LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
Energy Technology

Joonas Muikku

HYDRO TURBINES IN POWER SYSTEM BALANCING

Master's Thesis

Examiners: D.Sc.(Tech) Jari Backman
D.Sc. (Tech) Esa Vakkilainen

ABSTRACT

Lappeenranta University of Technology
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Hydro Turbines in Power System Balancing
Master's Thesis

2018
108 pages, 3 tables, 29 figures and 4 appendixes

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Keywords: hydropower, frequency control, Nordic power grid, time delay

This thesis was done for Fortum Heat and Power Co.'s, Hydro and Trading and Asset Optimisation teams. The goal of this thesis was to orientate to upcoming changes casted by the Nordic transmission system operators, to transpose the demands in to the Fortum owned Kaplan powered hydropower fleet.

This Master's thesis provides theoretical background for the Nordic power system, hydropower production, hydropower control systems and frequency control. Frequency control products are produced to large extent using hydropower, thus offering value increase for the existing hydropower plant fleet. To keep this value increase, a research is needed to examine the current state and capabilities of the hydropower fleet, so that preparative actions can be taken to maintain the offered frequency control capacity.

To achieve these goals, cooperation with Fortum hydropower specialists and Finnish transmission system operator, Fingrid was carried out. The results of this research are presented in a form of a ranking system, which illustrates the capabilities of hydropower fleet compared to a test case, which was done during this research.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT School of Energy Systems
Energiatekniikan koulutusohjelma

Joonas Muikku

Vesivoimaturbiinit sähköjärjestelmän säätösähkötuotannossa
Diplomityö

2018
108 sivua, 3 taulukkoa. 29 kuvaa ja 4 liitettä

Tarkastajat: Professori Jari Backman
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Hakusanat: vesivoima, säätösähkö, Pohjoismainen sähköverkko, aikaviive

Tämä diplomityö on tehty Fortum Heat and Power Oy:lle, Hydro ja Trading and Asset Optimisation tiimien tilauksesta. Työn tavoite oli tutustua uusiin Pohjoismaisten kantaverkko-operaattoreiden luomiin muutoksiin, ja kohdentaa uudet vaatimukset Fortumin omistamaan, Kaplan turbiineilla varustettuun vesivoimaan.

Diplomityö tarjoaa teoreettisen taustan Pohjoismaisen sähköverkon tilasta, vesivoimatuotannosta, vesivoiman säätösysteemeistä ja verkon taajuussäädöstä. Kantaverkon taajuuden säätötuotteet tuotetaan suurilta osin vesivoimalla, mahdollistaen lisäarvon olemassa olevalle vesivoimalle. Lisäarvon ylläpitämiseksi tarvitaan tutkimus, jossa selvitetään vesivoimalaitosten nykyinen tila ja kyvykkyys. Näin tarvittavat muutokset ja valmistelut voidaan tehdä ajoissa ja turvata tarjottu säätövoimakapasiteetti.

Näiden tavoitteiden saavuttamiseksi tehtiin yhteistyötä Fortumin vesivoimaspesialistien ja Suomen kantaverkko-operaattori Fingridin kanssa. Tutkimuksen tulokset on esitetty vertailutaulukossa, mikä kuvaa jokaisen vesivoimalaitoksen kykyä täyttää vaatimukset verrattuna tutkimuksen aikana tehtyyn verrokkikokeeseen.

AKNOWLEDGEMENTS

This thesis was done in collaboration with Fortum Trading and Asset Optimisation and Fortum Hydro. This enabled me to work amongst people with high competencies in various fields. I would like to express my gratitude to Fortum and its personnel, for the chance to do my Master's thesis on this interesting and highly current topic.

I would like to thank the supervisor of my thesis, Jari Backman, for the support and guidance. For the weekly meetings, advices, brain storming and patience for my ideas, I would like to express my gratitude to M.Sc. Roosa Nieminen and M.Sc. Timo Olenius. You helped me to reach the level I wanted. I want also thank my superior Tatu Kulla, for the possibilities to explore and research with the methods I found best. In addition I want to thank automation expert Timo Riikonen for his time and thoughts during this project.

