fingridin tekemää ansaintamallia, joka perustuu historialliseen tietoon tapahtuneista tehokaupoista. Lopputuloksena todetaan saatavilla olevan kapasiteetin riittävän kohtuulliseen takaisinmaksuaikaan huomioiden tekniseen toteutukseen vaadittavat investoinnit. Lisäksi todetaan kuormien aggregoimisen kysyntäjoustoon olevan toistettavissa muissa vastaavissa tuotantolaitoksissa työssä esitetyin menetelmin.

PREFACE

This thesis was written in UPM's paper mill in Jämsänkoski and office in Tampere in 2017. I want to thank my supervisor MSc Jari Saarinen and Energy's Jarkko Nyrhinen and the rest of the group coordinating the thesis. Many thanks to the examiner, Pertti Järventausta from Tampere University of Technology, for all the interest and comments helping in my work. I want to thank the personnel of UPM for the help during the work and supporting work atmosphere in both Jämsänkoski and Tampere.

I am grateful for my family for supporting me during my years of study. Special thanks to Hanna at home. Also, I want to thank my friends and fellow students for the fun study years.

Tampere September 19th 2017

Eetu Väänänen

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LIST OF SYMBOLS AND ABBREVIATIONS

AMR	Automatic Meter Reading
aFRR	automatic Frequency Restoration Reserve
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DCS	Distributed Control System
DER	Distributed Energy Resource
DLMS	Device Language Message Specification
DLMS UA	Device Language Message Specification User Association
COSEM	Companion Specification for Energy Metering
DR	Demand Response
DSM	Demand Side Management, older term referring to DR
DNO	Distribution Network Operator
DSO	Distribution System Operator
EPAD	Electricity Price Area Differential
EPEX	European Power Exchange
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal operation
mFRR	manual Frequency Restoration Reserve
NBS	Nordic Balance Settlement
NordREG	Nordic energy regulators
NZEB	Nearly Zero-Energy Building
OpenADR	Open Automatic Demand Response, standard for communication in DR related technology
OPC	Open Platform Communications, standard for communication in automation technology
OTC	Over-the-Counter
PCR	Price Coupling of Regions
PLC	Programmable Logic Controller
PM	Paper Machine
P&ID	Piping and Instrumentation Diagram
RR	Replacement Reserve
RTP	Real-Time Pricing
SEC	Specific Energy Consumption
TMP	Thermomechanical Pulping
TOU	Time of Use
TPA	TotalPlant® Alcont, Honeywell's system for plant's automation
TSO	Transmission System Operator
UPM Paper ENA	UPM Paper Europe & North America

1. INTRODUCTION

Traditionally, balance between production and consumption required for power systems operation has been maintained with controllable power production units, such as hydropower and condensing power. Increasing number of uncontrollable energy resources such as nuclear power and weather dependent resources such as wind and solar power along with the reduction of controllable condensing power, e.g. coal power, has introduced a balancing challenge in power systems. (Järventausta et al. 2015, p.16)

This development of power production has created a business potential for the control of power consumption on the consumer's side. Demand Side Management (DSM), i.e. Demand Response (DR), has arisen on the side of power production as a method for maintaining network balance. In the past, demand response has been utilized relatively little. There are not many companies with extensive experience in the subject and the number of new companies offering demand response services is growing fast as the potential has been realized.

From network companies' and electricity market's perspective, demand response along with decentralized production and energy storages present a notable Distributed Energy Resource (DER). The utilization of such resources requires evolving technology and business models, this operation can be called an aggregation business. Demand response guided by electricity market is based on the market's functions to enable distributed resources to participate in energy market. Aggregator, as a new operator in the business, may be used as a third party between resource owner and electricity market. (TUT, LUT, VTT, 2010)

UPM-Kymmene has many forest industry manufacturing plants. Forest industry is usually energy intensive and therefore UPM has brought up a question whether the company has potential power for DR. Large loads are already utilized in the power markets, but the potential of small loads has not yet been evaluated. Idea for the research of mapping the DR potential has been mutually constructed by UPM Energy and UPM Paper Europe & North America. To examine the power potential for demand response, two separate master's theses were coordinated, one focusing on the potential in Jämsänkoski paper mill and one in Rauma paper mill.

1.1 Targets, research questions and limitations of the thesis

The objective of the thesis was to review the potential of electrical loads in the paper mill to participate in reserve power markets. The most important task was to systematically find suitable loads for demand response. Reserve markets and adjustability of the loads had a large impact on the research and true potential of the identified loads in reserve markets was examined by further investigation for the loads with most potential. Emphasis of the research is on the technical implementation and therefore the technical readiness of the mill was evaluated. The research is a case study in Jämsänkoski paper mill although repeatability in other similar manufacturing plants was encouraged. The most relevant research questions are:

- What kind of potential loads for demand response exist in the factory?
- How much potential is there considering the market value?
- What are the methods used to find and control these loads?
- What must be done to enable demand response in Jämsänkoski paper mill?

Demand response in industrial environment is a relatively wide concept without clear boundaries. Therefore, it was important to set limitations for the research. Larger process units, i.e. woodchip's refiners, are already optimized and therefore the thesis focuses on identifying smaller controllable loads utilizable in reserve markets present in Finland. Boundaries were set by following three principles:

- Reserve use of the loads shall not affect manufacturing process negatively, or the negative impact is manageable and does not cause additional costs in any form.
- Aggregated reserves must obey the requirements of the reserve product set by Fingrid for each reserve type.
- Aggregated reserves are not traded in power retail or wholesale markets. Trading is only conducted in power reserve markets dedicated to maintaining network frequency.

1.2 Methodology used in the research

The research in the thesis was conducted in Jämsänkoski paper mill as a case study in 2017. The investigated objects of the research were the electric loads in the mill. The evaluation was performed without alteration to regular manufacturing processes and testing of applicable loads was performed individually. Evaluation helps answer questions "what" and "how much" and it was conducted by interviews and information from the systems used in the mill. The tests for applicable loads were conducted using automation system for the control and monitoring with minor exceptions.

Along with evaluation and testing, examination of enabling technology was conducted. This helps answering the question "how". The methodology consisted of conversations and interviews with the mill's automation staff.

The research was conducted with an idea of extensibility in mind. This refers to ability of the same research being performed in other similar manufacturing plants using methodology used in this case. Therefore, this case study may be considered as a pilot research.

1.3 Structure of the thesis

Thesis consists of three main topics. Theory behind the conducted research is presented first. Chapter 2 explains Nordic power systems and market. Electricity wholesale and retail markets, power exchange, financial commodities and power reserves in Nordic countries are reviewed. The power system balance and reserves dedicated to maintaining the balance are examined. The concept of demand response is presented in chapter 3. This includes the development of necessity for demand response, demand response in manufacturing and load aggregation methods for demand response in the paper mill.

The second topic is related to the conducted load identification research and evaluation of the loads in question. These are presented in chapter 4. An explanation of tools used in the research and the results, i.e. identified loads are expressed. Further review is conducted for the identified loads yielding estimated reserve power capacities. Also, a method for systematic load identification is presented to enable convenient identification in other plants.

Final topic discusses about the technical possibilities for enabling demand response in Jämsänkoski paper mill. This is presented in chapter 5 which focuses on two different groups of loads and their technical requirements in reserve markets. This is a case study type research utilizable in Jämsänkoski but also provides perspective for the other similar industrial plants.

Conclusions and discussion are expressed in final chapter 6. Discussion includes topics such as the future of demand response, development of power market and present state of aggregated demand response.

1.4 UPM

UPM-Kymmene (usually referred as UPM) corporation is a Finnish forest industry company. UPM-Kymmene was established in 1995 when Repola Ltd and Kymmene Corporation merged. UPM consists of six business areas: Biorefining, Energy, Raflatac, Specialty Papers, Paper Europe & North America (Paper ENA) and Plywood. UPM has global sales of 9.8 M and is served by 19 300 employees in 45 countries and 54 production plants in 12 countries. (UPM 2017; UPM 2016) This chapter presents the business units involved in the thesis, i.e. UPM Energy and UPM Paper Europe & North America.

1.4.1 UPM Energy

UPM Energy is responsible for electricity production and energy market operations. It is second largest electricity generator in Finland. Unit generates electricity with own hydropower assets and owns shares in other electricity companies. The total electricity generating capacity is 1480 MW and 2977 MW when including integrated CHP and hydropower plants at mill sites. UPM Energy employs 71 employees and sales in 2016 were 357 M€ with profit of 116 M€. (UPM Energy 2017a; UPM Energy 2017b) Table 1. presents UPM's power generating capacity.

Table 1. *UPM Energy's power plant capacity (UPM Energy 2017a)*

UPM's power plant capacity	**MW**
Hydropower	708
Nuclear power	581
Condensing power	191
UPM Energy	**1480**
Combined heat and power and hydropower at mills	1497
Total UPM	**2977**

In 1998, UPM Energy was among first companies to start trading electricity in Nord Pool Spot which is a power exchange operating Nordic power market. Since 2008, UPM Energy has been its own business area and it is a significant participant in the European energy commodities market. UPM Energy trades annually over 20 TWh of electricity and nearly 7 TWh of gas. The business provides support to other business areas by supplying energy. (UPM Energy 2017a)

1.4.2 UPM Paper Europe & North America

UPM Paper Europe & North America, usually referred as UPM Paper ENA, is a graphic paper manufacturer with different papers ranging from magazine papers and newsprint to fine papers. UPM Paper ENA employs approximately 8000 people and operates 15 paper mills globally. All production combined annual production capacity is 8.4 million tons with total sales of 4.8 billion €. (UPM Paper ENA 2017a)

This thesis was made in Jämsänkoski paper mill which is one of the two closely located paper mills in Jämsä river mills. The other mill is called Kaipola paper mill. Jämsä river mills include 6 Paper Machines (PM) with total production capacity of 1,370,000 tons per year. Two paper machines manufacture magazine paper, PM 6 in Jämsänkoski makes super calendered paper and PM 6 in Kaipola makes light weight coated paper. In Kaipola, paper machines 4 and 7 manufacture light weight printing paper and newsprint. UPM Specialty Papers operates paper machines 3 and 4 in Jämsänkoski. Jämsä river mills also include their own power plants to provide steam and electricity for the factories and a deinking plant which reuses two-thirds of the recovered paper in Finland. Mills employ approximately 850 persons and over 80 % of the products are exported. (UPM Paper ENA 2017b) Thesis was coordinated by UPM Energy and Paper ENA and therefore the focus was on PM 6 in Jämsänkoski.

Figure 1 *Jämsänkoski paper mill (UPM Paper ENA 2017b)*

2. NORDIC POWER SYSTEM AND MARKET

Nordic power market dates back in 1991, when Norway decided to deregulate the market of electrical energy trading. Nordic power market was created in steps during 1990s when other Nordic countries also started to deregulate their power market. In 1995, the framework for an integrated Nordic power market was made and Nord Pool was licensed to trade energy across borders. This created the foundation for Nord Pool spot trading. Norwegian-Swedish power exchange is founded in 1996 and Finland joined the Nord Pool in 1998. (Nord Pool 2017d)

Nordic power market was fully integrated when western Denmark and eastern Denmark were included in 1999 – 2000. The spot business was separated into its own company called Nord Pool Spot AS in 2002, and the shares were divided between the Nordic transmission operators (TSOs) and Nord Pool. In 2010, Nasdaq OMX acquired all Nord Pool shares (Nord Pool ASA at that time), except Nord Pool Spot AS which remained independent physical electricity market operator. (Nasdaq 2017a) Later, Baltic countries were also included into the Nord Pool spot market. Price formation takes place simultaneously within these areas (Nord Pool 2017d).

2.1 Electrical energy market

After the electricity market was set free for competition in Finland in 1995, the means to trade electricity became easier. Before, retailers were obligated to buy electricity straight from the generating companies, generate electricity themselves or through owned shares in generating facilities. After the renewal, it is also possible for retailers and large customers to trade electricity through the power exchange. (Partanen et al. 2016)

In power market, there is no risk of counterparty and all exchange players are responsible to the market holder. Trading can also be done by OTC-deals (Over The Counter) which refers to straight business between two parties without using power exchange. Nowadays, Nord Pool Spot is the power exchange in Nordic countries, but in future a rival company European Power Exchange (EPEX) may become a competitive market. (Partanen et al. 2016; ICIS 2017)

Price Coupling of Regions (PCR) is a project to develop single price coupling solution for calculating electricity prices across Europe. The project is run by European Power Exchanges using day-ahead market principles taking into account network capacity limitations. Integrating European electricity market aims to increase liquidity, efficiency and social welfare. PCR was initiated in 2009 and it consists of seven European power exchanges. (Nord Pool 2017f)

2.2 Electricity retail and wholesale market

Electricity retail market refers to electricity sales to end customer through a distribution network. Retailers sell the electricity they produce or buy from wholesale market. In Finland, the retailer with largest sales within the area of relevant Distribution Network Operator (DNO) is responsible for delivering electricity with reasonable price. These prices and terms related to them are public. Small residential customers usually make deals with retailers which allows the retailer to change the price with notice time, deals with firm price or temporary deals. Therefore, the market price fluctuation is not visible immediately in retail prices. Retailers may also offer power exchange based commodities. Then prices are usually reflective to relevant bidding area price. (Partanen et al. 2016)

Retail market have remained national even though the wholesale market has been united. Nordic countries' power market authorities have set a target to unite the retail market. NordREG, an organization for the Nordic energy regulators, has researched the need and possibility to harmonize regulation regarding universal service within Nordic countries. Regulations differ in Nordic countries, but there is no need to immediate actions for harmonizing, although universal service obligations are recommended to encourage customers to choose freely their supplier. Electricity wholesale market may be understood as trading mostly among large market operators. Electricity trading leading to physical delivery is conducted in Nord Pool Spot-market and financial commodities are traded in Nasdaq OMX Commodities Europe –financial market. (Partanen et al. 2016; NordREG 2014)

High volatility of hydro power and consumption of electrical energy is typical for Nordic power system. This leads to high fluctuation of the electricity price. Special characteristics like these demand flexible market for the wholesale of the electricity. Power exchange and OTC-market yield together a flexible and functioning market environment for the trading of electrical energy. (Partanen et al. 2016)

2.3 Power exchange and its commodities

Power exchange is a market for electrical energy trading. It is a neutral, open and centralized market in where the price of the electrical energy is formed. In power exchange, the counterparty of the trades is the power exchange itself. This refers to trading being anonymous and no risk of the counterparty is involved. Power exchange is market oriented which suggests that exchange parties are involved in decision making and therefore the commodity's structure is designed to accommodate parties involved in trading. Trade commodities are divided into physical and financial commodities. Trading physical commodities in power exchange always leads to physical electricity delivery. Physical market, i.e. Spot-market, was created to accommodate parties participating electricity trading and to form a reasonable reference price for electricity. In open market, optimized electricity production and purchase is the base for lucrative business. Even if production and purchase forecasts fluctuate from actual action, market must be able to buy and sell electricity for the demand. This has led to the Spot-market establishment. (Partanen et al. 2016)

Uniform power exchange requires sufficient amount of transmission capacity. This allows the Nordic countries to have a joint market. However, there are transmission bottlenecks in Nordic region which have led to division of market into different price (bidding) areas. Transmission capacity between these areas are reinforced to prevent price differences. Power market works better when there is no need for division of areas. Price areas in Sweden and Finland were uniform 49 % of the time in 2015 by the end of November (Energy Authority 2015). Problems caused by transmission bottlenecks may also be reduced by TSOs with counter purchases. (Purasjoki 2006) Figure 4, in section 2.3.1, presents Nordic transmission lines' power flows along with bidding area prices.

Spot-market in power exchange is equal to every party in the market. System price is formed for each hour of the following day, and it is usually the base for the price of other electricity commodities such as financial commodities, regulating and imbalance power markets commodities and OTC-commodities. In Nordic, Spot-market is run by Nord Pool and it is divided into day-ahead and intraday markets called Elspot and Elbas markets, respectively. (Partanen et al. 2016)

2.3.1 Day-ahead market

"Elspot" is a day-ahead market in Nord Pool and it is in a way a closed market. This suggests that bids are offered to the market without knowing other parties' bids. Trading is performed once a day for each hour of the following day in the price area valid to the bidder. This forms a reference price for the electricity. Smallest amount of electrical energy bid for the market is 0.1 MWh. Block bids may also be created to buy or sell certain amount of electrical energy for several hours in a row. Block bids must be traded for at least 3 hours at the time and they are valid only if price and volume criteria are met. All bids must contain the amount of power sold or purchased and price range for the power in question. In addition, bids may contain other combinations of power and price. Bids have to be made by 12 a clock CET when the market closes. If a bid was not made for the hour/hours in question, it is marked as a zero. After bidding, a reference price is formed for each hour for the following day. (Partanen et al. 2016) Figure 2 represents the price formation based on supply and demand.

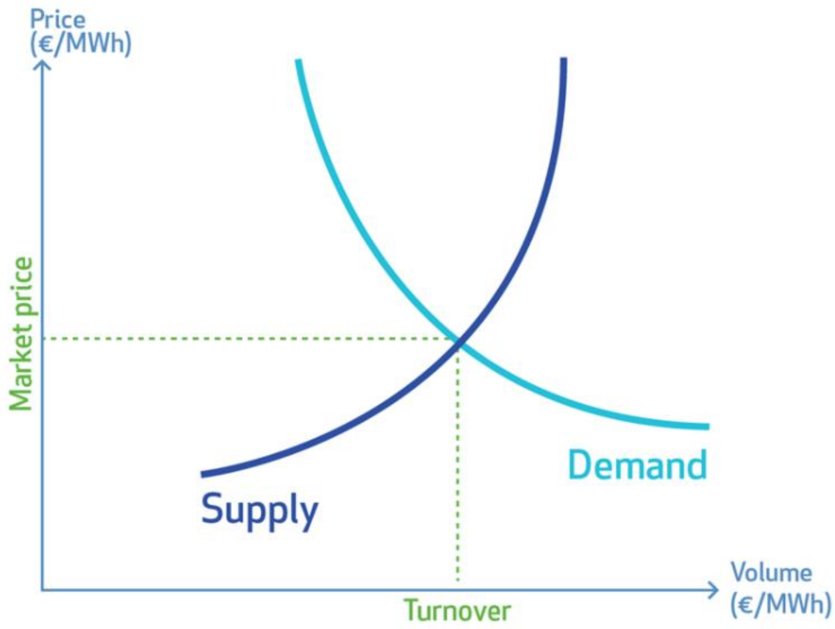

***Figure 2** Price formation based on demand and supply (Nord Pool 2017a)*

Competitive and properly functioning market enables electricity production at lowest possible price. Price represents the most expensive production capacity used to maintain network balance or it is the most the customer group is willing to pay to satisfy the demand. This kind of price formation supports the economy of the society. (Nord Pool 2017a)

There are 15 bidding areas in the Nordic power market as shown in figure 4. Five in Norway, two in Denmark and four in Sweden. Finland, Estonia, Latvia and Lithuania each form one bidding area. Bids are offered to the area where the market operator is located in. If transmission capacity is sufficient, bidding areas may merge into one with joint price. The bidding areas help indicate constraints in the network and power flows from low price area to high price area which correlates with demand. (Nord Pool 2017a)

After bidding, aggregated supply and demand curves are established for all bidding areas. System price is calculated based on sale and purchase bids without taking transmission capacity into account. After system price formation, each country's TSO decides in how many bidding areas the country is divided to depending on the available transmission capacity. (Nord Pool 2017a) Figure 3 shows price fluctuation of Finland bidding area and system price.

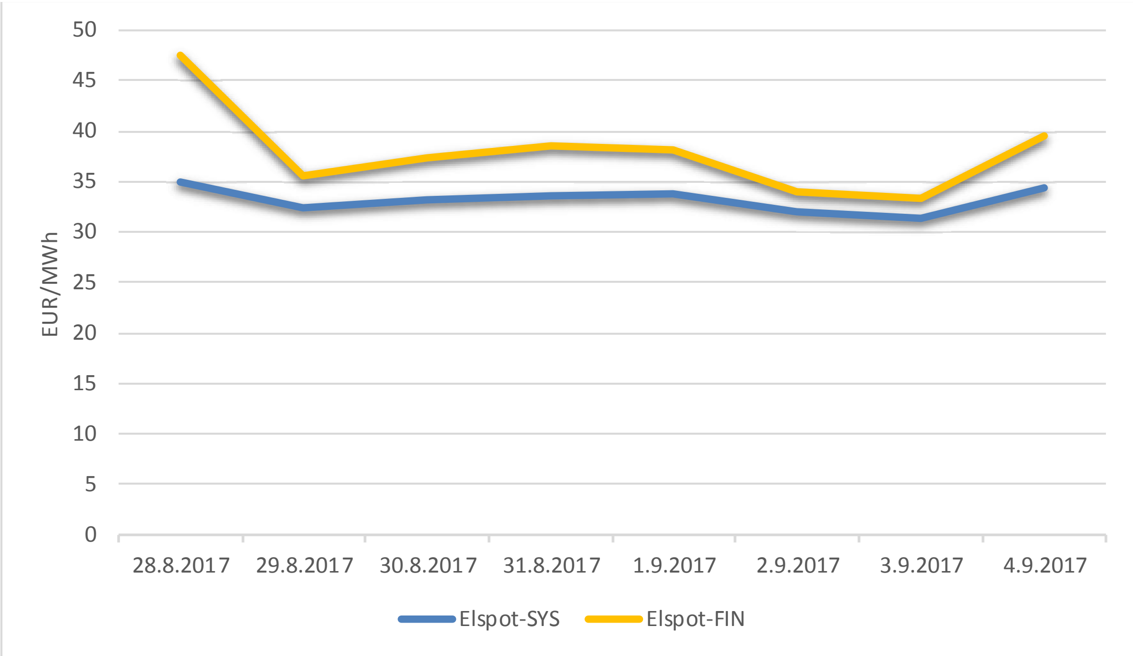

Figure 3 *Finland area price and system price in 28.8. – 4.9.2017 (Nord Pool 2017e)*

Due to transmission constraints, spot price in Finland differs from the system price as shown in the figure. If the transmission capacity is sufficient and no bottlenecks exist, the reference price is equivalent to the system price and it is the same in all bidding areas. Due to transmission capacity restrictions, the price in an area with overproduction decrease and the price in an area with higher demand than production increases compared to the system price. Figure 4 presents power flows between bidding areas (blue values) and area prices (red values) in 3.3.2017 at 9:12.

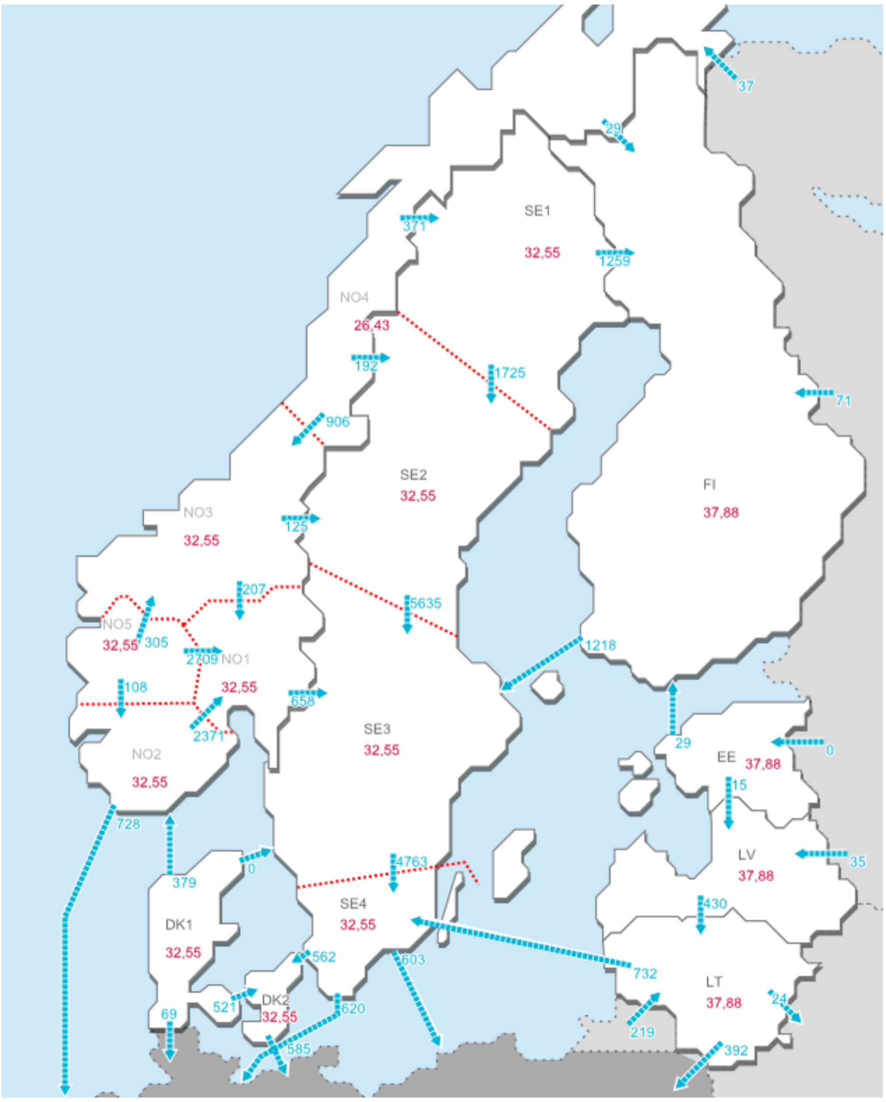

Figure 4 *Nordic power market bidding areas and transmission power flows 3.3.2017 at 9:12 (Statnett 2017)*

As shown in the figure, prices are uniform in most areas of Norway and Sweden, but bidding areas in Finland and Baltic countries show higher prices at the time of review. This is due to transmission capacity constraints and lack of production capacity in high price areas. Opposite effect can be seen in northern Norway where production capacity exceeds transmission capacity.

2.3.2 Intraday market

Intraday market, "Elbas" in Nord Pool, is a supplementary market for day-ahead market. It helps secure necessary balance between supply and demand in the market. Most of the electricity is traded in the day-ahead market, but after the day-ahead market closes incidents may happen before actual delivery hour. This changes the predicted production and consumption and balance correction is needed. For example, a production unit may halt due to malfunction or a wind turbine power output may fluctuate due to wind speed changes. At the intraday market, operators can trade volumes closer to delivery hour to correct their balance plans. (Nord Pool 2017a)

Capacities available for the intraday market are published at 14:00 CET after Spot-market prices are published. Intraday market is continuous market and trading can be done every day around the clock. Market for the delivery hour in question closes one hour before. Prices are formed based on best prices available – highest purchase price and lowest sale price. (Nord Pool 2017a)

Table 2 presents Elbas intraday market prices and trade volume in 3.3.2017 at 9:50 AM. Intraday market does not form one price for bidding area unlike day-ahead market. Instead, power exchange forms high, low and average prices based on realized trading. (Järventausta et al. 2015 p.46) Defined delivery hour in Elbas-market is the same regardless of the bidding area. As can be seen in the figure, trade volume increases when closing delivery hour, because balance prediction is more accurate the closer the delivery hour. More about power balance management in section 2.5.2 Power balance management.

Table 2 *Elbas intraday market prices and trade volume in 3.3.2017 at 9:50 AM (Nord Pool 2017c)*

Product	High	Low	Last	Avg	Volume
3.3.2017-01	29.90	26.50	28.50	27.74	404.70
3.3.2017-02	29.90	25.70	29.90	27.52	531.40
3.3.2017-03	29.50	25.50	28.30	27.91	565.80
3.3.2017-04	29.90	26.60	29.60	28.14	398.20
3.3.2017-05	33.00	24.80	33.00	28.71	627.30
3.3.2017-06	42.00	28.30	37.70	31.30	520.50
3.3.2017-07	39.80	29.60	37.80	32.80	289.00
3.3.2017-08	42.00	31.10	37.00	33.85	512.70
3.3.2017-09	44.00	30.10	40.00	33.52	429.80
3.3.2017-10	40.50	29.00	38.70	34.92	414.40
3.3.2017-11	42.00	29.00	38.30	34.42	119.60
3.3.2017-12	40.30	29.00	40.30	35.32	72.10
3.3.2017-13	42.00	29.00	32.50	33.48	59.00
3.3.2017-14	40.00	29.00	40.00	32.96	84.00
3.3.2017-15	119.90	32.70	119.90	55.21	100.20
3.3.2017-16	32.90	32.90	32.90	32.90	25.00
3.3.2017-17	33.00	32.90	33.00	32.92	13.00
3.3.2017-18	38.80	35.00	38.80	35.63	120.00
3.3.2017-19	40.50	40.50	40.50	40.50	43.00
3.3.2017-20	30.30	30.30	30.30	30.30	3.90
3.3.2017-21	0.00	0.00	0.00	0.00	0.00
3.3.2017-22	0.00	0.00	0.00	0.00	0.00
3.3.2017-23	0.00	0.00	0.00	0.00	0.00
3.3.2017-24	0.00	0.00	0.00	0.00	0.00
Sum volume					5353.60

Intraday market trade volumes may vary significantly but are quite low compared to day-ahead market volumes. Low volume may cause purchase and sell bids not to meet leading to lack of trading actions. This may complicate utilization of demand response potential. However, demand response utilization may offer operator alternative way to compensate balance error (2.5.2 Power balance management) if intraday market does not work due to low volume. To ensure liquidity, Market Makers are operating in Elbas market. There are three Market Makers in Nordic power market and they are committed to quote both buy and sell orders. Volume and number of power hours committed to place orders are individually negotiated. (Järventausta et al. 2015 p.46; Nord Pool 2017b)

2.4 Financial commodities

Financial commodities are meant to reduce the risks in power exchange by securing the price of produced or purchased electricity. It may be used to increase profit and it depicts the projection of future electricity prices. Financial contracts are long term contracts and they do not involve physical delivery. Reference price is the system price in the Elspot-market calculated by the Nord Pool in the Nordic Region. Grid congestion and access to capacity are not considered in financial market. (Nord Pool 2017a)

Trading is done in Nasdaq OMX Commodities -stock exchange with Futures, Deferred Settlement Futures (DS Futures) and Electricity Price Area Differential (EPAD) contracts. Trading is continuous and anonymous meaning that trading is done only between operator and stock exchange, this eliminates the risk of counterparty. Futures and DS Futures are contracts to buy or sell specific commodity in the future. Contracts are binding for both buyer and seller. Contract terms are defined when making the deal. Nasdaq Commodities Nordic Futures' contract period is day, week, month or year. DS Futures' contract period is month, quarter or year. Future and DS Future contracts differ in realization. (Partanen et al. 2016)

With Futures, a daily mark-to-market settlement and a final spot reference cash settlement is applied until the expiry date of the contract. Mark-to-market settlement covers profit or loss from daily price fluctuation. Final settlement beginning at delivery covers the difference between the price of the future contract and the system price. (Nasdaq 2017b)

With DS Future products, year is cascaded into quarters and quarters into months. No settlement is realized prior to expiry date for DS Futures although mark-to-market amount is accumulated throughout the trading period and finally realized in the delivery period. Settlement throughout the delivery period is performed the same way as with future products. (Nasdaq 2017c)

A risk is generated by physical electricity market when system price and bidding area price differ due to grid congestion. Electricity Price Area Differential –contracts may be used to protect from area price risk. Nordic EPAD –contracts are listed in Nasdaq Commodities for trading for the nearest two months, three quarters and three years. The market price reflects the market's prediction of the price difference during the delivery period. (Nasdaq 2017d)

Another way of trading electricity in financial market is options. Option is an agreement to buy or sell commodity in future. Buyer of the option pays the seller a premium for the risk it is taking. There are two types of options: Call and Put options. Call option buyer has a right to buy the commodity in question with predestined price. Call option seller is obligated to sell the commodity with predestined price. Put option buyer has the right to sell the commodity and put option seller is obligated to buy commodity with predestined price. Options are quoted in Nasdaq OMX Commodities exchange and they are European electricity options which are used for futures and DS futures. Potential profits with bought option are limitless and possible losses are at most the value of the paid premium. In case of sold option, the profits are at most the value of the sold premium, but losses may rise high. (Partanen et al. 2016)

OTC-market include all other wholesale trading done outside of exchange. OTC-market enable the operator to modify its own purchase and sale portfolio for its own needs. OTC-contracts always include the risk of counterparty since there is no exchange as intermediate. Power exchange and OTC-market fulfill each other and combined they form the mechanism to manage high electricity price volatility for wholesale trading. (Partanen et al. 2016)

2.5 Power system

Power system is one of the most important components of society. It consists of high-voltage transmission system, high-voltage distribution networks, distribution networks, power production plants and consumers of electricity. In Finland, Fingrid Oyj is the transmission system operator (TSO) which operates the whole transmission system designed to transfer power from production to consumption points. Finnish transmission system is part of the inter-Nordic power system along with systems in Sweden, Norway and Eastern Denmark. Finland's transmission system is also connected via DC-links to power systems in Estonia and Russia. Inter-Nordic system is similarly connected to the system in Continental Europe. (Fingrid 2017f)

2.5.1 System power balance

Electricity consumption consists of all the consumers within the network. The total energy consumption fluctuates all the time and the total level changes over different time domains such as hourly, daily and seasonally. Also, production within network fluctuates over short and long periods. Electricity market operators are responsible for planning and balancing their power consumption and production in advance. Planned balance is usually never completely accurate and therefore Fingrid, as TSO, is obligated to perform balancing actions to maintain power balance within the system during each hour. (Fingrid 2017f)

Frequency of the power system indicates the balance between production and consumption. When frequency is below 50 Hz, the system has more consumption than production. With the same logic, when system's frequency exceeds 50 Hz, the production is higher than consumption. In normal operating state, the frequency may fluctuate between 49.9 and 50.1 Hz. Power system balance is maintained by Fingrid with power balancing market (imbalance and balancing power markets) and power reserves. These are explained later. (Fingrid 2017f)

2.5.2 Power balance management

Power balance management is used to maintain balance between power production and consumption at every single moment. Also, it is used to figure out the electricity usage of the market operators. To ensure the best benefit in the market, it is important for the operator to predict own production and consumption as accurately as possible. Consumption forecasts are the basis for the planning of production. Forecasts always have error and therefore surplus or deficit is present. To fix this error, balancing power market is used. Operators' electricity usage is resolved using imbalance settlement. (Partanen et al. 2016)

Every electricity market participant is obligated to cover all electricity usage and sales with production and purchase contracts in every hour. This imbalance settlement is implemented using open supplier for the operator. Open supplier is responsible for the operator's balance error. Open supplier is therefore obligated to deliver the electricity based on realized consumption after which financial compensation is settled. In Finland, Fingrid's balance service unit is highest in the chain of open suppliers. Those responsible to system managing party are called balance responsible parties. The open delivery between balance service unit and balance responsible party is agreed with balance service agreement. Figure 5 shows the chain of open suppliers starting from Fingrid's balance service unit. (Fingrid 2017c)

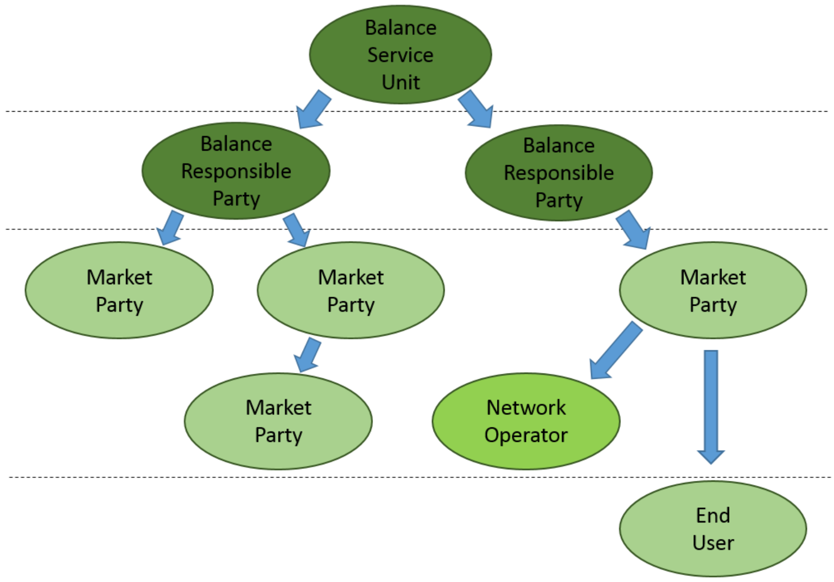

Figure 5 *The chain of open suppliers (Fingrid 2017c)*

Distribution System Operator (DSO) is obligated to arrange imbalance settlement within their own network operation area along with information exchange of open deliveries. This implicates that DSOs must define hourly electricity sales and production within operation area as well as transmission between networks and load profiles. Balance responsible party is responsible for arranging the imbalance settlement and information exchange of its open deliveries. This is done using metering information at the borders and electricity market parties' measured delivery information to the networks. Fingrid defines national electricity balance and balance between Fingrid and balance responsible parties. This yields balance error between Fingrid and balance responsible parties and between Finland and other countries. Imbalance is calculated for both production and consumption separately. (Fingrid 2012a)

Balance responsible party delivers production plan to Fingrid including all power plants belonging to the production balance. This information is used to calculate balance responsible party's production balance error. Production balance error takes into account realized production, production plan and power sales. Negative error implies deficit in balance and it is compensated by buying electricity from Fingrid. Similarly, positive error implies surplus and the surplus is sold to Fingrid. Consumption balance error is formed similarly. Balance responsible party's consumption plans are compared to realized consumption, firm electricity delivery, power sales and import/export. Negative error is deficit and it is compensated by buying imbalance power from Fingrid. Similarly, positive error i.e. surplus is sold to Fingrid as imbalance power. (Fingrid 2012a)

A harmonized balance settlement procedure for Finnish, Swedish and Norwegian TSOs was introduced in May 2017. The project is called Nordic Balance Settlement (NBS) and operational responsibility is outsourced to TSOs mutually owned company called eSett headquartered in Helsinki, Finland. The harmonized settlement procedure enhances and integrates power market in Nordic countries. Harmonized settlement procedure was created to introduce efficient and equal service for all TSOs regardless of the bidding area or country. TSOs are obligated to provide balance settlement service but now it is offered through eSett for all balance responsible parties participating in the power market in the Nordic countries. The harmonized balance settlement procedure is a step towards integrated power market in whole Europe. (Fingrid 2017g)

Integration of power balance settlement in Europe has been recently discussed according to a report (Finnish Energy 2015). The most probable settlement period is 15 minutes but also other options such as 10, 20 and 30 minute periods are considered. Shortened settlement period promotes integration of European balance settlement market and reduces the need for balancing resources such as power reserves due to power fluctuations being smaller in shorter 15 minute's time periods. Deadline for the harmonization has been set to 2019.

2.5.3 Imbalance power market

Financial compensation for error in balance management is realized using imbalance power market. Compensation is calculated for both production balance error and consumption balance error. Trading is done between Fingrid and each balance responsible party. Pricing is formed separately for production balance and consumption balance. Up- and down-regulation and Elspot-FIN prices are used as reference prices (see section 2.5.4. Balancing power market). (Partanen et al. 2016)

Figure 6 presents an example of price formation for imbalance energy. It shows the pricing for both production and consumption balance for both sales and purchases. Up- and down-regulating and spot prices are shown for comparison purposes.

	Production balance 2-price			Consumption balance 1-price			
	Up-regulating hour	No regulations	Down-regulating hour	Up-regulating hour	No regulations	Down-regulating hour	
Up-regulating price	100	50	50	100	50	50	€/MWh
Spot price	50	50	50	50	50	50	€/MWh
Down-regulating price	50	50	20	50	50	20	€/MWh
Fingrid's sales price for balance power	100	50	50	100	50	20	€/MWh
Fingrid's purchase price for balance power	50	50	20	100	50	20	€/MWh

Figure 6 *Example of imbalance energy prices (Fingrid 2017c)*

Pricing for production balance error consists of two prices; one for imbalance power purchases and one for imbalance power sales. In addition, balance responsible party pays a production fee to Fingrid for every realized production used during delivery hour in question. Surplus is sold to balance service unit with imbalance power purchase price. Purchase price is the down-regulation price of the hour in question. If down-regulation did not occur or hour is defined as up-regulation hour, Elspot-FIN price is used as purchase price. Deficit in balance responsible party's balance is compensated with sales from balance service unit and up-regulation price is used as sale price. If no up-regulation has occurred or delivery hour is defined as down-regulation hour, Elspot-FIN is used as sale price. (Partanen et al. 2016)

Consumption balance sale and purchase prices are the same. Consequently, the balance service unit purchases surplus energy from balance responsible party with the same price as they sell deficit energy during the hour in question. Consumption balance energy price is up-regulation or down-regulation price during up- or down-regulation hour respectively. If no regulation power is used during delivery hour, Elspot-FIN price is used as consumption balance energy price. Balance responsible party pays balance service unit a production and consumption fee for all their realized consumption. In addition, balance service agreement defines a volume payment for all consumption balance trades. (Fingrid 2017c)

As shown in the figure 6, balance responsible party cannot profit by trading electricity in production balance. However, with consumption balance electricity trading balance responsible party may generate profit. For example, during up-regulating hour Fingrid may purchase balancing power with higher price than Spot price or during down-regulating hour Fingrid may sell surplus balancing power lower than Spot price. In extreme situations, down-regulation price may become negative meaning that TSO pays for increased energy consumption. An example of such incident is presented in 2.5.4 Balancing power market (figure 9).

2.5.4 Balancing power market

Finland's TSO, Fingrid, does not have enough regulating capacity to maintain network frequency in acceptable limits. Therefore, Fingrid maintains balancing power market which is a part of Nordic regulating power market. Balancing power is also referred to as manual Frequency Restoration Reserve (mFRR). Other power reserves are explained later in the chapter 2.5.5 Power Reserves.

In Finland, participation to balancing power market is possible with a resource that has real time power metering available for Fingrid or other real time information which proves the activation of the resource (Fingrid 2012a). Currently, market participation is possible for balance responsible parties within the limits defined in the balance service agreement. Other participants must sign a separate balancing power market agreement.

After the launch of eSett in 2017, all participants in the balancing power market are required to sign a balancing power agreement. (Fingrid 2017d)

Production and load owners are able submit bids to the balancing power market based on their available capacity for regulating purposes. Regulating power bids must contain information about the power (MW), price (€/MWh), production/consumption, location and name with information about the generating method of the resource. One bid must contain at least 5 MW of power if the bid can be ordered electronically, otherwise the minimum bid is 10 MW (Fingrid 2017j). Bid may be aggregated from several lower power units and maximum up-regulation price is 5000 €/MWh. Capacity bid to the regulating power market must include real time power metering or power change must be otherwise verified in real time. Control of the capacity must be based on physical control and applicable in 15 minutes of the order moment. Minimum activation time is 1 minute (Fingrid 2017j). Control must be available during whole operating hour. (Fingrid 2012a) Figure 7 shows the types of balancing bids.

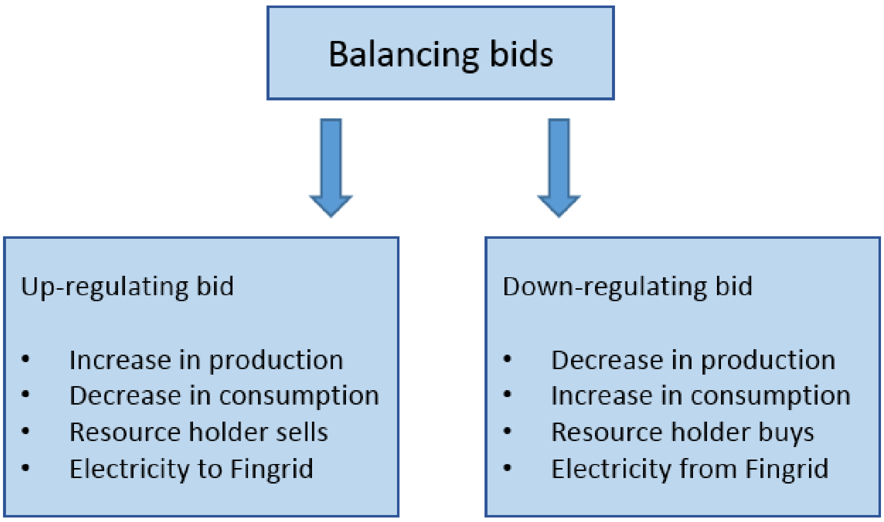

Figure 7 *Balancing Bids (Fingrid 2017c)*

Fingrid delivers balancing power bids to the Nordic balancing power market. There, a curve is formed based on the bids and bids are organized based on the prices. The most inexpensive bid for up-regulation comes first and for down-regulation, the most expensive bid comes first. For balance management and frequency maintenance, the bids are accepted by their price order. If bids have the same price, Fingrid decides the order of usage based on the bid capacity and location. (Fingrid 2012a)

Fingrid places the balancing power orders via phone calls or electronic activation. During phone call, Fingrid states the power, starting time and ensure the right price of the bid. Balance operator then verifies the resource and starting time is agreed within one minute accuracy. Balancing action is ended in the end of the balanced hour unless Fingrid notifies to end the balancing action via phone call before the end of the hour. (Fingrid 2012a)

Regulation prices are formed in the Nordic balancing power market based on the realized balancing acts. Up-regulation price is formed based on the most expensive up-regulation used and it is at least the Nord Pool Spot price. Down-regulation price is formed based on the most inexpensive action used and it is at most the Nord Pool Spot price. Figure 8 presents the balancing power price in Finland bidding area in 11th week of the year 2017. (Fingrid 2012a)

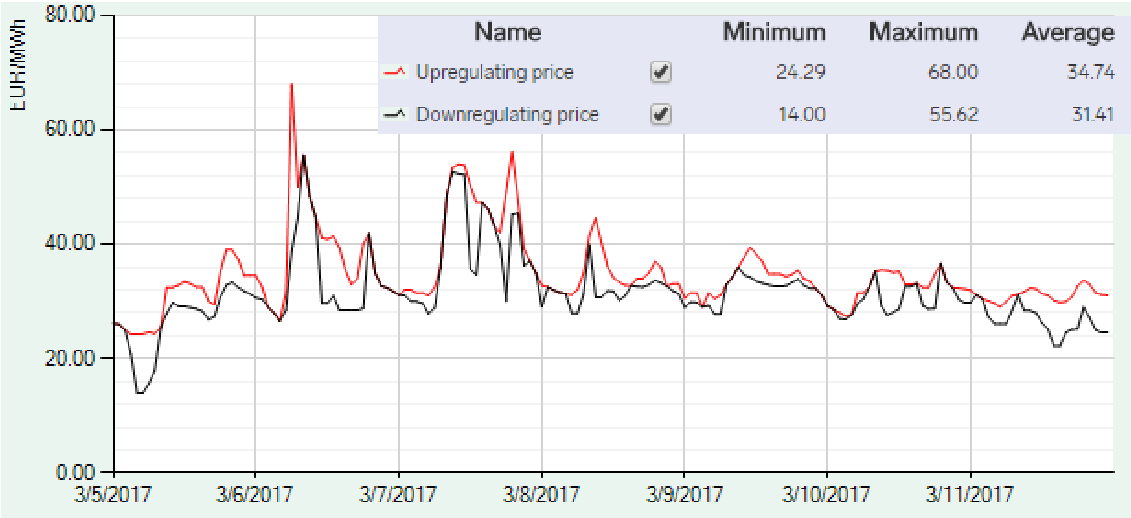

Figure 8 *Balancing power price in Finland bidding area in 5.3.2017 – 11.3.2017 (Fingrid 2017d)*

If transmission capacity between bidding areas is not at maximum, the price is uniform within Nordic region. If otherwise, balancing power market diverges. In case balancing bids cannot be used in a bidding area due to bottleneck situation, balancing power price in that area remains the same as the price of latest activated balancing action before bottleneck situation. (Fingrid 2012a)

Also, balance management error in Finland may cause the Finland bidding area to diverge from Nordic balancing power market. Then Fingrid maintains network balance with balancing procedures inside Finland. In this situation, the balancing power price is formed based on balancing actions used in Finland. Balancing power prices are published in Nord Pool Spot website not later than two hours after the hour in question. (Fingrid 2012a)

Occasionally balancing power price becomes negative giving good opportunities for market operators, especially energy consumers, to generate large profits. Figure 9, presents an example dated in 7th May 2017.

Figure 9 *Balancing power price in Finland bidding area in 6.5. – 8.5.2017*

Price of the balancing power in Finland became -500 €/MWh for two hours and -1000 €/MWh for four hours due to transmission system testing operation in Sweden causing a bottleneck situation between countries along with deviation in balance responsible parties' balance accounts. (Fingrid 2017i)

Balancing capacity market

Balancing capacity market was introduced in spring 2016 by Fingrid to secure sufficient number of balancing power bids for the following day. This is meant to be used in cases of power plant maintenance breaks and other needs for additional fast disturbance reserves. (Fingrid 2016a)

Fingrid procures fast disturbance reserves from balancing capacity market with bidding contest. Purchases are done for complete weeks. Fingrid publishes the amount of power and trading schedule for each procurement period. Accepted reserves' operators are obligated to leave a balancing power bid in the balancing power market one day prior to starting of the procurement period. (Fingrid 2016b; Fingrid 2017d)

A capacity compensation is paid to the accepted reserve's operator even if the reserve is not activated. The capacity compensation is paid to the reserve holder with "pay as bid" -principle with the correction made after the procurement period. The correction takes into account the amount of power bid to the balancing power market and to the balancing capacity market. Smaller balancing power bid compared to the balancing capacity bid means smaller multiplier for the capacity compensation. Also, activation compensation is subtracted from the capacity compensation. (Fingrid 2016b)

2.5.5 Power reserves

Obligations for maintaining frequency containment reserves have been agreed by Nordic TSOs. Procurement of the frequency containment reserves is meant to ensure sufficiency of power reserves all times and enable efficient competition within procurement conditions. To achieve this, transactions between countries may take place. Reserves, that reserve holders have sold to Fingrid, can be sold further to other TSOs. (Fingrid 2017a) Figure 10 shows the control processes used in Finland.

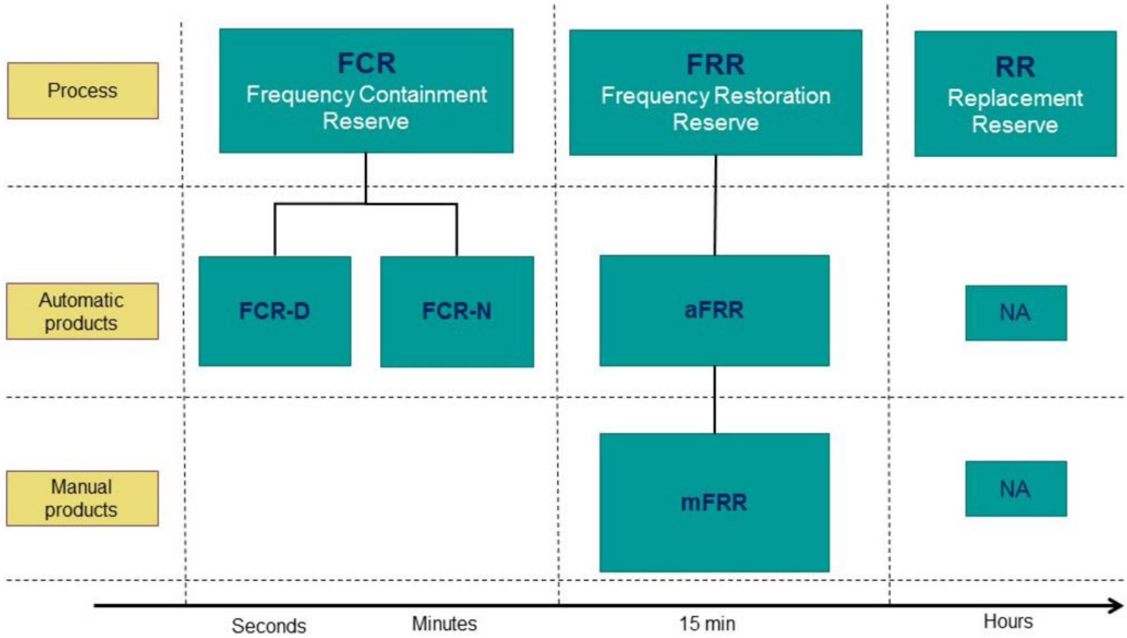

Figure 10 *Frequency control processes (Fingrid 2017d)*

Control processes are divided into following three categories. Frequency Containment Reserves (FCR) are constantly used to control frequency. Frequency Restoration Reserves (FRR) are meant to return frequency to normal range and release FCR back to use. On the other hand, Replacement Reserves (RR) are used to release FRR to ready state in case of new disturbances. (Fingrid 2017d)

There are two types of frequency containment reserves: Frequency Containment Reserve for normal operation (FCR-N) and Frequency Containment Reserve for disturbances (FCR-D). Also, Frequency Restoration Reserves are divided into two categories: automatic Frequency Restoration Reserve (aFRR or FRR-A) and manual Frequency Restoration Reserve (mFRR or FRR-M). The latter is the same as balancing power market (chapter 2.5.4).

Technical requirements of the frequency containment reserves are being renewed and the new mandatory requirements are expected in a year or two (Fingrid 2017h). Delivering a fully functioning reserve product to the market takes time and it is assumed that new requirements are relevant at the time of product release. The requirements in this chapter are presented based on the new requirements (Fingrid 2017h) with few exceptions described accordingly.