I want to express my deepest gratitude and thanks to my family, for the unconditional support with my dreams as well as studies and work. I wish to thank my friends for the time we had during our studies, you made it something to remember. Lastly, I want to thank Paula, for your never ending support, ideas and encouragement in life as well as during this thesis.

"The power of water has changed more in this world than emperors or kings"
-Leonardo da Vinci

Espoo, 1st of August 2018

Joonas Muikku

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SYMBOLS AND ABBREVIATIONS

Roman

$2D$	Total Backlash	
A	Area	m^2
a	Amplitude	
C	Control signal	
c	Capacity	W
E	Energy	J
e	Control error	
H	Backlash scaling factor	
h	Height	m
I	Moment of Inertia	kgm^2
K	Gain	%
KE	Kinetic Energy	kJ
l	Length	m
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
n	Normalization factor	
P	Power	W
PE	Potential energy	J
Q	Volumetric flow rate	m^3/s
r	Radius	m
s	signal	
T	Time constant	s
t	Time	s
u	Control variable	
v	Velocity	m/s

Greek

ρ	Density	kg/m^3
ω	Angular velocity	rad/s

Subindex

b	Bias
d	Derivative
f	Frequency
H	Head
h	Hydraulic
i	Integral
m	Mechanical
max	Maximum value
m&f	Measuring & Filtering
min	Minimum value
o	Operational
P	Power
p	Proportional
pe	Potential
pq	Prequalified
sp	Setpoint value
t	Turbine
test	Tested value
w	Water

Abbreviations

AC	Alternative current
AGC	Automatic Generation Control
aFRR	Automatic Frequency Restoration Reserve
DC	Direct current
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbance

FCR-N	Frequency Containment Reserve for Normal operation
FRR	Frequency Restoration Reserve
HMI	Human-Machine-Interface
HPP	Hydropower Plant
HVDC	High Voltage Direct Current
LFC	Load Frequency Control
mFFR	Manual Frequency Restoration Reserve
PID	Proportional- Integral-Derivative
PV	Photovoltaic
pu	Per Unit
RC	Ranking Coefficient
RES	Renewable Energy Sources
RoCof	The Rate of Change of frequency
RoR	Run-of-River
SC	Stability Coefficient
TG	Turbine-Generator
TSO	Transmission System Operator
VC	Valuation Coefficient
VRES	Variable Renewable Energy Sources

1 INTRODUCTION

The Nordic power system is undergoing a massive change. Various megatrends are affecting the joint power grid in Nordic countries; global climate change, resource efficiency, new technologies and more active customers, just to name few (Fortum, 2016). The affect can be seen especially as more renewable variable energy production, less consumption and fewer power plants using fossil fuels. This all adds up to more frequency deviations in the power system and more unstable power grid. (Fingrid, 2018a.)

The Nordic power grid has a nominal frequency of 50 Hz ± 0.1 Hz, which means that all the generators operating in this power system are synchronous and running at same frequency. This nominal frequency is an indicator of the state of the power grid. When the frequency decreases below 50 Hz there is a shortage of power or increase in demand in the power grid. When the frequency increases over 50 Hz the power grid is experiencing overproduction or lacking demand. The amount of electricity produced must equal the amount of electricity consumed at all times. (Fingrid, 2018a.)

The problem that the megatrends are casting to the Nordic power system can be seen as more frequent and larger deviations in frequency compared to the nominal value. In practice this means that the frequency quality of electricity provided is not as good as it used to be (Figure 1). To manage these new challenges the Nordic transmission system operators (from now on referred as TSOs) have worked together to establish new set of regulations and requirements for energy producers. These new requirements include more specific demands for the frequency, power output and reaction times when producing power system balancing products. (Fingrid, 2017.)