Frequency Containment Reserve for normal operation (FCR-N)

Under normal operation 600 MW of frequency containment reserve is maintained for frequency regulation. Joint reserve is divided between countries based on the total annual consumptions in each country. The obligation for Finland is roughly 140 MW (Fingrid 2017d; Fingrid 2017a).

FCR-N technical requirements are divided into 3 categories: stationary performance, dynamic performance and stability requirements. Present requirements include only stationary performance. Step response tests are performed to obtain the capacity and stationary performance of the reserve. Sine tests determine performance and stability of the reserve. Tests, and their conditions are defined by Fingrid. The requirements presented below may involve changes in near future.

Stationary performance requirement states that the frequency containment normal operation reserve (FCR-N) with relay control shall regulate within limits at the range of 49.90 – 50.10 Hz. Production units must increase power production and loads must decrease power consumption at frequencies below 50 Hz. Similarly, with frequencies above 50 Hz production units must decrease power production and loads must increase power consumption. Figure 11 presents the required regulating operation of FCR-N relay controlled resources in terms of frequency deviation. A linear response is required for reserves capable of continuous control.

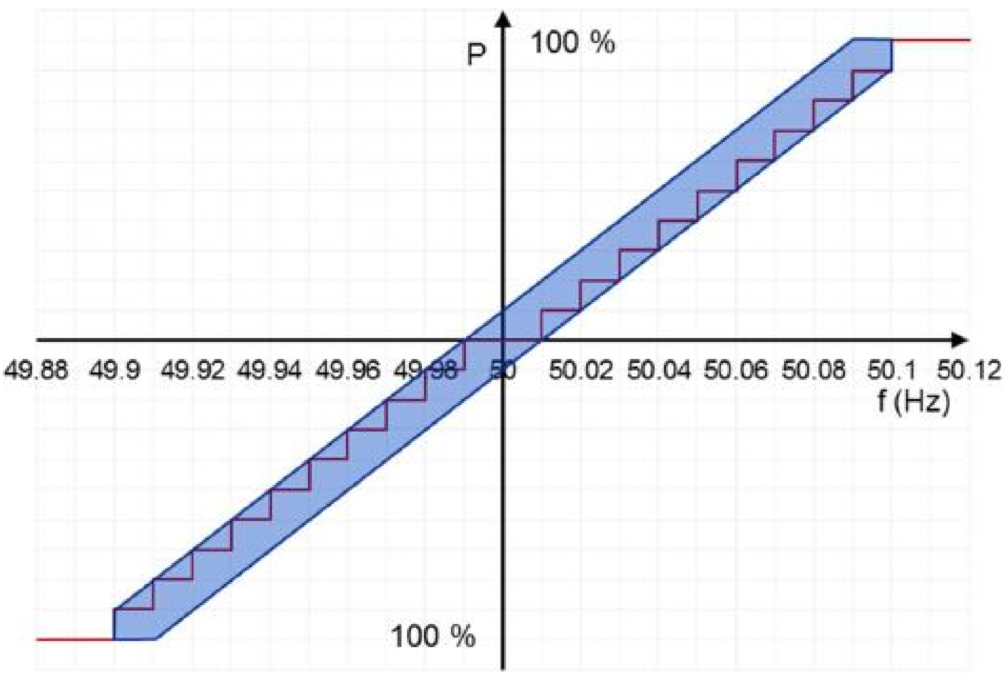

Figure 11 *Activation of frequency containment reserve in normal operation for relay controlled resources (Fingrid 2017h)*

According to the present requirements (Fingrid 2017a), dead band shall be at the most 50 ±0.05 Hz. If the frequency drops below 0.10 Hz, the reserve must be activated fully in 3 minutes. Y-axis presents the power of the reserve and x-axis presents the network frequency. Blue area is the area in which the reserve must respond and red line depicts one possible regulating solution.

Dynamic performance requirements are defined by FCR-vectors. These vectors are derived from a set of transfer function values obtained from sine and step response prequalification test data. Sine test is performed by applying sinusoidal test signal with amplitude of 100 mHz at the nominal frequency of 50 Hz. A set of responses are registered for different time periods ranging from 10 s to 300 s. Transfer function values are calculated for each period of the sine tests. Transfer function values are plotted as FCR-vectors in a complex plane. Vectors are formed for each period and these vectors are used to create the dynamic stability curve presented in figure 12 with blue color. Performance curve (blue) is below the requirement (black) in this example presenting capable reserve.

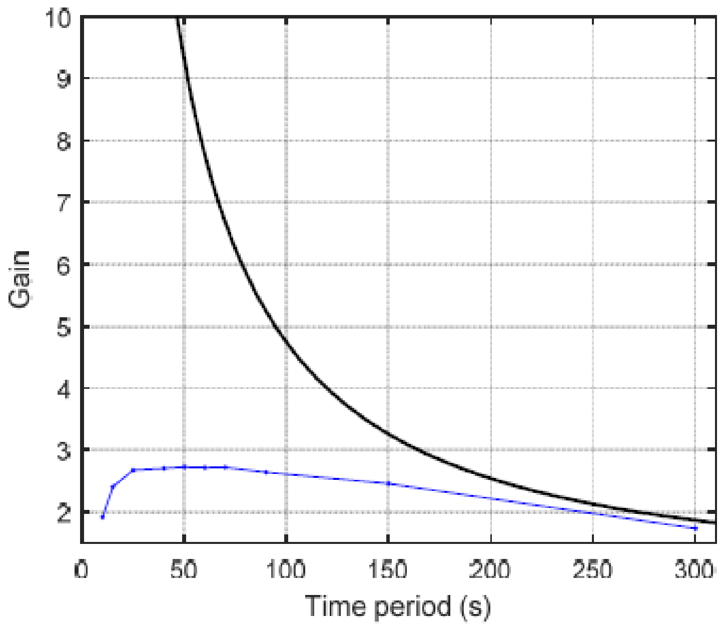

Figure 12 *Dynamic performance requirement for FCR-N, blue curve is the actual performance of a reserve and black curve is the requirement (Fingrid 2017h)*

Stability requirement states that FCR is required to have sufficient stability to maintain stable power system operation. It is presented with the same FCR-vectors as in the case of dynamic performance. Figure 13 presents the stability requirement.

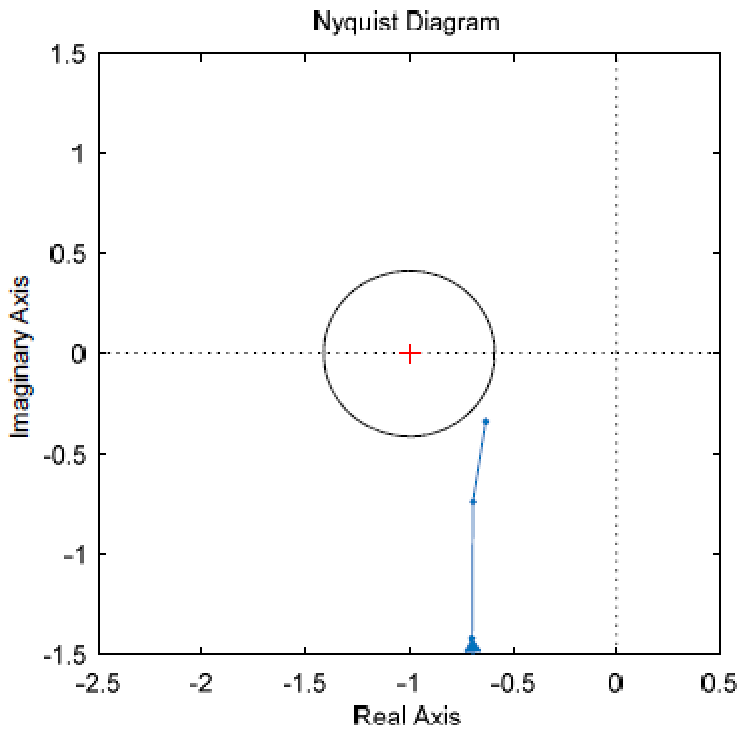

Figure 13 *Stability requirement (black circle) with an example response (blue curve) (Fingrid 2017h)*

Stability requirement is realized with Nyquist-curve presented with system stability circle. Response curve (blue) is not allowed to enter the requirement circle (black).

Frequency Containment Reserve for disturbances (FCR-D)

Frequency containment reserve for disturbances is maintained enough to keep the frequency deviation under 0.5 Hz in case of large deviation, for example in case of disconnection of a large production unit. Required reserve is evaluated and set weekly corresponding to the greatest single fault in the Nordic power system. A total of 1200 MW of FCR-D is maintained normal situation which includes the reduction of self-regulating loads in the system (around 200 MW). (Fingrid 2017d). Self-regulating loads refer to loads that naturally reduce their power consumption when frequency decreases, for example AC-motors directly connected to network. The obligation for Finland is around 260 MW (Fingrid 2017a). After new technical requirements for frequency containment reserves become mandatory, a market for FCR-D downwards regulation is available for the situations with system frequency above 50.1 Hz (Fingrid 2017h).

The FCR-D requirements are, like in the case of FCR-N, divided into stationary performance, dynamic performance and stability requirements. As in case of the FCR-N, the step response tests are performed to acquire the capacity and stationary performance and the sine tests verify the dynamic performance and the stability of the FCR-D.

Stationary performance requirement states that relay controlled FCR-D unit shall be activated within limits presented in the figure 14 similarly to the FCR-N. Up-regulation capacity activation occurs when frequency drops to 49.9 Hz or below and full capacity must be activated at frequencies equal or below 49.5 Hz. Similarly, down-regulation capacity must be activated when frequency rises to 50.1 Hz or above and full reserve must be activated at frequencies equal or above 50.5 Hz. With present requirements (Fingrid 2017a), if frequency drops step-wisely at least 0.50 Hz, activation times are 5 and 30 seconds for half of the capacity and full capacity, respectively. Blue area depicts the area in which the regulation operation must occur and red line is one possible control solution. For reserves with continuous control, a linear response is required. (Fingrid 2017h)

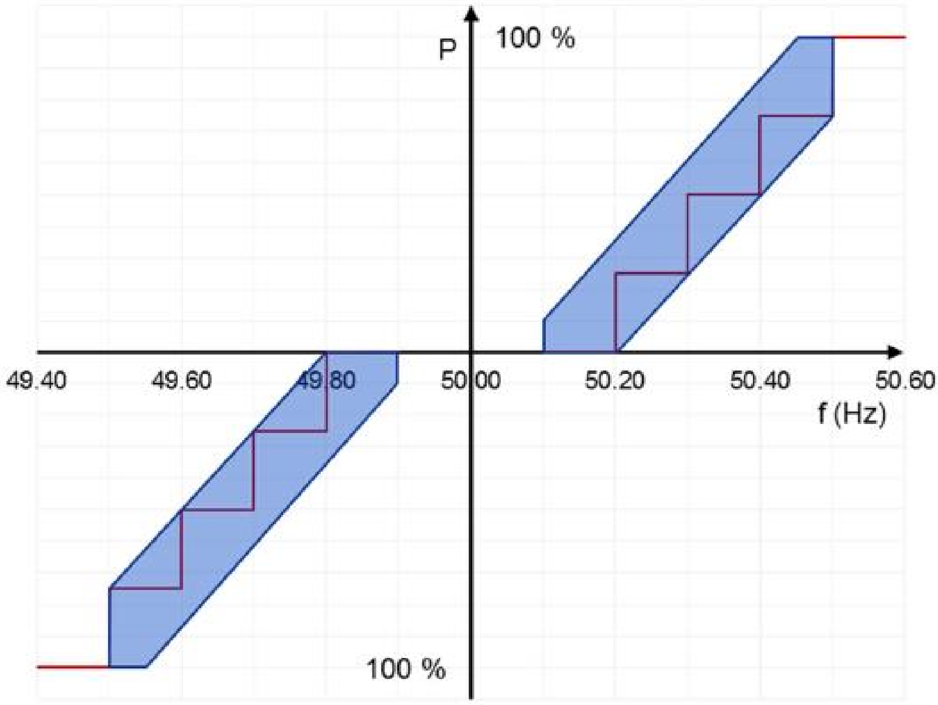

Figure 14 *Activation of frequency containment disturbance reserve (Fingrid 2017h)*

According to present requirements, relay-connected reserves may alternatively be completely disconnected at the same time based on the network frequency drop magnitude. If frequency drops below 49.70 Hz, the load (reserve) shall disconnect in less than five seconds. Similarly, when frequency drops below 49.60 or 49.50 Hz the disconnections times shall be at most three and one seconds, respectively. Connection back to the network may be performed after the frequency has been at least 49.90 Hz for three minutes. (Fingrid 2017a; Fingrid 2017d) This type of reserve utilizing five, three, and one second reaction times may be removed from the market when the new technical requirements are introduced (Fingrid 2017h).

Dynamic requirement of a FCR-D entity is described with its FCR-D capacity. Capacity is calculated using information of ramp and step tests. Stability requirement is the same as in the case of FCR-N (Nyquist curve).

Fingrid compensates the imbalance error caused by FCR activation. This error is referred to as reserve electricity. Reserve electricity is calculated as follows:

$$E_r = \frac{\sum R \cdot \Delta t \cdot 50\ Hz}{3600\ s} \cdot k \tag{1}$$

where, ΣR is the actual total volume of the frequency containment normal operation reserves in balance provider's balance multiplied by 10, Δt is the time deviation change during the hour in question and correlation coefficient *k (=0.7)* takes into account the effect of dead band on the activated energy.

The imbalance error is removed with transaction from the balance of the balance responsible party in conjunction with the balance settlement. Balance error caused by production unit and load are taken into account in the production and consumption balances, respectively. In a situation with a frequency below the normal range, reserve electricity is compensated with up-regulation price and in a situation with the frequency above normal range, reserve electricity is compensated with down-regulation price. (Fingrid 2017a)

Automatic Frequency Restoration Reserve (aFRR)

In 2015, automatic frequency restoration reserve was agreed to be maintained and it contains 300 MW of power reserve for predefined morning and evening peak loads (Fingrid 2017d). aFRR is a centralized frequency containment reserve activated by frequency deviation in Nordic power system. The amount of power needed for restoration of frequency and relieving of activated frequency containment reserves is calculated with the frequency deviation. The calculation is done by Statnett (Norwegian TSO) and activation request is sent to TSOs. The request is then forwarded by TSOs to reserve holders. Activation signal is sent in 10 second intervals to reserve holders by Fingrid. Information exchange is realized using ELCOM connection and signal's sign (plus or minus) tells whether up- or down-regulation is needed. Signals are distributed to the holders based on hourly market trading and the holder forwards the signal to reserve maintaining unit. Unit may be aggregated from several production units. (Fingrid 2017b)

Fingrid sends two types of activation signals to the reserve holders based on the reserve unit's speed of control. For the units with fast control, the signal is typically filtered to avoid overlapping of aFRR units in regulation situation. Slow control units are less filtered. The activation of the reserve must fulfill the requirements determined by the controllability of the unit. (Fingrid 2017b)

For the unit receiving filtered signal, the maximum activation time is 120 seconds and activation must start within 30 seconds of the receiving of the signal as depicted in the figure 15.

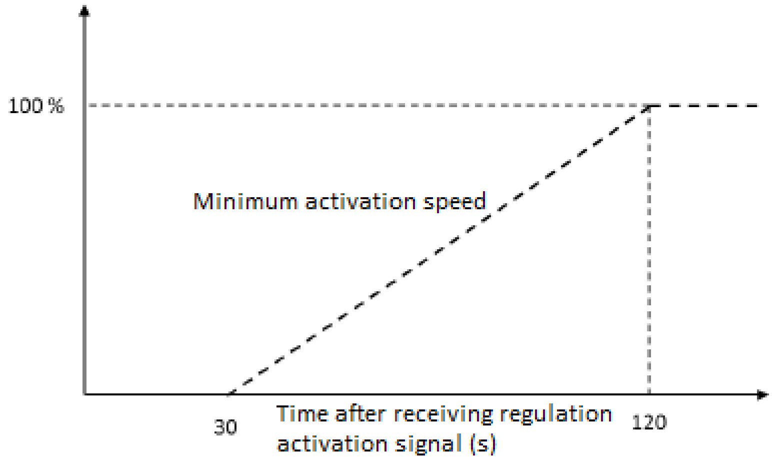

Figure 15 *Maximum activation time for the reserve unit receiving filtered activation signal (Fingrid 2017b)*

For the unit receiving unfiltered signal applicable for heat power production, the reserve must be activated step-wisely as depicted in the figure 16 with grey color. Activation process must start within 60 seconds of the receiving of the signal and minimum activation time is defined by the following formula:

$$\frac{1}{(1+sT)^4} \tag{2}$$

where, T is 35 seconds. (Fingrid 2017b)

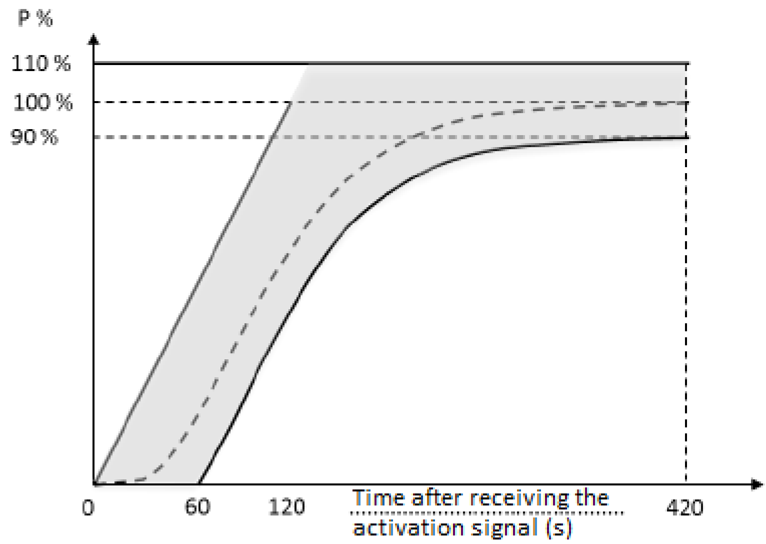

Figure 16 *Activation time when reserve unit receives unfiltered activation signal (Fingrid 2017b)*

Reserve holder is obligated to fulfill the technical requirements for the control of the automatic frequency restoration reserve. Requirements are realized with control tests before inception of the contract. These tests are also conducted if some changes are made to the reserve affecting its control ability. Reserve holder is responsible for the execution and reporting of the tests and Fingrid is entitled to send a representative to observe the tests. (Fingrid 2017b)

Testing sequence for the unit receiving filtered activation signal is as follows. Minimum and maximum power output are tested in the sequence and if the unit is less than 10 MW, only the first 25 minutes must be run. (Fingrid 2017b)

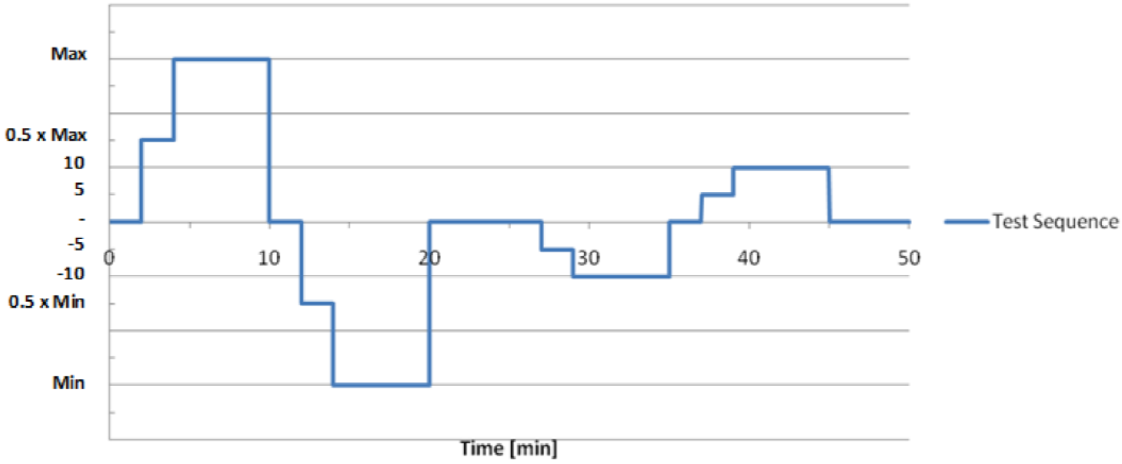

Figure 17 *Testing sequence for aFRR receiving filtered activation signal (Fingrid 2017b)*

Testing for the aFRR unit receiving unfiltered signal is as follows. (Fingrid 2017b)

1. Power production unit must have constant power output for 15 minutes.
2. Output is turned up in the following way: the speed of power change (MW/s) multiplied by 100 s which must be at least 1 % of the rated power.
3. Unit power output is turned down for at least 20 minutes.
4. Set value changes are done at least twice.

Information exchange between Fingrid and reserve unit holder is performed in real time and the following information is required by the holder: aFRR up-regulation capacity if maximum output does not restrict the capacity, aFRR down-regulation capacity if minimum output does not restrict the capacity, real time power metering if activation occurs and returning of the activation signal received from the Fingrid. Information exchange occurs in every 10 seconds and TSO uses the information to monitor reserve activation and maintenance. (Fingrid 2017b)

Billing information is monthly delivered to Fingrid by the reserve holder containing hourly information of the reserves used in the previous month for frequency restoration. Information contains the amount of aFRR and it is delivered as electrical EDI messages using MSCONS report message. TSO delivers daily the information about the realized trades of the reserve in question for the next day with average prices for both up- and down-regulation. Also, the information about the amount of reserve energy and the price of the previous day is delivered once a day. (Fingrid 2017b)

Energy caused by changes in the power are calculated hourly for both up- and down-regulation. Energy is calculated by multiplying the power with time of use and the power is the power in the activation signal sent by Fingrid. Power balance management is agreed with reserve's balance responsible party. Energies are removed from the imbalance settlement of the reserve producer's balance responsible party with a trade. (Fingrid 2017b)

Operation of the reserves with respect to each other

Figure 18 presents the operation areas of frequency containment and frequency restoration reserves. As shown in the figure, FCR-N is used constantly to control network frequency and FCR-D is used in case of high frequency deviation and when FCR-N capacity is already fully activated. The reserve power is activated proportionally to the frequency deviation. FRR reserves are used to restore the frequency to nominal level after frequency containment reserves are fully activated. It should be noted that currently FCR-D is only used in up-regulation whereas in future it may be also used in down-regulation (Fingrid 2017h). Frequency restoration reserves are used after full activation of frequency containment reserves to restore system frequency to the nominal 50 Hz level.

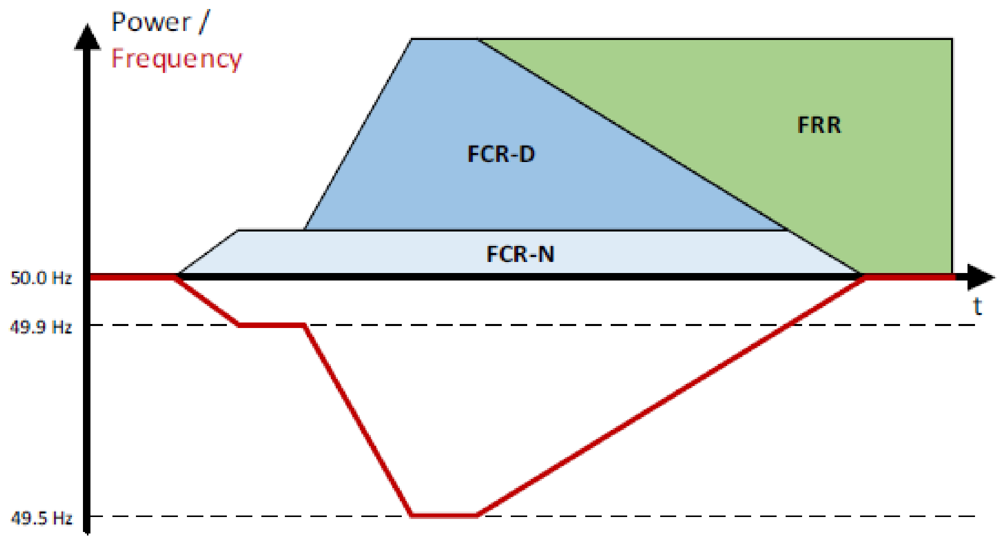

Figure 18 *Activation areas of FCR-N and FCR-D (Fingrid 2017h)*

Fingrid procures some of the reserves from the yearly market from power plants and loads in Finland. This market operates based on competitive bidding. A separate market exists for both frequency containment normal operation and disturbance reserves. Participation to yearly market is possible only in September-October for next year's reserves. However, hourly market is open for trading throughout the whole year. Reserve holder does not have to be the owner of the reserve but must have a consent of the owner for the reserve. Bid reserve may also be aggregated from several different balance accounts. In addition, Fingrid procures reserves from direct current transmission links connected to Russia and Baltic through Estonia. (Fingrid 2017a)

Other reserves

Fast disturbance reserves are also a way of maintaining grid balance. These are only used in serious power shortage situations. Fingrid has its own fast disturbance reserve, but it may also buy this capacity from other operators with long term contracts. Reserve power plants dedicated to this operation have strict technical and operational requirements. For example, plant must have at least 10 MW of power capacity with activation time of 15 minutes and it must not be in normal electricity trading or balance management. Fingrid pays the capacity seller a right to use fee (€/MW, month), plausible starting fee (€/start/unit) and energy fee (€/h or €/MWh). (Fingrid 2012b)

Energy Authority in Finland has a power reserve system which is separated from Fingrid's reserves. Energy Authority is also the supervisor of the power system operation and legal compliance. The amount of reserve capacity needed is defined and the authority publicly asks for bids. Reserves are confirmed to fulfill the terms defined for the reserve and bids are accepted by the best purchase price. (Energy Authority 2017b) For the time span of 1.7.2017 – 30.6.2020, Energy Authority has accepted 4 power plants and two demand response capable facilities for power reserves. Total reserve power is 707 MW and the plant with highest power rating is Meri-Pori with 308 MW. These power plants are run by coal, gas and oil and are only activated when demand and production do not meet in the electricity market. This happens rarely and most likely during winters' peak loads. (Energy Authority 2017a)

3. DEMAND RESPONSE

Demand response, sometimes referred to as demand side management, is a multidimensional entity which includes DR markets, controllable loads, technical solutions and questions related to information exchange and legislation (Järventausta et al. 2015, p.18). The basic idea of demand response is simple. As explained in the previous chapter, power system production and consumption must be equal, i.e. in balance. This balance is occasionally jeopardized for example in the case of disturbance or demand growing higher than production. DR means basically controlling loads to help network during congestion. DR has been used for years, but recent development of technology has enabled the use of DR more widely and it is under further examination. Demand response should be dissociated from energy efficiency, it does not mean necessarily energy savings, although that usually occurs. DR should be considered more as a support to power system efficiency and security by electricity market mechanisms. To benefit from DR in paper mill, aggregation of loads is needed.