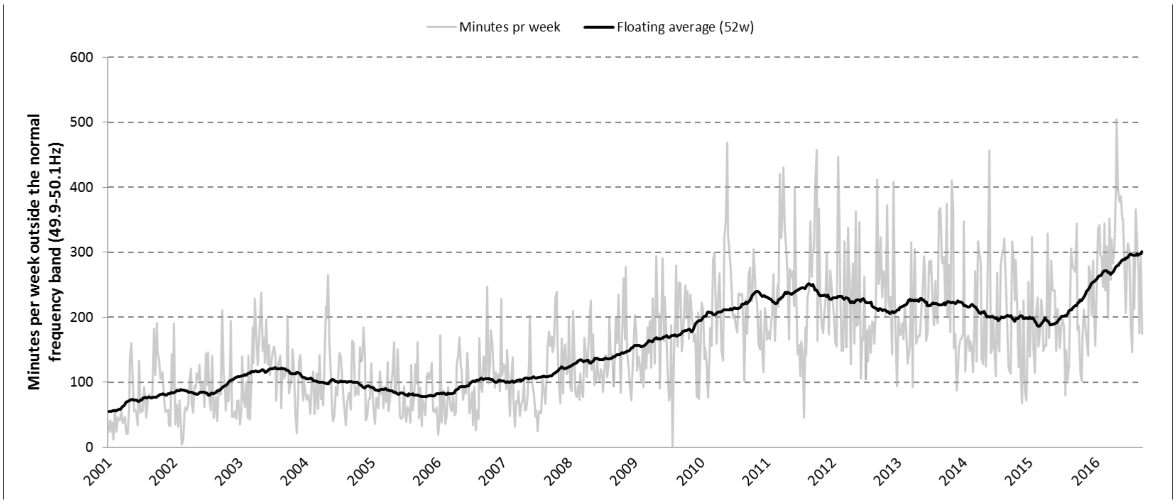

Figure 1. The quality of frequency in Nordic power system (Fingrid, 2017)

1.1 Literature review

This thesis addresses a gap in an academic literature field of hydropower produced frequency control. Hydropower has been used in frequency control a lot all over the world due to the favorable nature of hydropower power ramping and ecological capabilities, so research has been done previously on how to adapt hydropower in different types of situations. In the Nordic countries, hydropower has had a major role since the beginning of industrialization and the Nordic countries feature a significant amount of installed hydropower. This leads to an academic literature field where lots of different types of research is done on hydropower. Some universities provide hydropower studies as a major subject, which leads to new studies and fresh insights on the subject.

As the Nordic transmission system operators (TSOs) are designing new regulations for the frequency control products, a need is created for a study that could address the challenge on more specific and company orientated manner. As the main focus is around upcoming changes, the literature field on that part of the thesis is very limited. To compensate this, interviews are held with both, the operating TSO in Finland and the employees at Fortum who have experience on hydropower plant optimization.

This thesis addresses the challenge the transmission system operator demands pose for hydropower, instead of how the power grid should be operated. The objective is to create a joint between upcoming regulations and hydropower plants and their capabilities. This can then be used as a base for further research or as a report on how the frequency control producers face the new demands.

1.2 Research questions

The aim in this research is to orientate to the upcoming change that frequency control product demands cast on Fortum hydropower fleet. To achieve this the research conducted in this Master's thesis is divided under two main research questions.

How do the new TSO requirements compare to old ones?
How do the new requirements affect Fortum hydropower?

These research questions have a strong connection but a separate set of answers is desired. The TSO requirements are undergoing a change to a more controlled type, which means Fortum needs to take actions to keep up with the new regulations. Although the new requirement set is not yet complete, and is lacking the final version of regulations, now is the time to react to upcoming change and to do the needed preparations to maintain competitiveness in the field. This thesis is focusing on the main differences these changes have compared to present ones and to the actions needed.

The result shall be a list of Fortum hydropower plants, ranked by the capability to fulfill the new regulations and this list shall be applied to the existing Fortum hydropower fleet in Finland to find out what actions should be taken. This thesis also provides a base for further research on frequency control with hydropower and addresses wear and tear of hydro turbines due to frequency control. Thesis also provides a research, based on which a feedback can be given to TSOs concerning the feasibility of regulation reformation.

1.3 Scope and structure of the thesis

The scope of this thesis has been predefined to maintain high research quality. It was decided that even though Fortum owns and operates hydropower plants in Sweden and Finland, and most power plants are in Sweden, due to favorable turbine technology and clean entity, only Kaplan –turbine powered power plants located in Finland are taken account.

Even though all transmission system operators operating in Nordic power system, Fingrid (Finland), Svenska Kraftnät (Sweden), Statnett (Norway) and Energinet.dk (Denmark), are obliged to operate by same regulation and rules, this thesis will only research the changes introduced by Finnish TSO Fingrid.

1.4 Execution of the study

Execution of this study comprises of three segments; firstly, a vast literature research is done to achieve a reliable theoretical backbone to the study. Literature is the main source of knowledge in the theory part of this thesis. Second large segment is research by interviews. There is only a certain amount of literature provided on the subject as the main focuses mentioned in chapter 1.2, are very recent, like the new requirements, or very vaguely researched. Company behind this thesis also provides a vast network of professionals with preferences in significant fields considering the study. The third segment is data analysis and measurements conducted by the author of this thesis. The amount of data available is notable and the acquired data spreads over long period, providing reliable source information.

2 NORDIC POWER SYSTEM

The following chapter is to identify the key features of Nordic power system and to focus on the upcoming changes in the Nordic power system. This chapter also provides insight on the challenges the Nordic power system is facing, as well as solutions for these problems.

2.1 Introduction to Nordic power system

Between the years 1991 and 2000 the electricity markets in Nordic countries (Denmark, Norway, Sweden and Finland) were opened for competition. This meant that the electricity generation and retailing were no longer as tightly controlled and could now be exchanged at new Nordic electricity market, to which the four previous national energy markets had merged into. This provided a totally new type of electricity market which was heavily dominated by hydropower production, covering up to 50% of all electricity production. Also typical thing for Nordic countries was so called "national energy giants". Every Nordic country had a partly nationally owned energy company, which was covering a big part of the national energy markets, for example Vattenfall was covering 47% of the markets in Sweden and Fortum was covering 29% of the Finnish electricity markets. As the electricity markets merged into the Nordic energy market, the shares of market owned by these national energy giants were drastically decreased which enabled a static and fair competitive market system. (Amundsen et al. 2006, p. 148-150.)

The Nordic countries, Finland, Sweden and Norway, and East Denmark form a synchronous power system. In synchronous power system, all of the electricity producing generator rotors, which are directly coupled to the grid, rotate with the same frequency. This creates demands for the electricity producers in all listed countries but also helps to provide high quality electricity for the users. The Nordic synchronous area and Baltic area are also connected to outside countries via transfer connections (Fingrid, 2018b). In addition to the synchronous area, also Baltic countries, Estonia, Latvia and Lithuania, are participating in the same energy market. The total amount of energy the energy market traded in 2016 at this area was 391 TWh (Nord Pool, 2018). On 12th of March, 2018 the total energy production in Nordic countries was around 62 GW, from which the part of hydropower was 36 GW, and total consumption was around 61 GW. (Statnet, 2018.)

2.2 Frequency control in Nordic power system

The Nordic power system is controlled and secured using different types of control products, common to all nations, or TSOs, operating in the Nordic power grid, even though some requirements and testing methods may differ between TSOs (Saarinen, 2014, p. 35). Stability of the Nordic power grid is achieved by giving each participating country a national obligation of control products. The control products of Nordic power system are listed in Table 1. The main daily operations revolve around the primary frequency control products, FCR-N and FCR-D. (Fingrid, 2018b.)

Table 1. The control products used in Nordic power system to control the frequency of the power grid and the demands towards Fingrid.