This chapter explains the importance of demand response and its benefits. Financial potential of DR in different electricity markets is briefly evaluated. Also, load aggregation for the demand response purpose in general is clarified.

3.1 Need for demand response

Conventionally production in power system has followed consumption. Electricity production has been controlled based on consumption using e.g. hydro power and heat power plants. In near future, weather dependable renewable power resources will become more common resulting in the need of more controllable i.e. balancing power capacity in the power system. The increase of production that is not controllable or economical to control for balancing purposes introduces challenges for the power system balance maintenance. Also, power system inertia decreases when renewable resources are increasing in the system introducing more challenges. For these reasons, consumption needs to follow more production and therefore demand response and energy storages are potential balancing measures from power system point of view. Consequently, demand response is contributing to the power system security and introduction of emission free renewable electrical energy resources. (Järventausta et al. 2015, p.16)

Recent development has brought out interest to reduce energy consumption in manufacturing. This has been mainly driven by governments by setting new regulations to reduce the impact of manufacturing to the environment. (Frigerio 2014)

During the last decade, Finland has been net importer of electricity. Electricity has been mainly imported from Sweden, but before, power import and export used to be in balance between Finland and Sweden. Changes in energy business in Europe along with delays in building of new nuclear power reactor Olkiluoto 3 caused Finland to become net importer of electricity. In addition, declining prices in the Nordic wholesale market cause heat power to become obsolete in Finland. This development leads to risk in power system security due to lack of production in peak load situations. New nuclear power reactor unit and increasing amount of uncontrollable renewable resources with decreasing controllable heat power has increased the pressure towards flexible consumption i.e. demand response. (Fingrid 2015)

Dimensioning fault in the power system means the highest power of single production unit connected to system. After completion of Olkiluoto 3, the dimensioning fault increases from 880 MW (Olkiluoto 2, currently the most powerful unit) to 1300 MW. Reserve capacity then must be higher than before and demand response is used as part of reserves thus increasing the need for demand response. (Fingrid 2009)

Power wholesale market defines electricity price in system and it is based on demand and supply bids. The electricity price in each hour is defined by the most expensive production method needed to cover all the consumption. During national peak load hours, the price is significantly higher and usually means the use of high emission production methods. Demand response in large scale lowers the consumption enough to cut the peak load demand resulting in lower electricity price and inoperative expensive and high emission production during peak load hours. All electricity users benefit of demand response in this situation. (Järventausta et al. 2015, p.16)

Flexible and controllable consumption creates a significant potential for different power system reserves. Therefore, development of demand response is important in evolving smart power system. (Järventausta et al. 2015, p.16) Demand response enables the electricity usage to be deferred to a later time. The effect to power system is depicted in figure 19, peak load is reduced (peak clipping) and energy usage deferred to time of lower consumption (valley filling) (NW Council 2017). Similarly, during low priced electrical energy and low demand, other energy consumption may be substituted with electrical energy, e.g. plug-in electric vehicles. However, DR may cause peak loads to parts of distribution network that are already experiencing high loads during inexpensive electricity hours. (Järventausta et al. 2015, p.17)

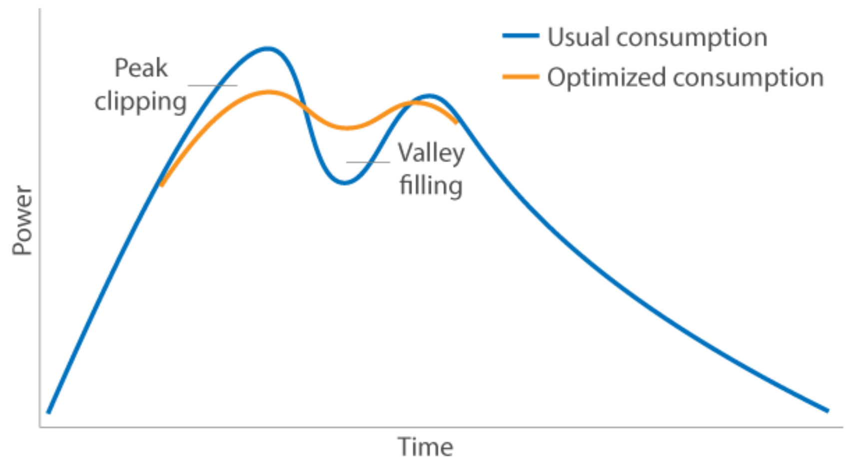

Figure 19 *Effect of load shifting for power system during peak consumption (NW Council 2017)*

Demand response may help controlling global warming through energy efficiency. Nowadays, renewable energy resources and energy efficient construction are trending, but different solutions for power system peak loads have not been researched due to energy consumption calculations conducted annually. When researching energy efficiency, peak loads and load profiles need focus. (Järventausta et al. 2015, p.18) In addition, it may be an important aspect of the Nearly Zero-Energy Building concept aiming to minimal energy consumption buildings (Järventausta et al. 2015, p.16).

Demand response also reduces the need of high price production by keeping the electricity price lower during peak loads. This high price production usually means power plants using highly polluting fuels such as coal. Therefore, DR contributes to controlling global warming by reducing carbon dioxide emissions.

Residential demand response capability in Finland was examined in (Järventausta et al. 2015). Finland is a pioneer in residential power metering due to installed AMR-meters (Automated Meter Reading). These enable hourly metering information, and therefore participation to power market. It is estimated that over 1000 MW of heating and boiler loads can be controlled in DR purposes through AMRs connected to control relay. The lack of data transfer systems integration and advanced controllability in more demanding electricity markets is a problem faced with wide spreading of DR. Incentives and large buildings' automation solutions were among others considered as key parts in development of demand response.

3.2 Industrial demand response

Industrial sector consumes more than 50 % of the world's energy consumption (Frigerio 2014). For demand response purposes, industrial loads have several advantages. Power magnitudes are usually very high, especially in paper industry, and therefore the power change they can provide is very high. In addition, industrial loads have usually already built infrastructure for the control, communication and market participation offering fast and accurate load control. Due to high power capacity, industrial loads have also high potential in power markets for gaining profit. This might be important in the paper manufacturing industry in developed countries such as Finland because global demand for paper has been going down recently. Hence, industry can use their assets more effectively by utilizing their production flexibility. (Zhang et al. 2015)

VTT, technical research center of Finland, researched DR potential of industries in Finland with questionnaires (Pihala et al. 2005). Research included all industrial electrical loads with short time DR potential, i.e. 1 to 24 hours, taking technical constraints into account. In forest industry, specifically pulp and paper manufacturing, total electrical power peak consumption was 3180 MW in 2004 of which 790 MW was flexible and capable for DR. When disturbance reserve power reserved for Fingrid was considered, maximum power of 464 MW was capable for electrical energy market. Metal industries offered 258 MW and chemical manufacturing industry offered 161 MW of power for electrical energy market. Total DR power potential was approximately 880 MW with the rest of the country's industries considered.

Demand response optimization in industrial manufacturing has been researched widely. In (Park et al. 2016), optimization model using integer programming was introduced. Production consists of several workstations with buffers between them and, as typical in most factories, one stage of production is considered as a bottleneck. This bottleneck is not schedulable like other stages as it is decisive in production throughput. The presented model schedules production stages thus minimizing electricity cost while guaranteeing throughput of production. Another production scheduling model for DR is presented in (Mohagheghi 2015). Presented model determines the status of each workstation using fuzzy terms to depict workstations' criticality and crew skills for multiple workstations.

Paper production also consists of different stages of production. Bottleneck of paper production is the paper machine. Considering the power consumption of each stage of production and the fact that large refiners in Thermomechanical Pulping (TMP) being the most energy intense is already optimized, production stage optimization may not be efficient. The scheduling optimization can be further evaluated in paper mill, but thesis' focus remains on aggregating small loads for demand response. Refining of woodchips and grinding of logs, which utilize production phase optimization, are explained further in 3.4.1 Load aggregation in paper mill.

Backup generators usually found in industrial plants are not directly part of demand response but may be used for the same purpose. Enegia Consulting Oy, a company focusing on energy management consulting, conducted a research (Hietaoja 2015) with Fingrid and two customers regarding the customers' backup generators in reserve power markets. One customer participated in FCR-D market and the other customer participated in mFRR market. In the first case, the control was realized with SCADA (Supervisory Control And

Data Acquisition) and centralized frequency monitoring. Power metering was local and Enegia was responsible for market participation and information exchange between reserve units and Fingrid. In the second case, the Enegia had similar objective, but this time control was realized with remote access to customer's controls. Separate power metering was installed to the reserve unit.

Both reserves were activated in trial period and both were successful in that period. Customers were satisfied and Fingrid was positive about third party involvement in power markets. However, challenges were encountered as well. These included the lack of information on behalf of customers and cautiousness towards the use of backup power in reserve power markets. Also, technical solutions were not sufficient and improvements were required. In addition, the question whether DSOs allow power feeding to their networks was unclear. Following topics were encountered as well: the need for real time power information to Fingrid in FRR causes additional investments, rapidly changing rules in the FCR-D market drives customers away and information exchange to DSOs need improving in start situations.

3.3 Demand response in power markets

Present electrical energy market's structure supports demand response. To activate large scale high energy consumers' demand response, it is essential to endorse consciousness over DR. Market participation is possible directly or via DR aggregator. During peak power consumption in Jan 2006, high price electricity led to industrial consumption reduction of 300 - 400 MW. (Segerstam et al. 2007, s.4,8)

In (Graßl 2014), demand response is categorized in 2 groups: price-based DR and incentive-based DR programs. These are shown in the figure 20. Price based program offers customers rates for electricity price in different time periods. Real-Time Pricing (RTP), for example, offers prices varying every hour reflecting the electricity power price. Time of Use (TOU) and Critical Peak Pricing (CPP) tariffs use more fixed prices for longer time blocks. Incentive-based program offers customers payments for participating in load curtailment requested by the service provider. This may be triggered by high electricity prices or grid stability problem.

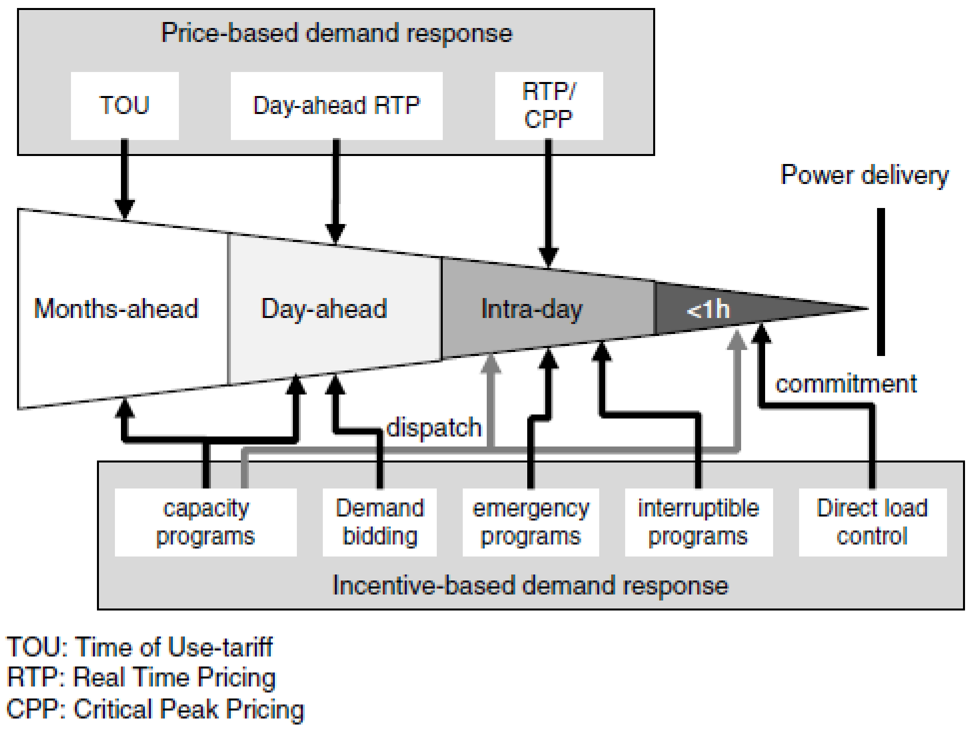

Figure 20 *Demand response programs in relation to time of trading (Graßl 2014)*

These programs offer production systems energy cost savings by utilizing energy usage at low priced energy and enhancing the energy use at high price time. To enable this, production systems' energy demand and possibilities to adapt production to energy price knowledge is essential. Thesis focuses on the incentive based power markets, i.e. power reserves markets.

Different power markets have different profit expectations, risks and obligations for load controlling and metering. DR electricity market potential can be associated to day-ahead and intraday markets, balancing power market as well as disturbance or normal operation power reserves and DSOs' power based tariffs (Järventausta et al. 2015, p.18)

DR profitability is usually better in the markets occurring closer to actual electricity delivery hour. DR financial potential was examined in a report investigating DR potential in Finland (Järventausta et al. 2015 p.33). Examination was done using direct electrical heating loads. Potential was analyzed in day-ahead, balancing power and reserve markets and using DR in power vendor's power balance management. Simulation results indicated that financial potential in day-ahead market was quite modest. When DR was used in balance management, profits were calculated to be over 3-times as high as day-ahead market potential. Balancing power introduced almost 7-times the day-ahead market profit and the best profit was calculated with frequency containment reserve for disturbances being roughly 17-times the day-ahead market profit.

When examining profitability of demand response, it is noted that possible power consumption peak of devices after the demand response event might cancel out the acquired profits. This high consumption after DR event phenomena is known as cold load pickup. For example, if heating is cut off for the demand response event, it is crucial to make sure the heating does not take large amount of power after being turned back on. This may lead to reduced profitability of demand response if high price electricity is used to cover the electricity consumption right after DR event.

DR in Finland may be traded in wholesale markets maintained by Nord Pool or in reserve power markets maintained by Finnish TSO - Fingrid. The markets for DR are presented in table 3. The table shows the type of contract made and technical requirements related to the power product in question.

Table 3 *Demand response markets (Fingrid 2017d)*

Market place	Type of contract	Minimum size	Activation time	Activating frequency	Price level in 2014	Market operator
Frequency Containment Reserve Normal operation (FCR-N)	Yearly and hourly market	0.1 MW	3 Minutes	Constantly	15.8 €/MW,h (yearly market) + price of electricity	Fingrid
Frequency Containment Disturbance Reserve (FCR-D)	Yearly and hourly market	1 MW	5 s / 50% 30 s / 100%, when f under 49.9 Hz OR 30 s, when f under 49.7 Hz and 5 s, when f under 49.5 Hz OR linear activation	Several times a day depending on frequency threshold and whether the control is linear	4.03 €/MW,h (yearly market)	Fingrid
Frequency Controlled Disturbance Reserve (on-off-model)	Long-term contract	10 MW	Instantly, when f under 49,5 Hz	About once a year	~0.5 €/MW,h + 580 €/MWh + activation fee 580 €/MW	Fingrid
Automatic Frequency Restoration Reserve (aFRR)	Hourly Market	5 MW	Must begin within 30s of the signal's reception, must be fully activated in 2 minutes	Several times a day	Hourly market + energy price	Fingrid
Balancing Power Market	Hourly Market	10 MW or 5 MW	15 minutes	According to the bids, several times per day	Market price	Fingrid
Fast Disturbance Reserve	Long-term contract	10 MW	15 minutes	About once a year	~0.5 €/MW,h + 580 €/MWh	Fingrid
Day-ahead	Hourly Market	0.1 MW	12 h	-	Market price	Nord Pool
Intraday	Hourly Market	0.1 MW	1 h	-	Market price	Nord Pool
Strategic reserves	Long-term contract	10 MW	15 minutes	Rarely	-	The Energy Authority

Day-ahead and intraday markets are hourly markets with minimum bidding size of 0.1 MW and physical energy delivery takes place every time trading takes place. Day-ahead market is the easiest way to calculate profit with DR since the delivery day's market prices are published in the previous day by 14:00 CET. Therefore, day-ahead market trading risks along with profits are quite low. Power wholesale market has the lowest technical requirements for the power product. Real time power metering is not needed and the product is activated for full hour regardless of the power system balance.

Due to higher price deviations, balancing power market (mFRR) has higher profit margins meaning the profits may grow high compared to the power wholesale market. In balancing power market, losing money is only possible if the power is reserved for balancing power market and therefore purposely left untraded in other power markets and then was not accepted in balancing power market. Technical requirements are more demanding than in the case of day-ahead or intraday markets. The reserve must be able to be activated to full power within 15 minutes of receiving the request from the TSO and real time power metering is needed unless reserve activation is verified in real time otherwise. Minimum size of a bid is 5 MW and pricing is based on balancing power market price and usually balancing power operations are activated several times in a day.

Power reserves also have high margins in terms of lucrativeness as mentioned before. DR implementation in reserve markets can be done with smaller amounts of capacity compared to the balancing power market. aFRR requires at least 5 MW of power for single product and FCR-N and FCR-D require only 0.1 MW and 1 MW of power, respectively. If product is sold as reserve, it should be noted that the capacity must be available all times, any unavailable capacity may be fined by counterparty (Fingrid). Yearly FCR market obligates the reserve provider to announce the available capacity for the next day's hours (01-01 in Finland, CET +1) by 18:00. Similarly, in the hourly FCR market, the next day reserve bids are provided to the market by 18:30. Therefore, the reserve capacity must be predicted day ahead and therefore may complicate the effective use of DR capacity (Järventausta et al. 2015, p.50). FCR involves the most demanding technical requirements of all present reserve markets.

Time frame of trading electricity in Finnish power markets is presented in figure 21. As shown in the figure frequency containment reserves are traded in yearly or hourly contracts and closer to the power delivery hour trading reserve power may be done in balancing power market. DR capacity may be bid to day-ahead and intraday markets also, but day-ahead trading usually means lower profit expectations as suggested in the research (Järventausta et al. 2015, p.33) even though it has lower technical requirements.

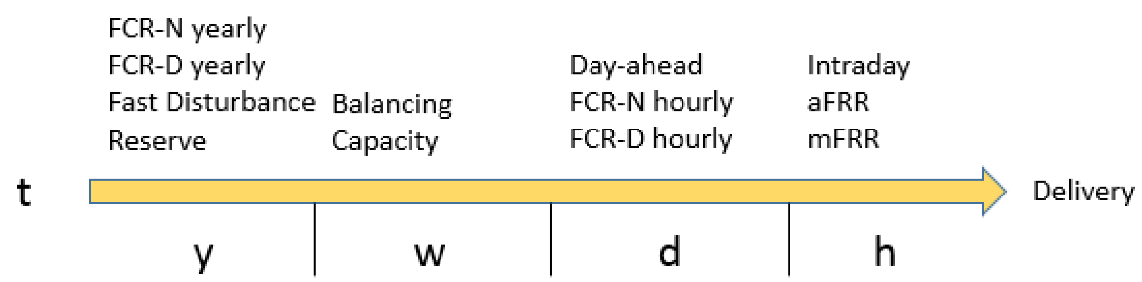

Figure 21 *Time frame of trading reserves in Finland*

As mentioned before, frequency containment reserves present the best profit expectations in relation to power capacity. Time frame of power trading encourages to bid hourly FCR the day before delivery, and if the reserve operator has available reserve power during the day of delivery, it may be bid in the balancing power market.

3.4 Aggregated demand response

Electricity markets have minimum power curtailing requirements. In residential demand response, most of the customers do not meet the minimum load requirements. Therefore, load aggregation is needed. Similarly, small loads in the industrial environment need to be aggregated to fill out the minimum requirements set by different power markets.

Accurate and reliable load aggregation is one of the key requirements for implementing demand response on smart grid functions. Initially, demand response was developed as a set of control actions applicable to large industrial loads to enhance the power system operation. Deterministic behavior of power demand of industrial loads has been the main reason for successful DR applications. This kind of load behavior has simplified the aggregation of loads in industrial environment achieving accurate DR. (Saleh et al. 2016)

Load aggregation can be compared to a stock portfolio, the more diversified the portfolio is, the less risk is involved. A load that does not participate in a DR event can be compensated with another one in some other facility. Load owner is not penalized as long as the entire portfolio meets the obligations. (Siemens 2011)

The literature reports several methods for load aggregation, but these mainly focus on aggregating loads from the transmission or distribution network point of view. The literature suggests load aggregation methods, for example through load models and profiles (Saleh et al. 2016), but practicality of such were considered too complex for the thesis' purposes.

3.4.1 Load aggregation in paper mill

Load aggregation for demand response may have different meanings depending on the context. It may be understood as combining geographically scattered load as one market ready product. On the other hand, as in this thesis, load aggregation relates to recognizing small controllable loads within plant and combining them locally. Also, aggregation may be considered as part of the control depending on the control strategy. There is large number of motors in the Jämsänkoski paper mill and therefore a mechanism for the aggregation of the loads was needed. However, no direct aggregation method is used in the research, but the whole process of load identification is considered as load aggregation.

Demand response potential of mechanical pulping was evaluated in a research (Björkqvist 2017). Economy of a groundwood mill is analyzed when new, more efficient, grinding surfaces are procured for the grinders. Cost savings due to lower SEC (Specific Energy Consumption), investment costs and savings obtained by scheduling pulping based on day-ahead prices are compared and concluded that the investment is more economic than investing in new regulating power production capacity. Figure 22 shows a two days' optimization result.

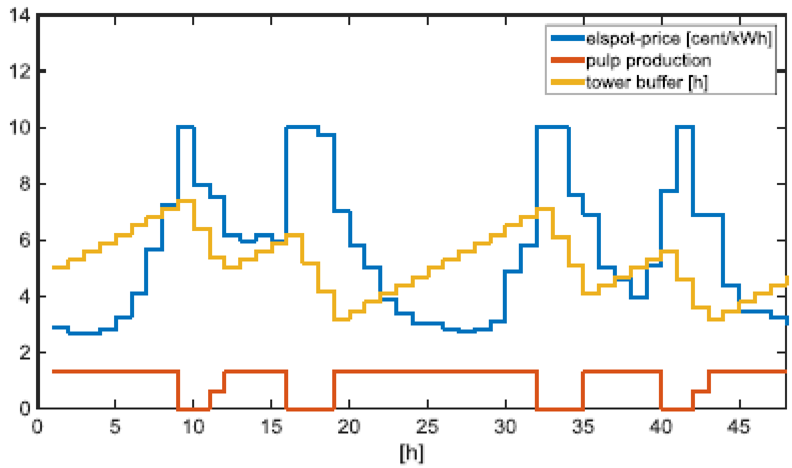

Figure 22 *Two day's optimization result for grinding of logs (Björkqvist 2017)*

As can be seen in the figure, pulp production can be halted for periods of high priced electricity taking tower buffer into account. In Jämsänkoski paper mill, high power synchronous machines for refining of woodchips in the thermomechanical pulping process are already scheduled similarly to operate according to electricity market prices. Therefore, the refiners are excluded from the research.

Literature suggests some load aggregation schemes. In (Saleh et al. 2016), the load aggregation to enable "Load-Follows-Generation" operation in system point of view was considered. However, in the paper mill, load aggregation is different due to power being traded through electrical energy market. Therefore, loads are not directly controlled by TSO or DSO and in each case the industrial plant makes the decision whether participating to the DR event (except in cases of long term reserve power products). Consequently, the aggregation is not possible through power system requirements, but the aggregation is done by considering the demand originated from power markets i.e. driven by market prices. The aggregation offers different possible power products to be sold to the market taking load availability and constraints into consideration. In other words, the key is not to follow power system demand as such but to get all the possible DR potential from the factory loads and sell them as power products in the most suitable market.

Smart grid functions related to demand response and peak-load management have motivated power systems to link loads to utility control centers with two-way communication systems (Saleh et al. 2016). The following diagram 23 presents a basic information flow in the event of DR. Electricity market initiates the DR product creation process. DR event information is sent to the operator of the DR power product, in this case the operator may be UPM Energy. Local load aggregation gathers power and availability information from each load and forwards the information to the market operator (UPM Energy). In all steps, the information exchange is bidirectional. This diagram applies when outsourced aggregation service is not used.

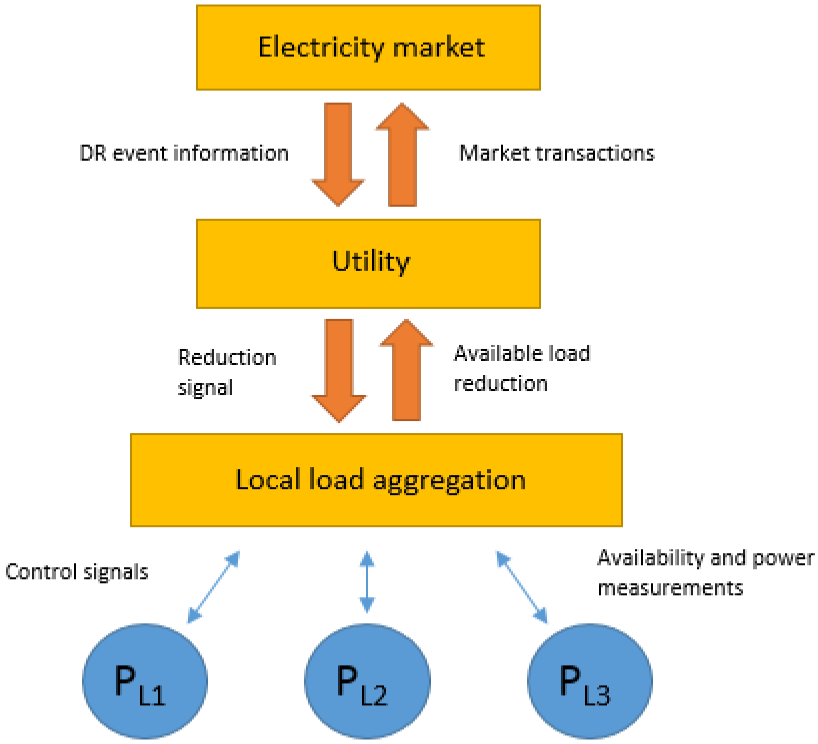

Figure 23 *Demand response information exchange and signaling diagram*

Load aggregation may be realized in various ways. It is important to figure out the best solution for the purpose. Different tools may be used for aggregation. For example, grouping of loads means aggregating loads by their features, e.g. based on loads' nominal powers or connections to other loads. To help grouping, databases offer information and may provide not only real-time metering information or static load values but also historical information for more precise load forecasting.