The control product	Abbreviation	Amount obligatory for Fingrid (Finland)	Ways of purchasing
Frequency Containment Reserve for Normal Operation	FCR-N	140 MW	Yearly market Hourly market Other Nordic countries DC link from Vyborg Russia Estlink 1&2 Estonia
Frequency Containment Reserve for Disturbances	FCR-D	220 - 265 MW	Yearly market Hourly market Other Nordic countries
Automatic Frequency Restoration Reserve	aFRR	70 MW (Only part of days hours)	Hourly market Sweden
Manual Frequency Restoration Reserve	mFRR	880 - 1100 MW	Balancing energy and capacity markets Fingrid's reserve power plants Fingrid's lease reserve power plants

2.2.1 FCR-N

Frequency Containment Reserve for Normal Operation, FCR-N, contains 600 MW of frequency controlled power output capacity in the Nordic power system. This 600 MW has been divided for participating countries, or TSOs, and the capacity obligation for Fingrid is around 140 MW. The national obligations are divided amongst electricity producers with an annual bidding competition, with additional hourly markets to fulfil the demand. A company can offer this product to its local TSO. If the offer is accepted, the TSO will be delivered with nominal amount of power which will adjust according to current state of grid frequency. This capacity is used to keep the grid frequency between values 49.9 Hz and 50.1 Hz. For the power producer, there is also requirements for power output capacity which has to be fulfilled to be allowed to offer FCR-N for the TSOs. The TSO can also purchase this control product from outside of the Nordic power grid. In such cases the direct current (DC) link from Russia and Estonia can be used. The FCR-N product is designed so that the Nordic power system can be kept within 50 ± 0.1 Hz at normal operation, even though the demand and production may vary due to natural reasons. The current requirements state that the offered output power must be activated linearly so that when frequency reaches 50.1 Hz the output power must reach 100% of the offered capacity, and vice versa if grid frequency reaches 49.9 Hz the power output must be decreased by 100% of the offered capacity. Nominal time minimum for this deviation is 3 minutes. With these requirements TSOs can count on power increase and decrease when necessary. (Fingrid, 2018c; Fingrid 2018d.)

2.2.2 FCR-D

Despite the FCR-N product, for abnormal deviation also a Frequency Containment Reserve for Disturbances, or FCR-D, must be maintained. The amount of FCR-D capacity must be so large that the power system can maintain its frequency within 50 ± 0.5 Hz even though a large power plant would drop off the grid, or a transmission line would shut down due to a failure. The capacity is determined on weekly basis so that after largest possible failure, the frequency can be maintained using the natural controllability of the grid and the FCR-D. The Nordic power system has a FCR-D capacity requirement around 1200 MW, and the requirement for Fingrid is around 220 – 265 MW. To provide FCR-D to the market, the provider has to fulfil the current demands which state that when grid frequency descends below 49.9 Hz, after 5 seconds 50% of the offered power output has to be active and after 30 seconds 100% of the offered power output needs to be activated, through a linear ascend. (Fingrid, 2018c; Fingrid 2018d.)

2.2.3 FRR

The FCR-N and FCR-D products are used to correct the ascend or descend of the frequency, but due to the nature of Nordic power grid, these products, or control algorithms do not have the capability to restore the frequency back to the nominal value of 50 Hz. For this task, another product is introduced to the system: Automatic Frequency Restoration Reserve, or aFRR. aFRR is fully controlled by the TSOs, and it is used only for restoration of the frequency. A separate test sequence is used to test the applicability of power plants offering the aFRR. (Fingrid, 2018e.)

Manual Frequency Restoration Reserve, or mFRR, differs from other products in the way that it is reserved completely for massive failures and disturbances. The obligation in Nordic power system is that the largest single electricity producing unit or transmission line, must be replaceable in case of failure. This means that in Finland the capacity needed is somewhat time related and varies around 880 – 1100 MW depending on operating power plants. The power plants participating in mFRR, does not participate in commercial electricity production. These power plants are kept in stand by condition at all times. Fingrid owns power plants, capable of producing 929 MW of electricity and has also leased reserve power plants for a total of 301 MW. (Fingrid, 2018f; Fingrid, 2018g.)