Aggregating loads for demand response has been researched in literature. In (Parvania et al. 2013), a price-based self-scheduling optimization model is proposed to determine optimal DR schedules executed by DR aggregator. In (Saleh et al. 2016), three aggregation methods are evaluated. These methods are not price based like in the previous case but considered more from technological aspect. Evaluated methods are *bottom-up*, *coordinated* and *bus-split* methods. Bottom-up method aggregates loads connected to low voltage feeders and uses constructed equivalent impedance matrix. Coordinated method uses ranking of loads by their characteristics such as power demand and storage capacity. Bus-split method combines 3ϕ induction and synchronous motor drives by equivalent circuits for each machine with transformer included. These methods may be directly applicable for the use in paper mill, but more simplified approach is taken in load aggregation in considered paper mill. However, the aggregation methods mentioned in the case study present a good perspective for the aggregation in paper mill. Load aggregation in the thesis is realized by categorizing the loads with their type of use and target market as explained later in 4.2.2 Identified loads.

3.4.2 Existing demand response aggregation services

Recent development has brought out third party services for aggregation of loads in the power system. These aggregators enlist the end users to participate in demand response. Aggregator then sells combined loads to utilities or TSO. Aggregator takes some of the DR profit and rest goes to the end user. (Siemens 2011) The benefit of an aggregator with many customers is the large portfolio of the reserves which allows more flexible use of the reserves. Large portfolio allows wider range of different solutions for the use of reserves. Commonly, aggregation service is responsible for the market participation, i.e. it is responsible for management of the units in reserve markets. Fundamentally UPM aims at handling DR operations inside the company.

Traditionally, participation to reserve markets has been possible to only holder, seller or owner of the reserve. In the beginning of 2017, Fingrid enabled a model for independent aggregator in frequency containment reserves for disturbances. Independent aggregator refers to an outside operator with no contract relations of the resources to the balance responsible party. Fingrid has also launched a pilot project for the participation of independent aggregator to FCR-N. By the end of 2017, Fingrid starts a pilot project for the independent aggregation model in balancing power market. The target is to enable more operators to participate in the balancing actions of the power system by combining balancing bids. (Fingrid 2017e, p.24)

Some companies offer demand response services for customers with different power consumption. For example, Helen Oy, a power company mainly located in Helsinki, offers demand response service for small, mid-sized and large companies with flexible power consumption (Helen 2017). The service takes advantage of reserves with long-term contracts which leads to activation of the reserve rarely. FinnEnergia also provides DR services utilizing the most relevant market by evaluating the potential of the subjected load and delivering the technology needed (FinnEnergia 2017). SEAM provides same kind of service by offering three different products based on type of load and target market (SEAM 2017). South-western energy company Turku Energia offers demand response services for high electricity consumption companies (Turku Energia 2017). Their concept called KOVERA, referring to comprehensive energy solutions, utilizes Fingrid’s power balancing market. The companies mentioned above all operate in Finland.

REstore is European company which provides demand response programs for commercial and industrial consumers as well as demand side management software for utilities.

REstore is the largest DR service provider in Europe and their primary products are Flex-Pond™ and FlexTreo™. FlexPond for commercial and industrial customers enables DR participation with cloud-based solution communicating with site's automation or building management system. Optimization program constantly runs to deliver right assets for power curtailment. This program takes into account operational constraints of the loads and therefore assures that productivity is not impacted. FlexTreo is a program for energy managers and it connects the site's energy management and plant management. It uses real-time market data and controls industrial loads accordingly respecting operational limits set by plant management. (REstore 2017)

4. IDENTIFICATION OF CONTROLLABLE LOADS

Jämsänkoski paper mill's power consumption fluctuates according to electrical energy price. During day time the mill's power consumption is around one and a half times the night time consumption. Power is used by three paper machines (PMs 3,4 and 6) in operation with related processes. By looking at the manufacturing processes and the factory, it was clear that the mill contains a great number of electric motors.

Due to the large number of motors in the factory, a method for handling vast amount of data was created using the tools provided by UPM Paper ENA. Also, a method for load identification in future for other similar plants is presented.

This chapter is divided into four parts. First part presents the tools used in the identification process. Second part explains the methodology used to find controllable loads and presents the identified loads. Third part focuses on evaluating reserve power capacity in Jämsänkoski paper mill. Fourth part presents a methodology for identifying demand response capable loads in future.

4.1 Tools for the identification

Several tools were used to create the identification method such as computer programs and databases and consultations of other employees. Using these tools in coordination with each other, the load identification method was constructed.

To find the identification method, it was concluded that acquiring a list of all motors within the inspection area was the most appropriate approach. SAP-software used in the factory contained the information about all motors in the factory. The list containing all induction motors within the plant was acquired using ZPM_BOMLIST -tool in SAP. The list confirmed that all the motors were included in the research as investigation with only operative programs easily leads to some small less critical loads being dismissed. Figure 24 presents the number of motors with power rating of at least 7 kW and their cumulative power in Jämsänkoski paper mill's PM 6 and related processes.

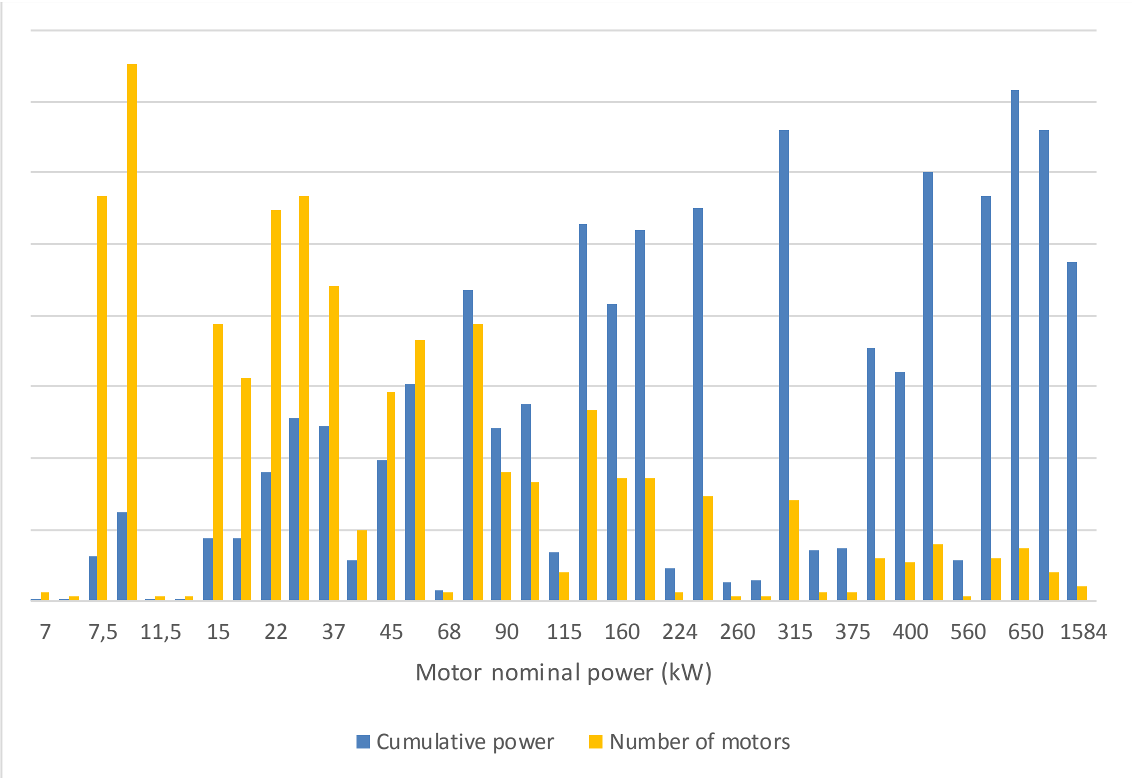

Figure 24 *The number of motors and their cumulative power in Jämsänkoski paper mill's PM 6 and related processes*

More than one and a half thousand motors were found within the area of inspection. 43 % of these motors are rated below 7 kW and are excluded from the chart to keep it clear. Combined nominal power of below 7 kW motors is 1.4 % of the total nominal power of all induction motors. Most of the motors are in lower power region as can be seen in the figure. On the other hand, the cumulative power output of motors grow as the power rating grows. This indicates that most of the DR potential may be acquired from high power motors.

Motors with frequency converter were found using database in SAP. A list with all electrical components for each position in the factory was run. This was done using IL03-command which brought out the directory including electrical center connections of all positions. Electrical centers were categorized by their feeding voltages: 400 V and 690 V. Each electrical center's list of devices sorted by positions was transferred to Excel into one list containing every electrical component in each position in the factory. By filtering the list with keywords such as "converter" and "inverter" and frequency converter models, a few hundred motors with frequency converter were discovered.

Another base tool for load identification process used was Piping and Instrumentation Diagrams (P&IDs). These diagrams were received for processes in the inspection area excluding PM 5 area and heat power plant. P&IDs include all the instrumentation and piping, and considering this research the most important information, positions of the motors related to the relevant process.

The most important software for gaining information about the manufacturing processes was the Valmet DNA –automation system which is used to operate paper machine and pulp manufacturing (PM 6, TMP and bleaching). Effluent treatment uses Honeywell's TotalPlant® Alcont (TPA) and provided similar help as the DNA. Automation systems may be later referred to as DCS which stands for Distributed Control System.

It was concluded that basic knowledge of the processes under investigation was crucial to figure out the possible potential and control strategies of each load or process for DR. Important information provider was the operation staff. Interviews and conversations with the staff were essential for the research as it was not possible to get sufficient understanding of the processes without their knowledge.

4.2 Demand response potential identification of loads

As stated before, the first step in recognizing the potential loads was to attain the list of the motors within the factory using SAP database. The acquired list included all induction motors in the areas of wood handling, TMP, refined mechanical pulp bleaching, PM 6 and effluent treatment. Other machine types were excluded from the research as there are only a few of them in the factory, mainly high power synchronous machines used in refining of woodchips. Induction motor list expressed the position in the factory, name, nominal power rating, nominal voltage and nominal rotation speed of each motor.

After acquiring the list and P&IDs, boundaries of the load identification were investigated due to high number of especially low power motors. Considering electricity market's requirements, it was concluded that no lower or upper limits for power were needed at the time. Small loads have potential through aggregation in the electricity market and no capital investments were assessed at this point i.e. cost of technical equipment needed for the load control compared to power reduction profits.

4.2.1 Identification process

To find out potential loads, ways to reduce loads' power consumption were assessed. Literature (Parvania et al. 2013) proposes 2 basic ways to change the load operation for demand response.

- *Load shifting:* load is shifted to a more favorable time. In the event of DR, load is shut down and after the event, load is activated. Total energy consumption stays constant, because load is only activated at different time.
- *Load curtailment:* power of the load may be reduced for the DR event. Total consumed power decreases and therefore, may be considered also as energy saving. This strategy requires advanced control technology such as frequency converter.

In this research, additional method is considered valid.

- *Load turn off:* load may be completely shut down in the DR event. This method also lowers the overall energy consumption and is relatively easy to implement (on/off switch).

A load may also be used in more than one of these ways. In (Parvania et al. 2013), utilization of energy storages and on-site generation are considered on top of load reduction methods. Currently Jämsänkoski paper mill lacks electrical energy storage possibilities although pulp towers can be considered as apparent electrical energy storages similarly to those examined in (Björkqvist et al. 2017). Pulp storages' utilization in power market is explained in 3.4.1 Load aggregation in paper mill. For the loads three options introduced above are the base for initial identification.

Figure 25 presents the diagram of the load DR potential identification process. The process was started by going through P&ID diagrams of manufacturing processes one at the time. Identification was started at thermomechanical pulping, and the first process investigated was woodchips' washing. P&IDs contain position numbers for each station in the process. By comparing position numbers with the induction motor listing's positions, the motors related to the processes were detected. The initial DR load identification was performed without considering target power market. Specific reserve markets are considered later in 4.2.2 Identified loads.

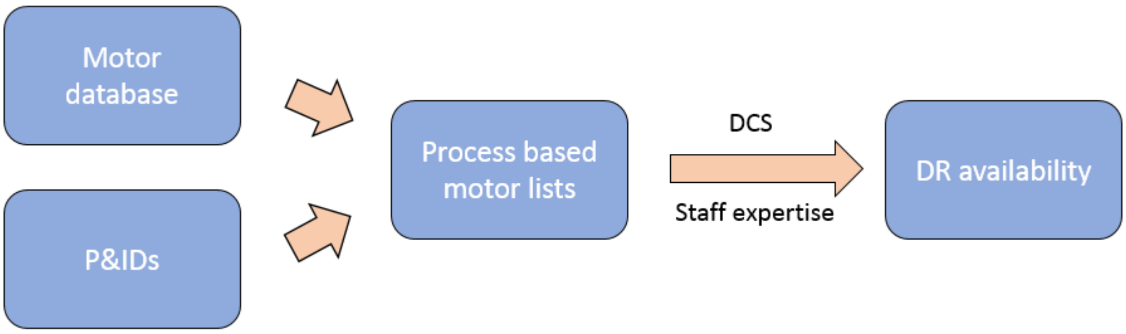

Figure 25 *Methodology used in loads' demand response potential investigation*

Process knowledge to a sufficient degree was achieved with the help of the automation systems and operators. From this point, the potential of each motor was easy to figure out. Loads with any chance of DR potential were considered and no constraints were needed to be investigated at the time. This method was used for each process in the manufacturing plant and a listing with all potential DR loads was created. The following information for each load was acquired.

- DR availability whether the load is directly available for the DR usage or a possibility exists and more comprehensive examination is needed.
- Cold load pickup after the DR event noted as yes or no. In cases of load taking excess power after restart following the DR event.
- Operation mode in DR event whether the load can be shifted, curtailed or turned off completely for the DR event.

- Process constraints noted as further examination needed or not needed.
- Actions to enable utilization in the event of DR.

TMP, bleaching and PM 6 were investigated one at the time. This covers most of the loads in the investigation area. The rest of the loads such as super calenders and rewinders were examined by simply interviewing operators as it was sufficient in these cases. These processes were simple to evaluate in DR point of view. Some motors were not marked in the P&IDs such as those in PM 5 area, these were investigated with the most appropriate means, mostly with the help of staff and DCSs.

It was concluded that the participation to FCR markets is realized with frequency converter driven motors due to their good controllability for the more demanding reserve. Therefore, additional examination was performed for frequency converter driven motors to figure out potential motors for FCR markets. These motors were analyzed considering FCR-N and -D requirements. Load categorization is explained further in next section.

4.2.2 Identified loads

More than 32 % of the plant's motors were identified as potential DR loads of which 8.5 % are frequency converter driven. Total nominal power of all DR potential motors is little over 27 % of all induction motors. This shows that DR potential in the paper mill is available quite well, although true potential is far less as clarified later.

Grouping of potential loads was performed to ease the handling of large number of motors. The loads were separated into following main categories considering how the load might be used in DR and the use in the factory. Figure 26 presents the corresponding percentages of the total power of each class.

- Process entities
- Mixers
- Air conditioning
- Pumps
- Filters and thickening machines
- Other

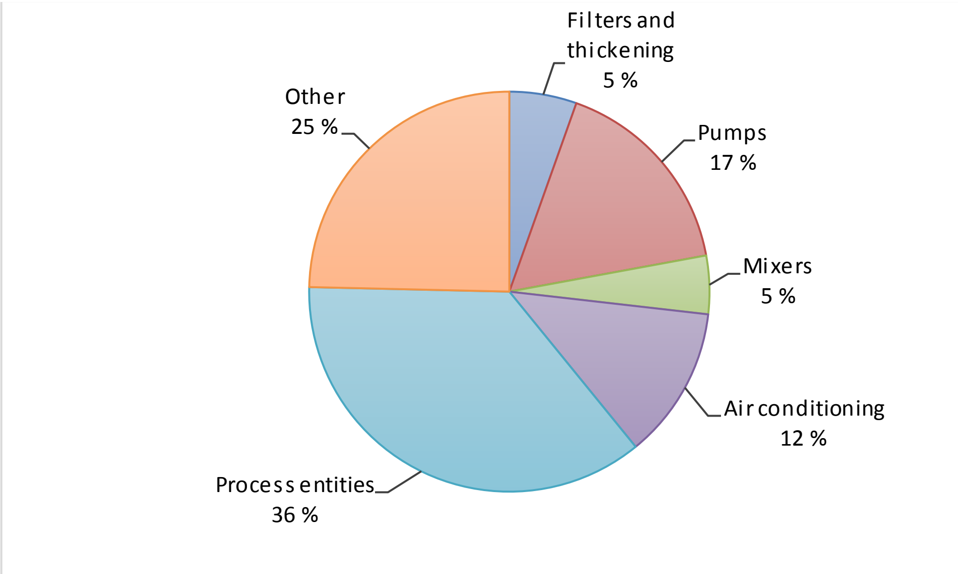

Figure 26 *DR capable loads' nominal power distribution in different categories*

A process entity covers all motors in a single entity operated as a complete DR controllable unit. These are, for example, super calenders, rewinders and hydrogen peroxide bleaching. Other, smaller entities, which are parts of larger process entities, also exist and may be potential. Process entities contains 36 % of the total power available for DR, although true potential varies depending on many things such as target power market and true power consumption.

Mixers attached to mass containers introduced motors with relatively easy implementation for DR. Total nominal power output of mixers is only 5 % of the total potential, but it is easily utilizable. Another type of loads with relatively easy implementation for DR is air conditioning devices. Separation from the manufacturing processes in most cases introduces good controllability and low constraints for these motors, although, some limitations must be considered. Total nominal power output for these motors is 12 % of the total potential.

Pumps used to transport mass inside the plant consume more power than other types of motors. Most of the pumps are important part of manufacturing and therefore not suitable for DR use. However, at least 17 % of the total DR potential was covered by mass pumps. Pumps were individually evaluated and constraints are very important to note as every pump behaves individually.

Filters and thickening containing 5 % of the total potential are also more complicated to use in DR, although possible. Pulp thickening in TMP and fiber recovery in PM are potential but hard to use without any negative consequences for manufacturing process. Disc filters are considered as part of bleaching process. Filters and thickening machines are relatively low power drives and therefore not very effective DR loads. However, in the case of the disc filters in Jämsänkoski paper mill, feeding pumps may also be shut down offering significant power output.

Lighting was included in the research but showed no significant potential. For example, shutting down third of the paper machine hall lighting leads to roughly 40 kW reduction. This was the only place where reduction was possible considering the safety issues that the lighting reduction causes in smaller spaces. Another way to reduce lighting is with adjustable power source to dim the lights but this requires additional equipment and therefore investments. Lighting is not examined further. Category containing other loads include single motors with potential in DR and cannot be grouped into other categories. The high rated power in this segment is mainly due to high power air compressors.

Further evaluation was done to the identified loads. Thorough assessment was not done before as it takes more time. The identified loads were evaluated for the DR based on following factors.

- Power of the load
- Ease of use in DR
- Negative effects for the manufacturing process.

Evaluated loads were categorized into two groups based on the market participation capability. Motors capable of continuous power control were allocated to frequency containment reserves (FCR). These motors are driven with frequency converters. Rest of the loads were allocated to frequency restoration reserves (FRR) including those frequency converter drives not capable to continuous control needed in the FCR. FRR group only requires on/off function for the load control, although with frequency converter load curtailment may be possible in addition to the turn off and the shifting properties.

Loads with immediate switch off can be used in the frequency containment reserves for disturbances (FCR-D). This is realized with switching of on/off motors in a manner that the reserve overall power reduction remains within limits described in the chapter 2.5.5 Power reserves (figure 14) for relay connected resources. This adds the amount of FCR-D reserve available, however due to complicated control of such entity it is disregarded in the thesis and only frequency converter driven motors are considered.

Evaluation narrowed the number of potential motors down to little more than half of the original potential motors. Total combined nominal powers of FRR and FCR motors was reduced by 37 %. Distribution of FRR power to each category is shown in figure 27.

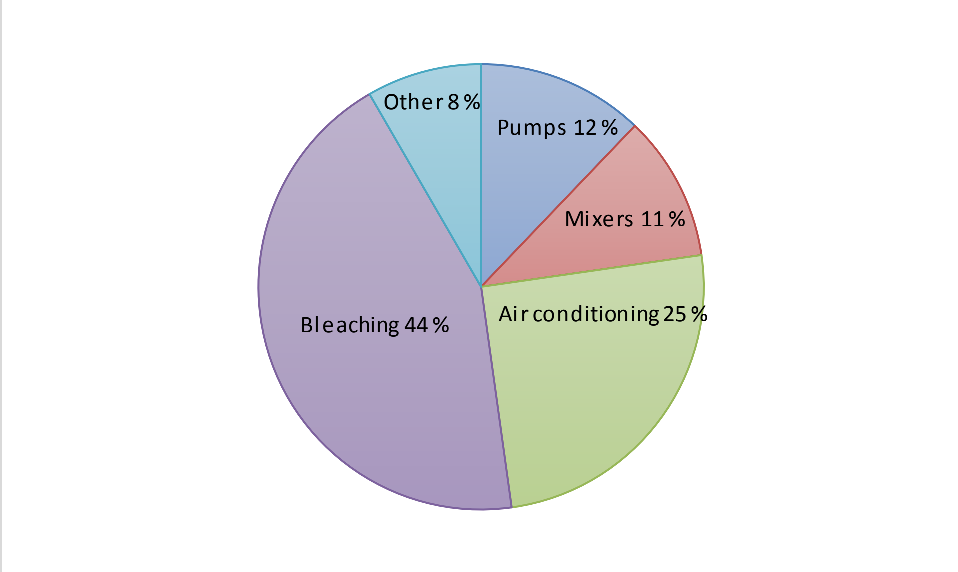

Figure 27 *Distribution of FRR power in different categories*

The filters and thickening are no longer present in the chart 27 if compared to the chart 26. Motors in this category were rejected from the potential motors as they were considered too complex along with air compressors which caused significant reduction in the segment of other loads.

Due to continuous nature of paper production, motors related to manufacturing are complicated to implement in DR. To get more DR capable power, process entities may be considered for temporary shutdown. This is also challenging as the production rate is high and inventories are small. In Jämsänkoski paper mill's PM 6, these processes are pulp bleaching and post-processing. Post-processing includes three super calenders and two paper rewinders. Controlled shutdown is necessary and time consuming. Therefore, process entities may be utilized only in mFRR market as it is the only market allowing 15 minute's activation time. Entities cannot accommodate the response time required by automatic reserves. Post-processing is not reviewed further in the research as this requires optimization of production phases and cost analysis therefore being a large field of research. Post-processing was therefore removed from the process entities segment as seen in figure 27 and the segment was renamed to bleaching.

4.2.3 Challenges in identification process

Several aspects were found challenging in load potential identification process. The most basic requirement of demand response is load reduction which requires turning off or curtailment of loads. On the other hand, paper production is a large entity with many sub processes. Paper manufacturing is continuous process with relatively long shut down time. Since demand response usually requires load reduction actions repeatedly, shutting down the whole manufacturing process is not an option as it reduces the production rate. Therefore, the loads for DR purpose must be non-critical for the manufacturing process to prevent any major problems. Most of the motors found in the factory are important and too critical for load reduction purposes which narrows down the available loads. Continuous nature of manufacturing process also prevents for the most part load shifting abilities.

Most of the motor drives in the factory are straight drives without frequency converter. Some machines are driven by frequency converter and therefore are capable for DR by load curtailment and some machines introduced the possibility for converter connection. One challenge is related to these drives concerning DR availability. If a machine has a converter, it is usually driven as economically as possible i.e. with low power. Therefore, it is difficult to curtail anymore without causing issues to the manufacturing process. Thorough economical assessment is needed if a frequency converter is procured only for DR purposes.

Motors with continuous action are easy to use in DR if process requirements allow. Motors with periodical use may be difficult depending on the type of timing. If the motor is driven in cycles with constant time intervals, DR use is relatively simple to implement using load shifting. However, if the load is driven by other measures, for example a pump used to pump liquid after reaching certain level, load shifting becomes more complicated. In these types of situations, the load prediction is usually difficult and load usability for DR becomes complicated.

Some motors were found relatively easy to use in DR but introduced issues in other areas. For example, a pump may be shut down for the event of DR, but it causes overflow of a container to a canal. This may be safe but causes other expenses. Also, another pump may be activated for compensation and thereby cancel out the benefit of power reduction. On the other hand, if only one of the two pumps participate in the DR and is therefore monitored, the power reduction still occurs considering the DR product. However, this reduction cannot be seen in the main transformer since the total power consumption does not change. This situation is not allowed as the total consumption is supposed to be reduced to maintain network power balance and this kind of action may be fined by TSO. As responsible actor, UPM absolutely acts according to rules and does not operate in this manner.

Common challenge in demand response identification of paper mills in Finland is the fact that energy consumption is well examined and minimized. This may be due to challenging market in paper industry and therefore energy efficiency has been improved. The minimum consumption means there is no slack in that area which leads to lack of curtailable objects. Pulp manufacturing plants may present more capacity as it is self-sufficient in energy production and therefore energy efficiency may not be as improved.

4.3 Reserve power capacity in Jämsänkoski

After the identification of controllable loads, power consumptions of the motors with DR potential were examined. Power consumption of any single load had not been measured before in the paper mill except some high rated power motors such as TMP's refiners. Therefore, there was not any historical information of load consumption except some converter drives' control signal data and measured power in transformer level. This chapter presents the capacity available for the reserve power markets and the methodology involved in the research.

4.3.1 Power consumption of the FCR motors

Frequency converter drives are usually used when precise adjustment is needed, such as motion drives (PM rollers). Loads with converter are almost always controlled by production related constraints. Therefore, instantaneous current was improper and consumption monitoring over longer period was needed for FCR potential loads. Current measurement over longer period was not possible with present available equipment.

Frequency converter drives' power consumptions for FCR motors were acquired using the frequency converters' feedback to the DCS. Capability to this depends on the converter's generation and connection to the building automation system. Converters without feedback to DCS were analyzed using their control signal data.

The drives with connection to the DCS initially provided torque information. This information is not monitored or used for control in any drives under the investigation. To acquire power consumption, the torque signal was changed to power signal. Power was then monitored in Savcor's Wedge-software which is used to analyze measured data in the plant. Figure 28 presents an example power consumption curve of a pump drive during 28.-31.7.2017.

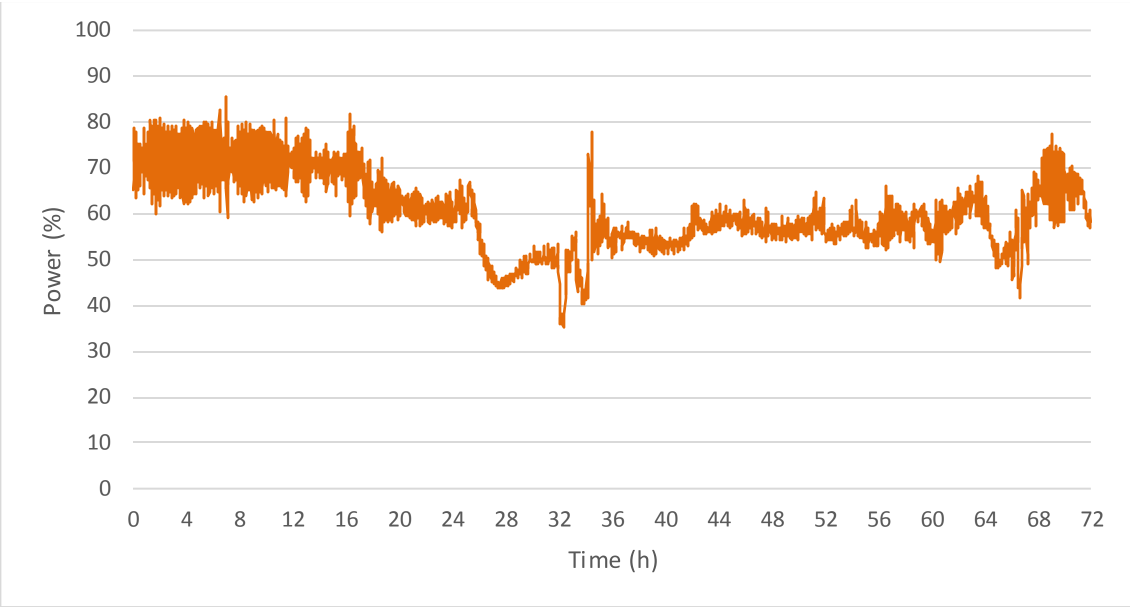

Figure 28 *Power of a pump used to move filtered water in 28.-31.7.2017*

The power consumption of the filtered water pump drive fluctuates between 35 % and 85 % of the nominal power in 72 hours indicating reserve potential to both directions. Process limitations set the high and low power limits which are examined further below. Similar examination was performed for four frequency converter driven motors.

Frequency converter drives without feedback to the DCS were evaluated using their control signal and manually measured power. The control signal history was send from the DCS to the Wedge. Manual power measurements were conducted by setting specific control signals in DCS for each motor and power reading was acquired from the display of the converter. The power and corresponding control set point were drawn in a figure and a trend line was added. The trend line provided an equation which presents the correlation of control signal and the actual power drawn by motor. Following figure 29 shows the correlation of power and control signal for a refined mechanical pulp pump.

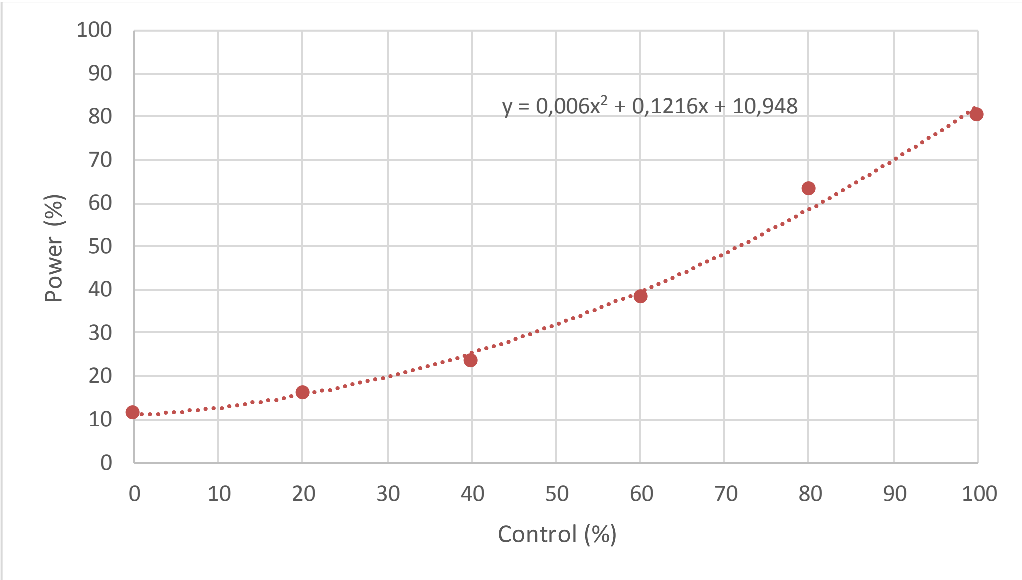

Figure 29 *Correlation of set control signal and actual power of a refined mechanical pulp pump*

The actual power depends on the control setting as seen in the figure. Equation shown in the figure was used to convert control signal into power. Using control signal history monitored in the Wedge and by converting it with equation presented above in figure 29 power over time was acquired. Figure 30 presents the power of the refined mechanical pulp pump in 21.7.-24.7.2017.

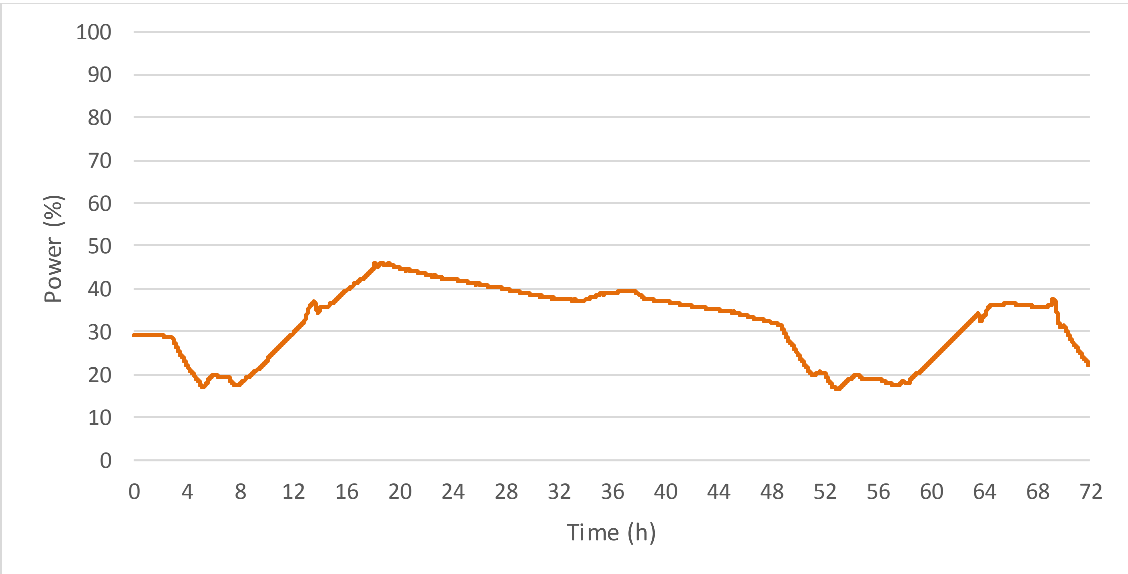

Figure 30 *Power fluctuation of the refined mechanical pulp pump in 21.7.-24.7.2017*

The minimum and the maximum powers drawn during the examined period are 17 % and 46 % of the nominal, respectively. By comparing figure 29 and 30 the gap between minimum power drawn and minimum power possible to set is 5.5 %. Similarly, the gap between high peak power and maximum possible set is 37 %. This indicates that much more power is available for down-regulation compared to the up-regulation capability. Process limitations examined later set the true limitations. Each drive has individual control settings and therefore similar analysis was conducted for approximately half of the potential motors. Figures 31 and 32 represent two FCR potential drives with different power consumption behavior.

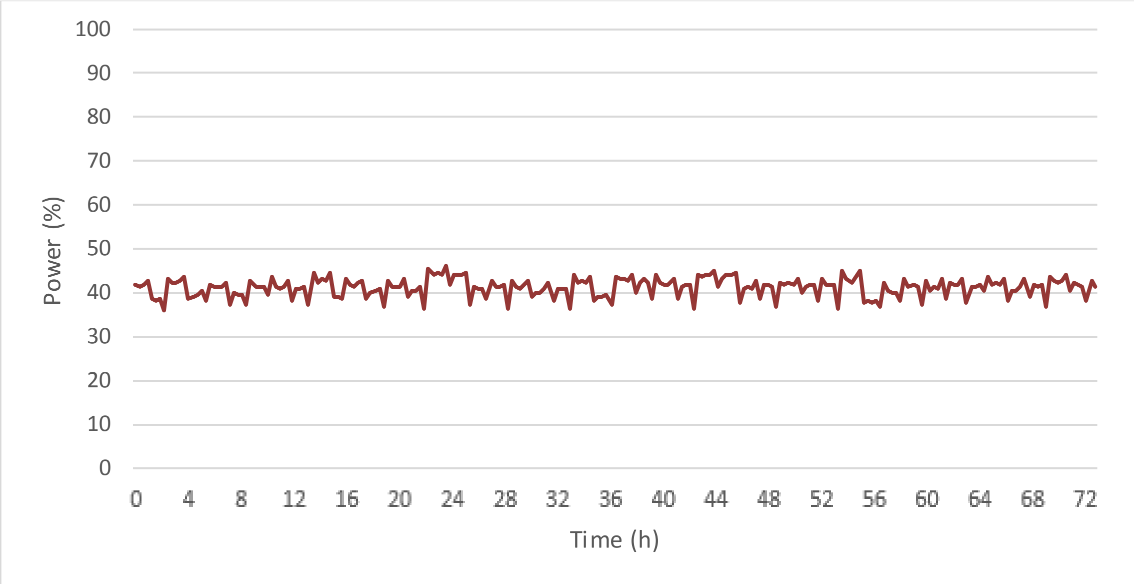

Figure 31 *Power consumption of a reject pump in 21.7.-24.7.2017*

Reject pump is controlled automatically based on a container's surface level. The pump has power fluctuation of only around 10 % as shown in the figure indicating great potential for power control in both directions. When compared to the figure 30, the mechanical pulp pump, which is also controlled based on container's surface level, the reject pump shows far less fluctuation. Figure 32 presents a flatter power profile.

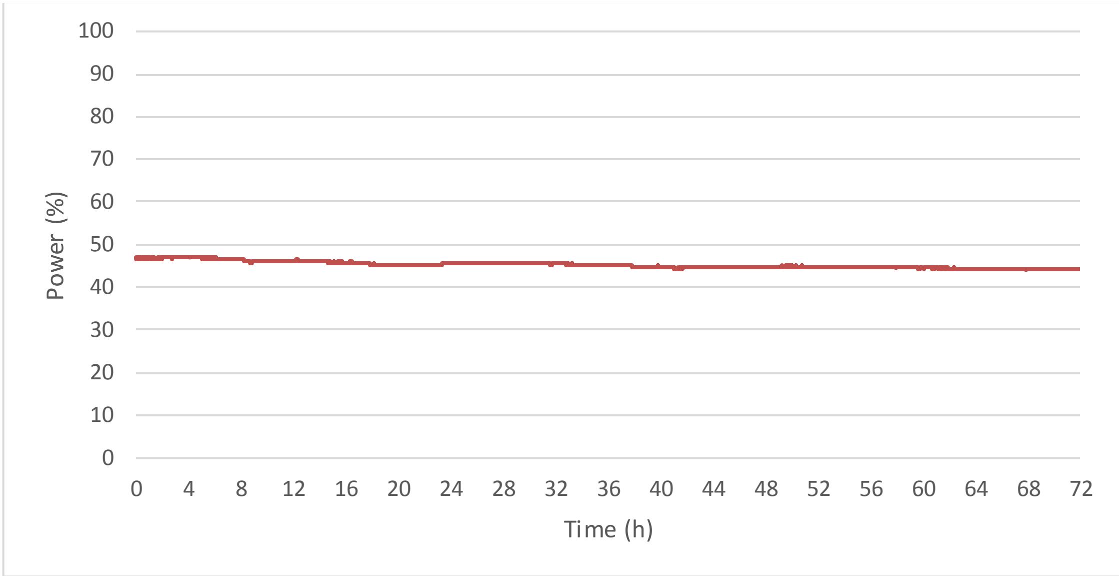

Figure 32 *Power of a blower in 30.7.-2.8.2017*

A blower presented in the figure is used to blow air to clean a wire in the paper machine. Power consumption of the blower is very flat as the figure suggests. The drive shows plenty of play in both up and down directions. In addition, it is controlled manually and set point is changed very rarely. This type of motor is ideal for reserve use when process limitations are not considered.

4.3.2 Process limitations for the FCR motors

Previously, power consumption of frequency converter connected motors were investigated which yielded information about the power fluctuation capabilities of the drives. To acquire realistic estimation of FCR reserve potential in Jämsänkoski, limitations by the manufacturing process were taken into account.

Evaluation of process limitations were considered by determining power limits, i.e. minimum and maximum powers, of each drive. The evaluation was performed in coordination with operators by testing manually each drive. The tests yielded minimum and maximum control percentages, i.e. control signals which can be used in normal operation without endangering the manufacturing process or cause additional costs indirectly. The correlation of control signal and power depends on the used power monitoring method.

The tests were conducted by decreasing and increasing the control signal manually to desired minimum and maximum limits. For the drives providing power measurements to the automation system, the limit power figures were registered in the Wedge. For the drives without direct power measurements the minimum and maximum control signal values were registered and correlation to the actual powers were acquired from the power curves determined before for the drives in question. As an example, figure 33 shows the behavior of a water pump during a testing procedure.

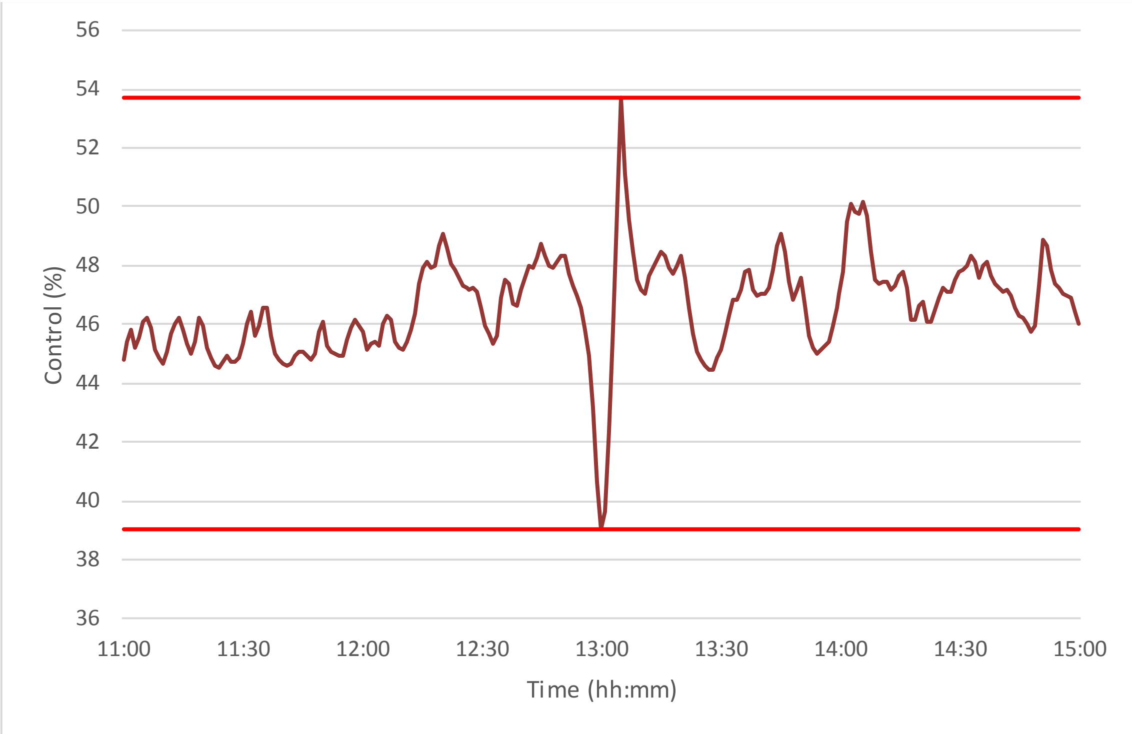

Figure 33 *Behavior of a water pump in 2.8.2017 during a testing procedure*

The water pump is used to provide chemically purified water to different processes in the plant. The pump's control is adjusted by pressure request. To assure safe operation, certain pressure must be maintained. It is difficult to determine the minimum pressure required by the processes and therefore the minimum was set relatively high. The test occurs at around 13:00 as the low and high peaks indicate in the figure. The low and high peaks determine the process limits for safe operation marked as red lines in the figure. The differences between normal operation and minimum requirement as well as normal operation and maximum request suggest quite modest capability for both up- or down-regulation. It is important to notice that all drives under the examination are individual and therefore needed consideration of certain limitations although the testing procedure was fairly similar to all drives.

Many motors under examination have very limited capability for load reduction compared to load increment. To increase the up-regulation capacity of such motors, control set point in normal operation may be increased. On the other hand, this increases the power consumption of the motor and causes indirect costs such as increased water and energy consumption. This issue leads back to the challenge related to the identification of frequency converter driven motors described in section 4.2.3 Challenges in identification process. In addition, many systems within the factory are optimized for production efficiency. Consequently, motors' operations are related to other motors and measures. By taking an optimized motor to reserve use most likely disrupts an optimization causing indirect additional running costs.

Absolute limits, i.e. minimum and maximum power limits, were relatively simple to test. Thorough evaluation of the process limitations is needed for the participation to reserve markets. At this point absolute limits are enough as only indicative power figures are needed in this research. Complete evaluation of process limitations includes many variables. For example, the refined mechanical pulp pump presented before involves factors such as pulp production rate, manufactured paper type and directly linked other processes determine the time limits for the pump usage. These time limits most likely reduce the available reserve capacity. Many factors and relations to other process parts is typical for the motors under research. This must be considered if investigation is taken further.

4.3.3 Forecasting FCR capacity and revenue in Jämsänkoski

After the examination of power consumptions and production limitations the reserve power capacity was calculated. A tool was created in Excel for the purpose. Target of the tool is to calculate available reserve power capacity of each motor using historical power information. Inputs needed for the tool are as follows:

- Time series
- Power series corresponding to the time series in kW
- Upper and lower power limits in kW
- FCR-N and FCR-D reserve market prices

With this information, the tool calculates FCR-N as well as FCR-D up- and down-regulation capacity for the unit and recommends the most lucrative reserve market. Table 4 presents an example calculation of hourly capacities for the first four hours of a day.

Table 4 *Example of a capacity calculation, capacities are expressed in kWs*

Hour	Min	Max	Average	FCR-N	FCR-D up	FCR-D down	Most profit
0	25.64	40.54	33.54	15.64	15.64	39.46	FCR-D down
1	27.51	56.24	40.87	17.51	17.51	23.76	FCR-N
2	29.30	35.59	33.34	19.30	19.30	44.41	FCR-D down
3	44.65	68.55	55.41	11.45	34.65	11.45	FCR-D up

It should be noted that currently FCR-D down-regulation market does not exist. However, this may change in near future (Fingrid 2017h). Down-regulation price used in the calculation is the same as up-regulation price. Figure 34 depicts graphical representation of FCR-N capacity of the refined mechanical pulp pump in 8.8.2017.

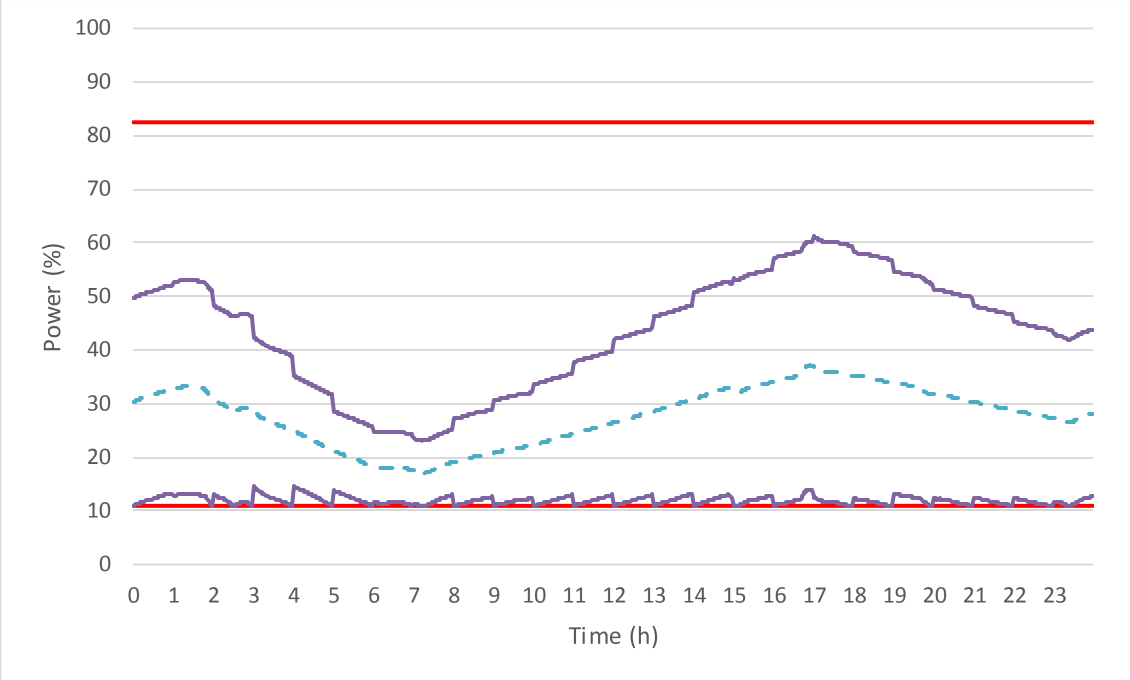

Figure 34 *FCR-N capacity of the refined mechanical pulp pump in 8.8.2017*

Dashed curve represents realized power behavior of the pump and solid lines are minimum and maximum limits set by manufacturing process. Solid curves are calculated by the Excel tool and represent the reserve power limits. In reserve use, the pump must operate within the area between the solid curves. Reserve power is calculated as follows:

1. Limiting power for each hour is calculated by calculating the lowest power available for either up- or down-regulation during each hour whichever is lower.
2. Low limit (lower solid curve) is set by subtracting the limiting power of each hour from the realized power curve (dashed curve).
3. High limit (higher solid curve) is set by adding the limiting power of each hour to the realized power curve.

As shown in the figure, the limiting power curves have notches between each hour which is due to varying power limit for each hour. FCR reserves are sold as one hour blocks and therefore the power limit is calculated for each hour. In the case of the refined mechanical pulp pump during the examined period, the limiting power is always the minimum power, therefore the capacity is never at the maximum limit.

After calculating available reserve capacity for each drive, the complete reserve power capacity of Jämsänkoski paper mill was calculated. Capacity was calculated for each hour of the day by summing capacities of each drive in the corresponding hour. Figure 35 presents the calculated capacities in 8.8.2017.

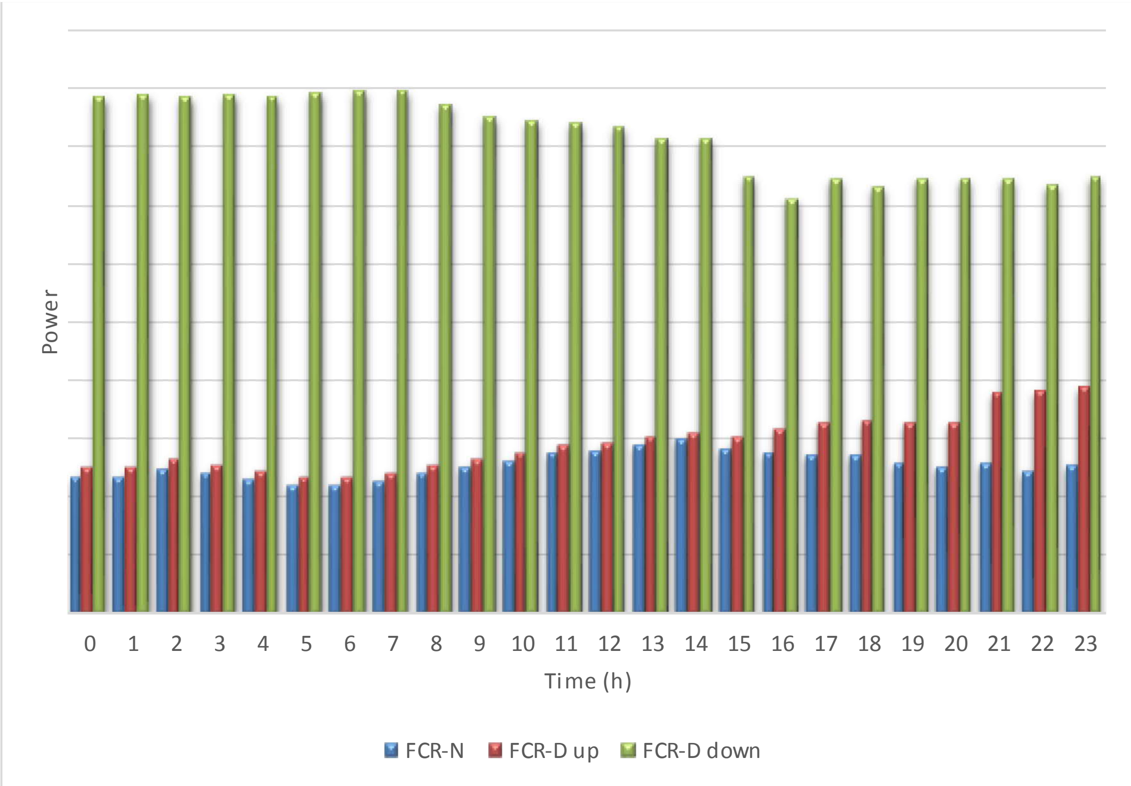

Figure 35 *Calculated FCR capacities in 8.8.2017 in Jämsänkoski*

FCR-D down-regulation contains the highest amount of reserve capacity as shown in the figure. FCR-N and FCR-D up-regulation capacities show very little difference except during the last hours of the day. The small difference is explained by all drives being almost always limited by load reduction instead of load increment. This also explains the major difference between FCR-D up- and down-regulation capacities.

With the calculated capacities, income expectations were evaluated. Following income calculations were done using Fingrid's model (Fingrid 2017d) for reserve sale revenue. Frequency containment reserves (FCR-N and FCR-D) were examined in both yearly and hourly markets. The calculations represent annual revenue if capacity of each day in a year is similar to the capacity of 8.8.2017. True capacity may vary daily more or less. Yearly revenue by calculated capacity in yearly market is calculated with the following formula. Energy payments are not considered.

$$\sum R_y = C_h P_{r,y} t_c \tag{3}$$

where R_y is yearly income, C_h is capacity in the corresponding hour, $P_{r,y}$ is price in the yearly reserve market and t_c is the constancy, i.e. the duration of procured reserve in a year. Similarly, yearly revenue is calculated with the reserve participating in hourly market.

$$\sum R_h = C_h P_{r,h} t_a R \tag{4}$$

where R_h is yearly income, C_h is capacity in the corresponding hour, $P_{r,h}$ is price in hourly reserve market, t_a is the amount of hours in a year and R is procurement rate, i.e. the ratio of procurement in a year. Numerical values for variables used in the calculations are shown in table 5.