2.3 Challenges of the Nordic power grid

Even though the Nordic power system is ahead of its European counterparts, what comes to power grid and power market management, the Nordic power system is still facing major challenges in upcoming years. These challenges are casted by global megatrends as well as more local Nordic trends. The biggest megatrend affecting the Nordic power system is the global warming. Climate policies are taking over as nations have joined forces to cut emissions, and this is done by offering subsidies to renewable energy sources (RES), among other things. Global warming is also the reason for heavier taxation and fees for common fossil fuel –based energy production. This is leading to heavy changes in the Nordic electricity market prices and quality of frequency. (Statnett et al. 2016, p. 2-13.)

The Nordic TSOs have made a report in 2016 (Challenges and Opportunities for the Nordic Power System, 2016) listing the already observed and predicted challenges and opportunities in the Nordic power system. The report has a scenario for the year 2025, which is used to demonstrate the state the Nordic power system is heading.

The challenges pose also a need for new solutions to cope with the megatrend driven changes. This chapter also provides partial solutions to presented challenges. One action that is already been planned and is in planning phase at the moment, is the updating of frequency control product tests and demands, which will affect the Nordic way of producing hydropower powered frequency control.

2.3.1 System flexibility

Power system flexibility is an important asset in power system control. One of the key tasks of transmission system operators is to maintain the balance between production and demand, and the power system flexibility is a vital part of this process. The term flexibility means the ability of adjusting the electricity production on demand, either upwards or downwards, depending on the balance in the grid. The different power sources can be listed by their flexibility, and the most flexible power sources are the ones with least external factors affecting the electricity generation. This types of power plants are for example, hydropower plants with sufficient water reservoirs, coal and gas powered power plants and batteries among other energy storage options. The least flexible electricity production is affected by external factors. For example, intermittent wind power, photovoltaic (PV) solar power and hydropower with run of river power plants are heavily affected by external factors, such as weather condition, thus making it highly inflexible. Only flexible action these kind of power plants can provide, is the short-term down regulation, when they are operational and running. (Statnett et al. 2016, p. 16.)

The amount of flexible power is decreasing. The Nordic trend of terminating traditional thermal power plants as unprofitable is reducing the flexible power production. The termination of thermal power plants is due to low electricity market prices. This means that not just the amount of flexible power is decreasing, but it is being replaced with variable renewable energy sources (VRES) which are highly inflexible. The role of flexible energy production is more heavily transferred to hydropower and HVDC links to external countries. (Statnett et al. 2016, p. 16.)

The consequences from having a power system with very limited flexibility causes problems affecting the power grid and power market. As the power system becomes more dependent on external power systems, due to increase in electricity import from HVDC links, the short-term price volatility in the day ahead power market increases and market prices develops higher towards the continental European prices. Less flexibility results also in arisen prices on flexible power and power grid balancing costs. The decrease in flexibility is an unwanted step away from independent power system. (Statnett et al. 2016, p. 17.)

2.3.2 Generation adequacy

The generation adequacy is a value which sets the barriers between continental Europe and the Nordics. Generation adequacy is desired to maintain as unified and locally operating power market as possible. Due to security issues, also independent countries are very interested in national generation adequacy and this is seen as an important value. Sufficient energy production helps keeping the market prices at desired levels and creates security in price formation. The undesired path is to become more and more dependent on import energy, and thus expose the Nordic power market to external price volatility. From TSOs report (Challenges and Opportunities for the Nordic Power System, 2016) can be seen that Nordic countries have composed national studies about the generation adequacy. Despite of the studies being conducted on national level, the results are somewhat similar; Finland, eastern Denmark and southern Sweden have been predicted to suffer from capacity issues. On behalf of Finland and eastern Denmark, this means heavier rely on import energy from outside of the Nordic power system. The interdependency inside the Nordic power system is predicted to grow as well as the interdependency between external power systems and Nordic power system. (Statnett et al. 2016, p. 21-27.)