Table 5 *Price, constancy and procurement rate for each market*

Market	Reserve price $P_{r,y,h}$ (€/MWh)	Constancy t_c (h)	Procurement rate R (%)
Yearly FCR-N	13.0	7000	-
Hourly FCR-N	23.1	-	74
Yearly FCR-D	4.7	7000	-
Hourly FCR-D	5.3	-	30

Price data of 2017 and three first quarters of 2016 are used for yearly and hourly market participation, respectively. Procurement rates are based on the data of first three quarters of 2016. Figure 36 presents the income calculated in yearly market with the mill's capacity in 8.8.2017.

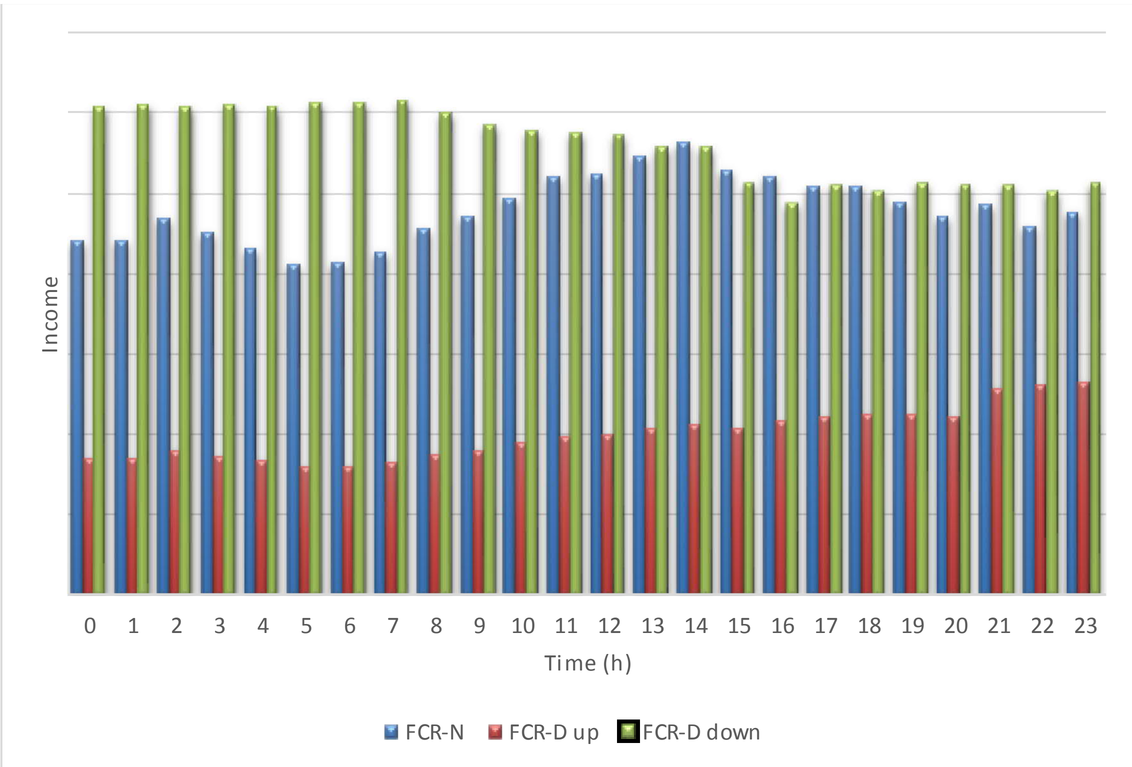

Figure 36 *Income expectations in yearly market calculated with FCR capacities of 8.8.2017 in Jämsänkoski*

FCR-D down-regulation shows the most profit in the calculation as suggested by the figure. During hours 13 – 18 the income of FCR-N is closer to FCR-D down-regulation.

High amount of down-regulation power available is the reason for being the most lucrative. Figure 37 presents calculated income in hourly market with the mill's capacity in 8.8.2017.

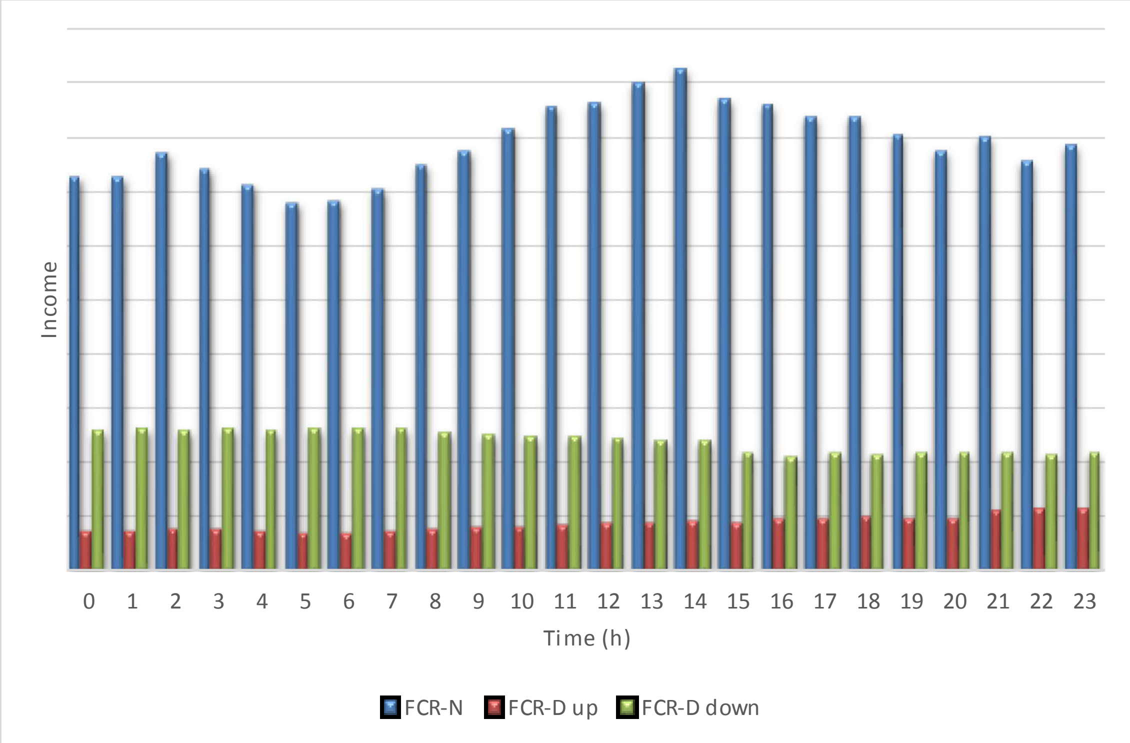

Figure 37 *Income expectations in hourly market calculated with FCR capacities of 8.8.2017 in Jämsänkoski*

As the figure indicates, with hourly market participation FCR-N is the most lucrative reserve market for the capacity available. This is caused by the price and procurement time differences. High price of FCR-N also causes the fluctuation of income between hours. FCR-D up-regulation reserve shows quite modest income. Down-regulation is little better but not as lucrative as FCR-N even though the capacity is 2-3 times the FCR-N capacity.

Most likely capacity is bid in the hourly FCR market due to the behavior of the drives in the factory. Presented calculations provide only indicative results as the behavior of the reserve capacity is evaluated for only one day. The number of drives in the reserve is directly related to fluctuations in capacity between days. The more drives in the reserve, the less there is overall fluctuation.

Calculations have shown that for every hour of the day the FCR-N is the most profitable reserve market with hourly market participation. It is important to notice that energy compensation was not included in the calculations which most likely decreases the profits of FCR-D reserve products. Compensation for error in imbalance caused by activation of FCR is calculated as explained in 2.5.5 Power reserves. Energy unused during regulation may be used after the regulation hour and the imbalance electricity price of the hour after regulation dictates whether energy compensation produces profit or loss. FCR-N is less affected as long time net energy consumption remains the same as without the reserve usage. This is caused by regulation to both up and down canceling each other out in the long run.

Power consumption of frequency converter drives under investigation is very challenging to forecast. Every drive is dependent on many factors in the manufacturing. Possible forecasting methods are analyzation of historical power consumption data or by larger factors involved in manufacturing such as manufactured paper type or operation schedules of the refiners. These have the largest impact on power consumption of FCR capable units. Even so, smaller factors, individual for each drive, have large enough impact to make forecasting challenging and a subject to further research.

The most effective tool yet is the Excel tool presented above even though so far it only handles historical information. Historical information can be analyzed to figure out estimations of the capacities. Historical information provides high and low power peaks which are useful when considering how each drive might behave in future. For example, if a drive is operated mostly within certain limits, it is most likely going to be operated similarly in future.

The Excel tool calculates the reserve capacity for each hour based on the low and high peaks during the hour in question. If a drive has stable power consumption, it presents more capacity to the FCR reserve compared to one with peaks lowering the available hourly capacity. If the past has shown that the drive has stable power consumption, it is likely to remain that way in future offering high reserve capacity. For each drive or complete reserve product, risk can be managed by altering the amount of capacity. Ultimately, the true reserve power capacity comes to risk management. The capacity figures presented are on the safe side meaning low risk capacity. The more the power from each drive is taken to the reserve market, the more the risk of negative impact on manufacturing increases leading to possible issues in delivering traded reserves.

Another important note is that when procured, FCR-N reserve is always activated. However, FCR-D may not be activated even if it is procured. Consequently, FCR-N sales might have larger impact on manufacturing processes over time compared to the FCR-D sales. More comprehensive research is needed to figure out true capacities for each reserve market.

Figure 34 presented the calculated FCR capacity by adding the reserve power capacity to the realized control signal. This kind of realization of power control introduces most likely problems with the existing controller. For example, container liquid surface level is adjusted by the controller which has certain parameters. If power of the drive is altered by increasing or decreasing the existing control signal, the controller might not be able to reach the wanted liquid level with present controller parameters. Correction to parameters' settings might fix this issue. The issue concerns almost all automatic controllers and is not present in manually operated drives.

4.3.4 FRR reserve capacity

For the evaluation of the capacity for frequency restoration reserves, true power of the motors and possible bidding phase were evaluated. To acquire true power figures for the FRR, the motors were assessed in terms of their behavior over time. Loads were categorized into constant load motors and motors with varying load.

The motors for FRR with constant load were simple to measure. These loads only require instantaneous current measurement and feeder voltage. Measuring currents for the loads with current clamps was relatively easy and fast objective and it was performed by plant's automation personnel. Loads, like fans and mixers in containers with certain assumptions, are typical loads in this category. Such loads are on/off loads for DR mainly allocated to the FRR. Using the current measurements and the feed voltages real power consumption of the motors were calculated with equation 5.

$$P = \sqrt{3}UIcos\varphi \tag{5}$$

where P is the real power, U is the voltage and I is the current at the time of the measurement and $cos\varphi$ is the power factor. Universal power factor of 0.84 was used for all the motors which is typical for induction motors installed in the factory. Acquired real power ratings for constant power (current) motors are accurate enough for the estimation of DR potential of the on/off loads.

The second type of motor has varying load over time. For accurate consumption information, these loads require, like frequency converter connected motors, some sort of trend or assessment through production situations. For example, mass pumping motors are these kind of loads as mass flow, pressure, etc. determine the power drawn by the motor. For accurate power consumption, thorough assessment is required, but due to limited resources, estimated powers were used. This is based on the momentary current measurements.

Some loads were not possible to measure and estimation of true power consumption was performed. The measured power of each category was multiplied with a factor compensating missing measurements. This yielded an approximation of the true power for each category. Figure 38 presents the distribution of nominal power and estimated true power to different categories based on their type of use. Estimated powers include power calculations based on momentary current measurements and estimations presented before.

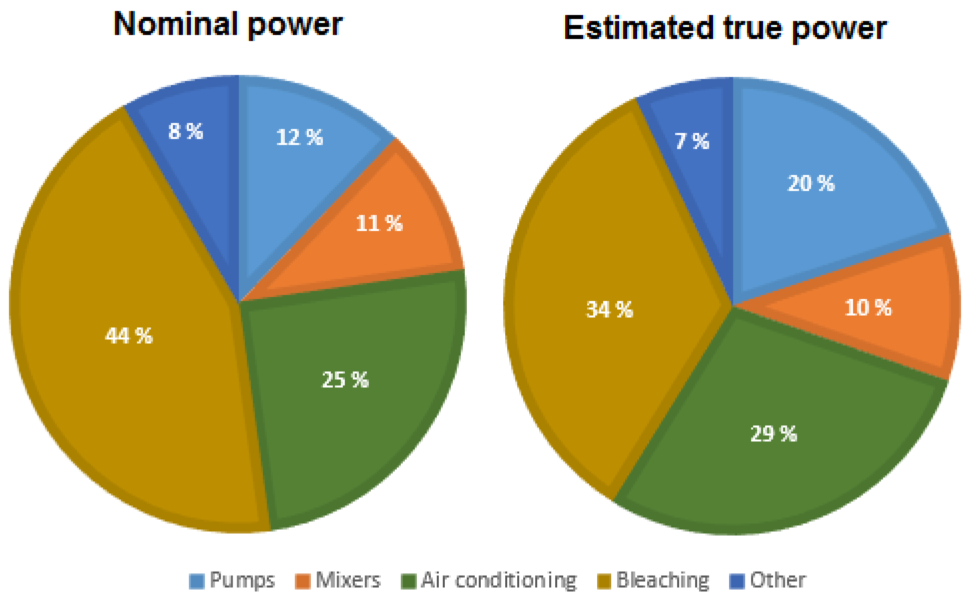

Figure 38 *Power distribution by the use calculated with nominal and estimated true powers*

Total estimated true power is 27 % lower than the total nominal power of the FRR motors. Pulp bleaching has the largest amount of DR capable power as shown by both pies in the figure. True power of pumps show increment over the nominal ratings indicating high utilization degree. Opposite phenomenon can be seen with the mixers, air conditioning and other motors. True power of bleaching is reduced significantly compared to the nominal rating. This may be caused by higher amount of frequency converters resulting in better energy efficiency by optimized electricity usage.

The amount of power possible to bid to the balancing power market is less than the absolute available potential presented before. The true market potential depends on the bidding mechanism of the reserve product. All capacity cannot be bid at the same time for the following reasons.

- Some motors may not be available at the time of reduction and therefore sufficient quantity of power must be saved as a backup reserve to ensure the reduction when the reserve is activated.
- Loads have different reduction and recovery durations which must be considered when constructing reserve product. Final aggregated reserve eventually consists of small blocks, i.e. motors, with predefined time limits.

True market ready mFRR potential is difficult to estimate without individual evaluation of the motors for the reasons stated above. Final estimation for available power reduction was performed by considering how the blocks are bid in mFRR market. Figure 39 presents the amount of power available for the first five hours bid to the mFRR market.

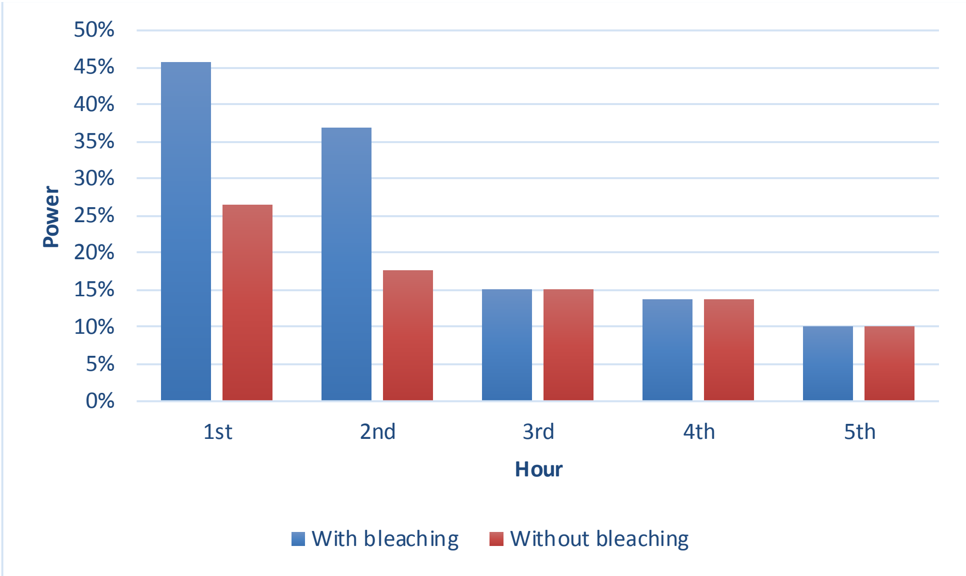

Figure 39 *Predicted available mFRR power for first five consecutive hours with and without bleaching available*

Reference power is the full mFRR true capacity estimation. As shown in the figure, highest power can be bid for the first hour. After that, the amount of power descents if consecutive hours are bid. Depending on the production situation bleaching might not be available at all for the reserve use. Removing bleaching decreases 19 % from the first two hours, leaving only 27 % and 18 % of the full capacity for the first and second hour, respectively. Bleaching is only available for two hours at most and therefore is not present after first two hours if utilized in the first two hours. The powers in the figure were acquired with following calculations presented in table 6.

Table 6 *The power available for mFRR in consecutive hours by the type of use*

Hour	Pumps	Mixers	AC	Bleaching	Other	Total
1st	8 %	7 %	9 %	19 %	3 %	**46 %**
2nd	5 %	5 %	5 %	19 %	3 %	**37 %**
3rd	5 %	5 %	4 %	0 %	1 %	**15 %**
4th	4 %	5 %	4 %	0 %	1 %	**14 %**
5th	4 %	5 %	0 %	0 %	1 %	**10 %**
Initial P	20 %	10 %	28 %	34 %	7 %	**100 %**

Table 6 shows the available power of each category for the first five consecutive hours. Rightmost column shows the total power as shown before in the figure 39. Bottom row is for the comparison, it presents the initial available power of each class as shown before in the figure 38 as estimated true power. As shown in the table, even the power available for the first hour is less than half of the initial estimated power consumption of the on/off loads. The percentages in the table above were acquired with approximations based on following limitations in table 7. The estimation considers each motor to be shut down for a minimum duration of one hour.

Table 7 Limitations considered when estimating the power bid to the mFRR market

Type	Limitations
Pumps	• Frequency converter drives → partial power available • Motors without measured power • Estimated time limits
Mixers	• Motors without measured power • Estimated time limits
Air conditioning	• Outside air temperature • Air pressure balance in plant premises • Motors without measured power
Bleaching	• Pulp towers indicating time limits • Power depends on production → minimum power considered
Other	• Assessment individually

Limitations issued a coefficient for each load category for each hour. After multiplying the power with the coefficient, final safety margin of 20 % was used for all categories and additional 20 % margin for the air conditioning due to high uncertainty of availability. As the table suggests, there are a lot of assumptions involved when estimating mFRR market ready power. It should be noted that the power ratings acquired may differ from true potential but express decent estimation. Accurate investigation is time consuming as all motors need individual examination for possible constraints. The best solution is most likely testing procedures for better results.

In the estimation, resolution of one hour was used in shutting down of the motors. In chapter 2.5.2 Power balance management shorter 15 minute's balance settlement period was mentioned. This transformation also effects the balancing power market and 15 minute's power products may be introduced. Therefore, mFRR motors are also reviewed to be used in the balancing power market as 15 minute bids. In this case, the minimum time of power reduction is decreased from one hour to 15 minutes. Shorter blocks introduce more possibilities in creating aggregated reserve power products due to shorter units in use. Blocks can be brought together in several combinations. Two possible combinations are considered in figure 40 as follows.

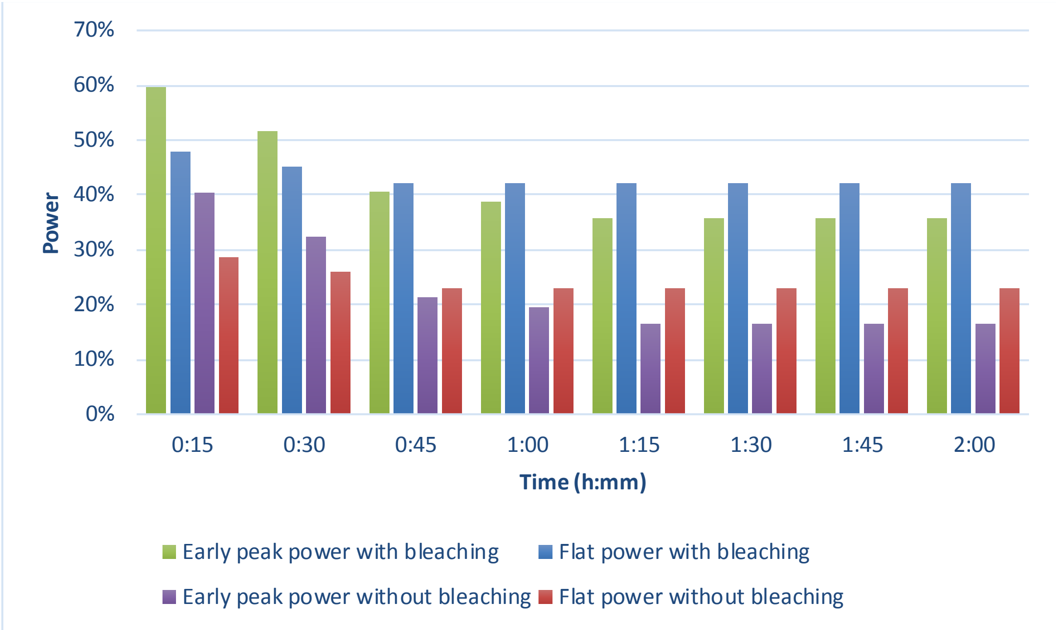

Figure 40 *Prediction of available mFRR power for two consecutive hours and 45 minutes both with 15 min resolution*

The first power reserve has emphasis on maximizing power in early time periods, this is shown as early peak in the figure. This strategy may be used if short reserve products are bid to the balancing power market. Downside is the recovery periods the motors need and therefore the available power starts decreasing fast. The second power product has emphasis on providing the power over longer period and is shown as flat power in the figure. With this strategy, peak power is deliberately set lower to secure sufficient recovery time for the motors. This may be used if longer reserve products are offered to the market. Bleaching has high probability of not being able to participate at all and therefore both strategies are shown in the figure with 19 % power reduction. Also, bleaching has long shutdown and restart times and is therefore not sensible for below one hour products.

The estimation for the quarter hour products was performed the same way as it was performed for the full hour products. Considerations shown in the table 7 were taken into account. It is noted that 15 minute blocks can also be used to create products for the balancing power market with full hour resolution. When quarter hour blocks and full hour blocks are compared, quarter hour blocks provide more flat power profile. This is due to better ability to use the motors since shorter blocks introduce more play. Downside of quarter hour blocks is more complex control scheme and more wear and tear to the motors' contactors due to higher amount of switching actions.

Prediction of the FRR motors is not as important as for the FCR motors. The FRR motors have relatively stable power consumption as it was a criterion during the identification process. However, these motors have some power fluctuation, but this is compensated by large number of the motors.

The profit generated by balancing power is calculated similarly to the FCR profit calculations. Calculations are performed using Fingrid's model (Fingrid 2017d) and realized market data of three first quarters of 2016. The calculation does not take into account energy consumption that is used sometime after the regulation event. Energy shifting reduces the amount of profit. Income was calculated as follows:

$$R_{mFRR} = 10\ MW \cdot 155 \frac{€}{MW} \cdot 8760\ h \cdot 0.02 = 320\ 204\ €$$

R_{mFRR} is the profit in a year with 10 MW of balancing power bid in the balancing power market. Price set point is 155 €/MW, the reserve is procured when it is surpassed which is 2 % of the time. Similarly, potential in the balancing capacity market with the same capacity for one week is evaluated as follows:

$$R_{mFRR,cap} = 10\ MW \cdot 500 \frac{€}{MW} / week = 5000\ €/week$$

$R_{mFRR,cap}$ is the weekly profit, when constancy is 100 % and bid is accepted but not activated in the balancing power market. Activation reduces the amount of compensation for the available regulation power as explained in 2.5.4 Balancing power market. It should be noted that the minimum bid in the market is 10 MW, therefore aggregation from several locations may be needed depending on local capacity available. Present rules of the market allow load aggregation (Fingrid 2016b).

4.4 Demand response identification method

A method was created to enable universal systematic identification of demand response capable loads in industrial environment. After successful identification of loads in Jämsänkoski paper mill, this method was created with the experiences attained in the identification process. The purpose of the method is to ease identification of DR loads in other UPM paper mills and industrial plants.

The base function of the identification method is to help identify the loads which can participate through aggregation in frequency containment reserve markets (FCR-N, -D) and frequency restoration reserve markets (mFRR and aFRR). This calls for basic technical requirements of the markets. The requirements were presented in the chapter 2.5 Power System. The identification is performed based on these requirements. The method is valid if the target markets are Fingrid's reserve markets in Finland. Block diagram of the identification process is presented in appendix.

Base information

A good way to start identification process is to obtain a list of all electrical loads within the inspection area using a factory-specific database. In paper mills, these loads are mostly motors. Therefore, a list of all motors is sufficient, although also those electrical loads that are not motors are important to notice. These may be, for example, heating or lighting loads. However, it is worth mentioning that these loads may not present significant amount of curtailable power in a paper mill due to low number and low power of such devices. Paper mills utilize separate power plant steam in heating needs.

In addition to the motor listing, frequency converter connection information is needed. Therefore, a list of frequency converters is one solution. The most suitable tool for this depends on the software and databases used in the factory in question. Frequency converter connection note may then be added to the motor list for each motor with the converter.

On-site backup generators might introduce well controllable power for reserve use. Compliance for the target market needs confirmation by evaluating the generators' technical readiness. Generators may be used individually, together or along with the loads.

Manufacturing priorities

The main target of the aggregated demand response is to utilize scattered power resources without causing harm to the production output of the factory. Manufacturing priorities refer to the most important processes within the plant or the bottleneck processes. Those processes that are not to be disturbed need recognizing. In a paper mill, main manufacturing processes are the paper machines. Disturbing these affects the production rate and shall therefore be avoided.

Motors with frequency converter

The first motors to be evaluated are motors with frequency converters. These loads present a possibility to participate in the most technically demanding as well as the most lucrative frequency containment reserve markets. Direct motion drives, such as roller drives, are common in paper mill, unfortunately these are not capable motors in DR for their importance and inflexibility. However, paper mills also contain frequency converter driven mass pumps which may introduce FCR capacity. Usually, this requires a mass reserve container in both ends to enable DR event based control. Also, air conditioning, blowers and aeration in effluent treatment present flexible consumption.

Motors capable for continuous control, i.e. for FCR participation, may also be used in FRR markets as their technical readiness enables it. The most important factors for the drives are presented in the block diagram. It is encouraged to prioritize the identified loads by their simplicity to use in DR. This helps the future work when reserves are examined and tested for true capabilities, especially for FCR motors due to their high technical requirements.

Load entities

After evaluating the motors for the FCR, process entities need evaluation for mFRR. They may also be smaller entities, such as filtering of pulp or reject handling. These entities introduce much larger power compared to single motors and they can be used as on/off loads in the balancing power market.

All loads involved in an entity proven applicable for shifting need to be recognized and considered as one package for mFRR market. However, it is important to notice that the loads utilized as part of shifted entity may be able for use as individual loads in other reserve markets. Therefore, if a load is applicable for the FCR as well as part of shifted entity for FRR, it must be noted.

Optimization of production schedules for the entities is needed for prediction of the schedules of available power. This is evaluated individually in each factory. Reduction response time shall be 15 minutes at most for mFRR and the minimum duration of reduction depends on the bid product and duration of balance settlement period. If the reduction duration of entity is shorter than the balance settlement period, i.e. reserve product duration, there must be enough other available loads to compensate for the unavailability of the entity. In a paper mill, pulp production, wood handling and post-processing of paper may be suitable for shifting.

On/off loads

Loads, that cannot be utilized in FCR or as a part of an entity, need evaluation. The three basic ways to alter the consumption of an electric load explained in 4.2.1 Identification process are considered. If the load is active during normal production, shutting down or reduction is examined. If the load is not always active but the operation is predictable, load shifting can be considered. Without predictable operation, load cannot be utilized reasonably in reserves. 15 minute's response time for the reduction is required and the duration of reduction depends on the balance settlement period or capability for compensation of the related reserve.

To manage the large number of on/off loads, categorization of loads is encouraged. Categorization may be performed similarly to the one presented in 4.2.2 Identified loads which utilizes categorization by the type of use. Typical uses are similar in terms of factors such as predictability, consumption patterns and dependency on production.

Results of the identification and follow-up

Investigation yields separate lists containing suitable loads for each reserve. Categorization of mFRR loads is recommended especially in cases of process entities. Next step is to figure out the true power consumption of the loads. Methodology for this depends on the plant's resources. Means presented in 4.3 Reserve power capacity in Jämsänkoski may be used. Finally, examination of process limitations shall be conducted. Most likely individual evaluation for the FCR motors is needed.

5. TECHNICAL SOLUTIONS IN PAPER MILL

DR may be demanding when it comes to technology. Load control usually means at least metering in the load point along with power switch, or more complex methods if power is controlled more accurately. Loads may need real time information exchange with controller which in turn must be connected to electricity utility or other facility that provides the DR event information.

At low power consumer level (mostly residential customers), a Finnish DSO, Elenia, has started to contribute to developing DR by replacing approximately 30 000 first generation AMRs with second generation which are better suited for DR. Information infrastructure and metering technology are provided by Sonera (Nowadays Telia) and Aidon. (Elenia 2017) In Finland, demand response is relatively new subject and utilities as well as other service providers have their own technical solutions. At the time, there are no standards related to DR technology in Finland.

Technical solutions to enable aggregated industrial demand response are based on the requirements of the target power market. Different power markets require different technical capabilities. Technical requirements of the frequency containment reserves are changed in a year or two to more demanding according to Fingrid (Fingrid 2017h). Considering the duration of creating a market ready reserve power product, new requirements are considered more important.

Proposed technical solutions to enable DR in the Jämsänkoski paper mill are presented in this chapter. Solutions in other plants may vary depending on the systems in use.

5.1 Standards and acronyms

Required technology depends on technical requirements of the reserves set by Fingrid. As explained earlier in 4.2.2 Identified loads, the FCR is realized with the frequency converter driven motors and the rest of the potential motors (including some frequency converter drives not capable for FCR) are categorized to the FRR.

The tests to verify the compliance of the reserves are conducted if the reserves are bid in the reserve markets. FCR-N, FCR-D and aFRR must be tested and testing is performed by test setups and rules instructed by Fingrid. Technical requirements of these reserves were briefly reviewed in chapter 2.5.5 Power reserves. Technical solutions enabling control of FCR and metering of mFRR motors are presented in this chapter. First, standards and technologies related to the DR and automation technology relevant in the research are clarified.

DCS

Distributed Control System, i.e. DCS, is a system used for monitoring and analyzing data from processes as well as controlling of processes using readings from process instruments. (Metso 2013) DCS is in the thesis also referred to as automation system. Two different automation systems are used in Jämsänkoski paper mill: Valmet's DNA in PM 5/6 and TMP and Honeywell's TotalPlant® Alcont (TPA) in power plant and effluent treatment. TMP's and PM 6's DNAs are different version and therefore they are separate units.

DLMS/COSEM

Device Language Message Specification, i.e. DLMS, is a concept for modelling communication entities. DLMS is usually associated with COSEM which stands for Companion Specification for Energy Metering. COSEM is a set of rules for data exchange with energy meters based on the existing standards. DLMS/COSEM is was made to help different parties understand each other via common language. The concept is maintained by DLMS User Association i.e. DLMS UA. (DLMS 2017) DLMS is one feasible option for power monitoring purposes in paper mill if such is needed.

OPC

Open Platform Communications, i.e. OPC, is a standard for reliable and secure exchange of data between industrial automation systems and devices. OPC-platform ensures information flow between devices regardless of the vendor. The OPC standard is maintained and developed by the OPC Foundation. OPC standard was initially restricted to Windows operating systems, but introduction of service-oriented architectures in manufacturing systems led to the development of OPC Unified Architecture (OPC UA) which presents interoperability across the enterprise. (OPC 2017) OPC is used in Jämsänkoski paper mill for integration of devices and different software such as DNA and TPA.

OpenADR

Open Automatic Demand Response, i.e. OpenADR, is a standard designed to alleviate the communication between electricity providers and system providers and their customers. It is developed and maintained in the U.S. by OpenADR Alliance which consists of industry stakeholders. Automated demand response helps system operators by reducing DR operation costs and increasing DR reliability. Also, customers can take part in DR programs with reduced effort. Automation enables the translation of market changes to retail rates and therefore makes responding to DR easier in reduction situations. OpenADR utilizes common IP-based communication network like the Internet and by being the most comprehensive standard for ADR it has achieved widespread support in the industry. (OpenADR 2017) OpenADR is not currently relevant in Finland, however, in future OpenADR may spread or similar standardizations may take place in Europe.

PLC

Programmable Logic Controller, i.e. PLC, is a computer designed to control machines in harsh environmental conditions. It resembles very much a PC but designed for more flexible connectivity to different inputs and outputs to the real world. It consists of power supply, central processing unit and input/output section. Devices come in many different sizes and shapes depending on the functionalities included. (Young 2017)

5.2 Required technology in Jämsänkoski

FCR capable motors' power measurements for authentication purposes can be realized with direct power measurements or indicative measurement of the power drawn by the motor. Direct power measurements are realized with frequency converters. Indicative measurement means monitoring of control signal sent to the converter, this is not yet confirmed as possible solution and therefore must be agreed with Fingrid. Control of converter drives for FCR needs more attention due to higher complexity and the technical state for such in Jämsänkoski is evaluated.

Required technical solutions for the FRR motors depend on the required metering accuracy. Control of FRR motors can be realized with present DCS with ease and therefore only power metering is evaluated. The information provided in this chapter is based on interviews with the staff throughout the project.

5.2.1 Control for the FCR motors

Frequency converters used in the paper mill are either multi drives used to control multiple motors such as the paper machine's rollers or single drives such as mass pumps. Every examined DR potential converter drive is a single drive. These drives were evaluated regarding the FCR participation. It was concluded that investing in additional frequency converters for the DR purpose is not reviewed as it is most likely unprofitable due to high prices of frequency converters. For the existing frequency converter drives, following cases were encountered.

- Drives with late model converter and connection to the factory automation system
- Drives with late model converter but no connection to the factory automation system
- Drives with older generation converter with no ability for the output measurement to the factory automation system

Most of the frequency converter drives capable of DR in the factory are late models (ABB ACS-series and Vacon NX-series) capable of delivering power measurement to the factory automation system. Few are older generation converters (ABB Sami-series) with insufficient connectivity to automation system. Locally needed hardware for the late model converters is analog connection from the converter to the DCS if the control signal monitoring approach reviewed in 4.3.1 Power consumption of the FCR motors is not sufficient.

Comprehensive information exchange between the DCS and the drives is realized in a modern factory setup with fieldbus connection to local I/O centers which are connected to the drives. This enables monitoring of multiple variables of the drives with minimum cabling. However, Jämsänkoski paper mill uses analog I/O connections with exception of converter drives in the bleaching facility. Converter drives under examination are driven by control signals from the automation systems. Only few motors in the plant are driven by PLCs. Automation system may be connected to a PLC for information exchange, but actual control is realized by either PLC or DCS.

Control scheme

Frequency containment reserves require the motor to adjust power consumption based on the network frequency and therefore frequency metering is needed. An accurate frequency monitoring device providing real-time frequency information exists in site's power plant.

Figure 41 presents a centralized solution of the information flow within the factory used to control the loads in the DR event. Centralized, in this case, means the frequency monitoring is realized with one separate device instead of local metering in each drive or system. Constant information exchange between automation systems and converters is needed as well as one way data exchange between network frequency monitoring and automation systems. Power plant and power station are in the same factory site as the paper mill.

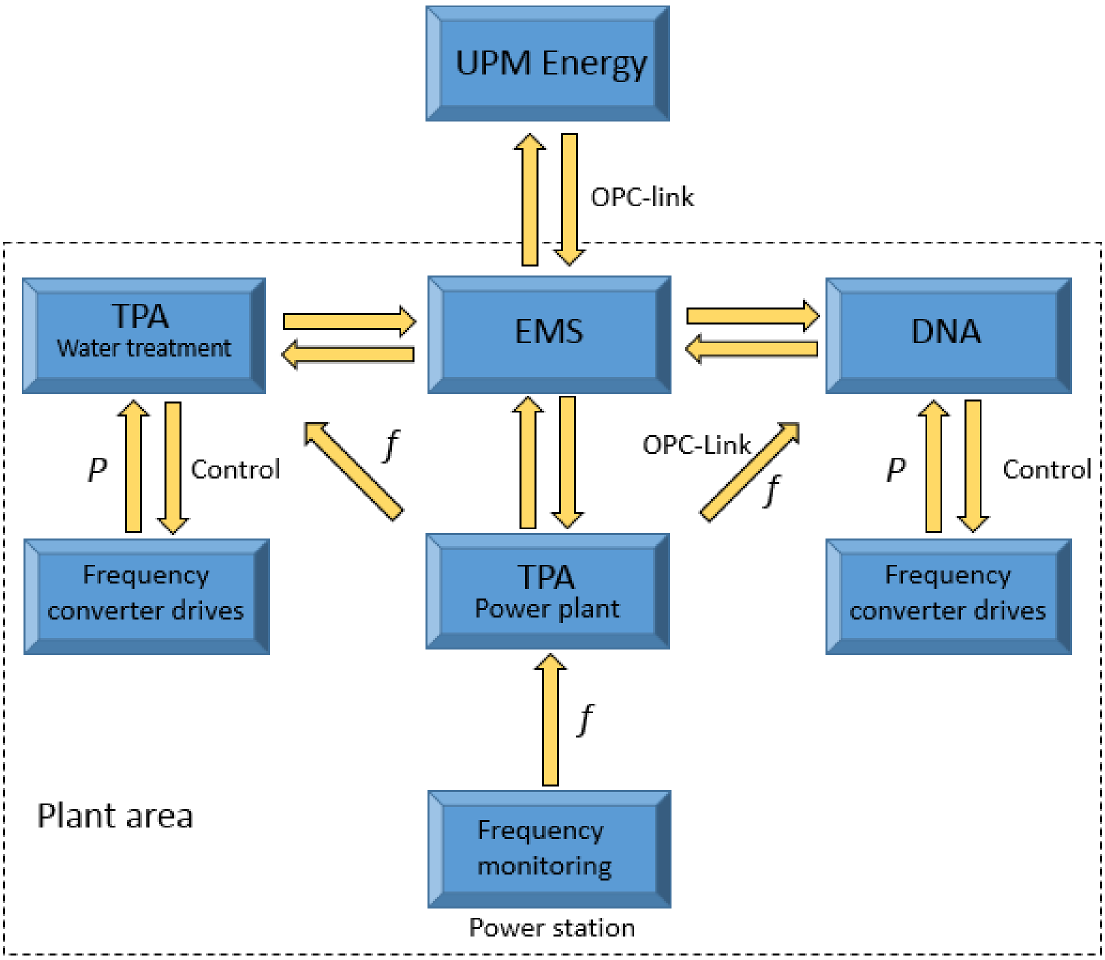

Figure 41 *Centralized solution for controlling frequency converter drives for FCR in Jämsänkoski*

Utility's, e.g. UPM Energy's, control room communicates with the automation systems in the paper mill through EMS (Energy Management System). Utility sends the information of the power reduction to the factory in DR event and receives the available power for trading in reserve markets. This connection is relatively slow, varying from seconds to minutes but sufficient for the purpose. An issue may arise if larger reserve portfolio is used which includes other sites as well. For example, if a load is not available and substitute load is needed in any other site, fast communication is needed. If the portfolio holder, e.g. UPM Energy, controls the actions, fast connection is needed between the holder and the sites.

Network frequency monitoring device is connected to the power plant's TPA. Frequency converters under the scope use connection to either TPA, TMP's DNA or PM 6's DNA. Therefore, network frequency information needs transferring to DNAs. To transfer frequency information from TPA to TMP's DNA, either fixed connection or OPC link can be used. OPC is already supported by the systems and the connection does not involve any costs. Information through OPC link takes around one second, therefore supporting the required speed for frequency containment reserves. However, real delay may vary and total delay between network frequency change and converters' reaction may cause OPC to be too slow. If faster data flow is needed, fixed analog connection is more sensible solution. This is realized with connection via existing main line between the power plant and the TMP in the mill. Signal ranging from 4 to 20 mA supports the needed accuracy for frequency information exchange. To transfer the frequency information further to PM 6's DNA, cabling may be needed. Another approach is connecting the frequency monitoring device directly to TMP's DNA which means one less analog to digital and vice versa conversions in the TPA end. No hardware is needed for communication between the power plant and the effluent treatment, their systems communicate with each other in real time since both use the same version of the TPA.

A decentralized solution refers to an arrangement with frequency monitoring locally. This can be realized by procurement of device for frequency monitoring and connect it directly to the DCS. TPA already has a connected metering device and therefore only DNA requires procurement of such device. For example, eQL Quality Meter (Electrix 2017a) by company called Electrix can be procured for the purpose. The Quality Meter monitors network frequency along with other measurements and by connecting the device directly to DCS via wired connector, delay is minimal. Other measurements provided by the Quality Meter also presents future proofing. On the other hand, costs are higher compared to transferring frequency information from the power plant. This is due to planning and realization of installation and cabling to the system as well as possible software licenses needed for operation.

Rough estimate for the potential frequency converter drives with control modification or creating new control circuit is around 120 hours of programming labor. The amount of labor is somewhat similar with both approaches. Most of the work is due to examination of sequences crucial in preventing damage of the equipment in fault situations.

By transferring the frequency information from the power plant to the TMP's DNA with fixed analog connection introduce planning and physical connection work. In addition, cabling from TMP's DNA to PM 6's DNA is needed. By procuring separate frequency monitoring device, such as eQL Quality Meter (Electrix 2017b), the total costs for the device, planning and installation as well as procurement of the software is around the same as by using existing meter in power plant.

Present state of hardware in the paper mill with minor investments is most likely sufficient to provide the automatic control of the frequency converter drives for the FCR. Automation system can be used for the control. To enable DR control, programming is needed for each converter to the automation system. Programming is outsourced work and total cost depends on the amount of time needed for the job. Both centralized and decentralized solutions are valid for the purpose but have different properties and costs. At this point, it is not completely clear how the control is realized and further examination is required.

The planning determines the true actions and costs. At least following questions need further clarification.

- OPC-link speed sufficiency for the purpose
- True amount of labor needed
- Ability of interfaces between systems to handle the data
- Analog to digital and digital to analog conversion accuracy
- The effect of time differences between systems

The presented solutions apply in Jämsänkoski and due to varying systems in other factories different solutions may be better suited. However, nowadays automation in industrial plants is advanced enough to enable controlling of devices without major modifications. Technical solutions for large scale utilization of aggregated demand response in industries may need unified solution for data exchange between reserve holder and plants. For example, a specific device comparable to the FlexTreo™ presented in 3.4.2 Existing aggregation services may be installed in each factory and used as an interface to enable communication of between the plant and the reserve operator. To make large scale utilization of converter driven motors profitable, programming costs need evaluating. Programming takes time and therefore causes costs in labor. To reduce the labor, similarities among drives may be discovered and these typical drives may use the same control program.

5.2.2 Metering of the FRR motors

Most of FRR motors can be used as on/off motors, and some have frequency converters with possibility to power curtailment. Focus is on the mFRR as the aFRR market is still developing and requires significantly more in terms of technology.

Control of on/off motors as well as frequency converter driven motors is easier compared to the frequency converter drives used in the FCR. Hardware, e.g. contactors, for switching each motor on or off remotely already exists. Almost every load is connected to DCS, i.e. to TPA or to DNA. Automation system manages the control with ease and only programming is needed.

The question whether on/off loads are sensible to use in power reserves depend on the required metering accuracy determined by Fingrid. Three possible solutions are considered as follows.

Power calculations without energy meters

Power of each motors can be estimated with power calculations e.g. using current information measured beforehand. Current measurements and real power consumption calculations were performed when investigating the true power consumption of the loads in the chapter 4.3.4. Using these power figures and the on/off information provided by automation systems, the total power reduction capacity can be calculated automatically by automation systems though programming is needed.

The issue concerning this practice is the inaccuracy of power figure due to several approximations. The currents measured are momentary values and may vary significantly in different manufacturing situations depending on the use of motor as explained in 4.3.4. Also, calculations were done using a universal power factor based on typical induction motor in the factory. The real power factor is given for each motor by the manufacturer. Voltage used in calculations is the nominal voltage and may also vary few percentages. Alternatively, power can be measured in transformer level using the on/off information of the loads. Accuracy may be poor as power measured in the transformer fluctuates quite much in any situation due to large amount of load fed by the transformer.

Power calculations using individual energy meters

Power metering can be realized with energy meters procured for each motor. The meters are installed to feeders of the motors. Modern energy meter is capable of measuring power and delivering information in real time. For example, meters supporting DLMS can be used. Automation systems can be utilized to do the total power reduction capacity calculations. This practice yields accurate real time power information. Downsides of this practice are the procurement costs of the meters and lack of space in most feeders.

Power calculations using partial metering

Loads' power can be measured indirectly using energy meters installed to the electrical center measuring the total power flowing though the center. Combined with the on/off information of the loads connected to the feeder in question, automation system can calculate the power reduction after turning off a motor. This practice presents relatively precise power information and if further developed, the system may be able to identify consumption patterns taking into account different manufacturing situations helping in consumption forecasting. Downside is complexity of the system. Table 8 presents a comparison of the three presented methods considering their features. Colors are determined in relation to each other. Green, yellow and red are good, mediocre and bad, respectively.

Table 8 *Comparison of metering methods for FRR motors*

Power metering	Accuracy	Price	Metering availability	Technical demand
Without meters	Poor	None	Fixed power	Low
Partial metering	Good	Mediocre	After transition	High
Individual metering	Excellent	High	Real time	Mediocre

Feasible solution for power verification is either realization without meters or with individual metering as shown in the table. Most likely no meters are installed due to high costs and if power verification with present equipment is found sufficient by Fingrid.

6. CONCLUSIONS AND DISCUSSION

Power balance in power systems has faced challenges due to increasing amount of renewable poorly adjusting production and more fluctuating consumption. In addition, well adjustable condensing power has been recently run down due to environmental reasons. Control of production to maintain power balance has not been economical anymore and therefore consumption adaptation, i.e. demand response, has introduced an alternative way of covering the system balance. Aggregation of low power loads for demand response e.g. in Jämsänkoski paper mill is needed to enable participation in the power markets.

The purpose of the thesis was to figure out the demand response potential of small loads in the paper mill. Demand response power product was targeted to Fingrid's power reserve markets FCR-N, FCR-D and mFRR. Technical requirements of the reserves set the principles for the identification and due to high technical demand of the FCR-N and -D, only motors driven by frequency converter were examined for these reserves. Motors with direct network connection were examined for the balancing power market. The load identification consisted of evaluation of each load with tools provided by UPM. 32 % of the motors showed some kind of potential.

Potential motors with frequency converters and their power consumptions were examined with historical information provided by direct power measurements or control signal data. Further analyzation was conducted by considering process constraints, after which historical information was fed to an Excel-tool created to analyze loads for the FCR markets. The tool provided a set of power capacities for each hour of a sample day. Acquired capacities indicated sufficient amount of power for the FCR-N market considering the minimum requirement. FCR-D up-regulation capacity was relatively low, only slightly more than FCR-N capacity. On the other hand, FCR-D down-regulation capacity was double or triple the FCR-N capacity but still below the minimum requirement of the market. These indicate that motors under investigation are almost always limited by their down-regulation capacity. Income calculations showed that the FCR-N is the most lucrative reserve market with the calculated capacities when participating in the hourly market which is where the reserve is most likely traded. Also, FCR-D down-regulation does not have a market at the moment.

The identification was performed according to the normal manufacturing situation. Many drives showed similar challenges when considered in the DR use. Especially the frequency converter driven motors showed difficult utilization at their present state. However, by altering the behavior of some drives with, for example, different control parameters, more potential may be acquired. On the other hand, this introduces challenges in production such as losing an optimized drive operation. This may lead to higher costs in production. Also, true capacity is dependent on the manageable risk. The capacities were calculated using the limits set with minimal risk of failure in reserve use. Higher capacity may be bid, but the risk of not being able to adjust the loads rises in situations of high frequency deviation. This is especially true with disturbance reserve i.e. FCR-D.

Forecasting of motor behavior is the key element in figuring out the capacities to be bid in the market. This is especially true with the FCR motors. Accurate forecasting provides the ability to bid capacity with low risk. Forecasting of power consumption is very difficult for most FCR drives as their power depend on many factors in manufacturing. One way to predict is by analyzing the effect of paper grade under production at the given moment. Also, operation schedules of the TMP's refiners may affect some drives' operation. Historical power consumption data was used as a reference of what the power consumption may be in the future. One approach is to create a smart application for the purpose which learns the effects of different variables and provides forecasts.

On/off motors targeted for the balancing power market were analyzed by measuring momentary current of each motor and calculating powers based on the measurements. Calculations yielded a power approximation for each motor. Real power consumption differs slightly due to power fluctuation of these drives. Also, some objects were not measurable. Reserve capable capacity was examined by considering the bidding mechanisms for the mFRR. A simulated bidding of the available capacity was created with motors being hourly blocks or quarter hour blocks based on present and possible future balance settlement periods, respectively. Simulations involved approximations based on the knowledge of the processes in question. As expected, the power available for the market was highest during the first periods of the bidding depending on the emphasized duration of the bid. Longer duration bids have less available power due to recovery times needed for the motors.

The thesis discusses about the technical solutions needed to enable aggregated demand response in Jämsänkoski paper mill. Solutions are based on the technical requirements of the reserves set by Fingrid. In practice, the relevant requirements needing more attention are control of the FCR motors and power monitoring of the mFRR motors. There are many ways to realize the control of the FCR motors. Actual control is performed using DCS, but frequency metering may be realized in various ways. Decisive method depends on the delays and investment costs of the implementations. Information exchange through OPC may be used, but delay using the link may be found too high. In this case, analog connection may be used depending on the application. The scope of the research does not include comprehensive investigation of the possible solutions. It is meant to provide a reference for the cost estimates of the technical solutions needed in demand response utilization.

Metering of power for FRR motors may also be realized in various ways. Three ways were evaluated: metering without energy meters, partial metering with energy meters and energy metering in each motor. Due to relatively low requirements set by balancing power market and high cost of energy meters, it is unlikely that any meters are procured for the purpose alone. It is assumed that metering with present equipment is sufficient although this is confirmed in testing phase if such is performed. The technology evaluation was conducted as a case study in Jämsänkoski paper mill and systems in other plants may vary. Therefore, also cost analysis varies. However, it is worth mentioning that other plants most likely use more or less similar systems. With both FCR and FRR motors, the costs are kept minimal and the cost of enabling technology is low enough for decent payback period with the calculated capacities.

The load identification was performed in a manner which is repeatable in other industrial plants containing large number of electrical motors. For this purpose, a method was created. Load identification requires basic knowledge of the reserves. Loads may also be analyzed for reserve use in similar manner presented in this thesis. The Excel-tool may be used for the purpose. However, it should be noted that frequency converter drives are most likely individual units. Consequently, evaluation must be conducted individually. Reserve capable on/off loads with similar uses as in this thesis can be found in other industrial plants, especially air conditioning and mixers to some extent are universal groups. As for the technical solutions, evaluation in each factory is required individually.

Currently, flexible consumption has been under research as it considered as a potential way to maintain network balance security. However, energy storage systems are also developing rapidly and flexible consumption may not become as important as it is seen now. It is difficult to predict the technological advancement of this matter, for example the improvement of battery technologies. The future network balancing methods may therefore vary in near future. The network balancing solutions may involve all the solutions; flexible production and consumption as well as energy storage systems. In addition, industrial plants may have backup generators and their potential may be quite high. Therefore, the utilization of these generators may also have large impact on the balancing methodology.

Nowadays, flexible consumption i.e. demand response has high profit potential in current Nordic electrical energy market. However, power markets change rapidly and the role of the DR may change to better or worse. On the other hand, reserve markets’ price formation is connected to balancing technologies indicating that the development of technology is the most decisive for demand response profitability in power reserve markets. In addition, the new requirements for the frequency containment reserves raises market prices by eliminating the least capable reserves. This thesis discussed the DR potential of a paper mill in reserve markets. DR may be utilized in power exchange as well. In power wholesale market, the balance settlement period may have an impact on DR utilization. Shorter settlement periods allow more play with the loads and otherwise unprofitable loads may become cost-effective.

Aggregated demand response is quite hot topic today. There are many companies trying to get as much controllable loads as possible for their portfolios with tempting contracts. Targeted reserves are usually simpler reserves such as backup generators and on/off motors targeted mainly to the balancing power market. Load aggregation for frequency containment reserve markets has not been examined as much. These reserves have mainly consisted of controllable production units. Therefore, aggregated demand response products present a business opportunity in FCR markets. However, realization requires more research.

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APPENDIX: BLOCK DIAGRAM OF THE IDENTIFICATION