2.3.3 Frequency quality

Power system frequency is a direct indicator of the condition of the power system. In Nordic countries, the nominal frequency of power grid is 50.0 Hz and any deviations from this means deviation in the relation between energy production and energy consumption. The electricity is traded in day ahead market between producer and consumer, and in intraday market, which takes place on hourly level during the current day to correct the errors. Despite of this there is still imbalances in the real-time production and consumption relations. (Statnett et al. 2016, p. 11, 28.)

As stated in the beginning of this thesis the quality of frequency in the Nordic power system is deteriorating (Figure 1). According to TSOs report the deteriorating is not decreasing but increasing in the future. Even though the Nordic TSOs have various tools and lots of data from the power grid for balancing the production and consumption, the task of keeping the frequency ± 0.1 Hz from the nominal 50.0 Hz has been proving to be increasingly difficult (Figure 2). The incapability to keep the frequency at ± 0.1 Hz from the nominal value is giving an alarming message from the condition of the power grid, as the control of the frequency becomes even more challenging the deviations in frequency will become larger and more common. As the frequency deviations approach the 1 Hz, the risk of large industrial disconnections rises, thus increasing the risk of blackouts. (Statnett et al. 2016, p. 29-30.)

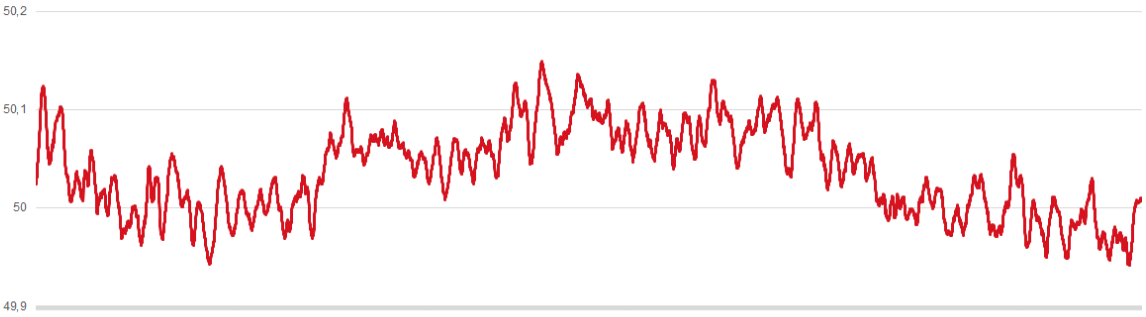

Figure 2. The frequency of the Nordic power system on Friday 12.5.2017 clock 07:00 - 08:00 (Fingrid, 2017)

The frequency quality is a sum of two main factors, the Nordic power grid and the Nordic power market. It is highly important to make the difference and also to understand the connection between the power grid and the power market. The frequency control is a good example of an asset affected by both. The main challenges for preserving an adequate frequency of the power system are larger structural intra hour imbalances and increased number of forecast failures, increased need for diminishing reserve capacities, changes around hour shift, and new components with higher power output rate. These challenges can be divided to ones arisen because of technical demands and to ones arisen because of market behavior. (Statnett et al. 2016, p. 29-30.)

The power system is undergoing a change in consumer habits and production methods. The production methods affect directly to the power grid. As the power production moves more and more to VRES sector, the forecasting becomes a major factor in production planning. The forecasting methods used nowadays still lack in accuracy and this affects directly to the market situation when the sold products in day ahead markets do not match with real time production. In addition to that the VRES lack in controllability which leads to intra hour situations where the power production does not stay stable, which leads to increase in reserve demand. The VRES however has replaced a lot of conventional power production, so the reserves used to balance the grid are becoming scarcer. Finland has also given up on lots of thermal power, which will be at least partly covered by new nuclear reactors. This introduces a new larger power capacity generators in to the power grid, which can increase the risk of major frequency deviation when suddenly disconnected due to a fault. These types of challenges pose a responsibility to the TSOs to adjust the power grid to fit the situation. (Statnett et al. 2016, p. 29-30.)

As the previous chapter described the challenges arisen from the technical demands towards the power system in this chapter the market based challenges are described. The Nord Pool power market works on an hour based system, in which every hour of the day has production and consumption, sold and bought one day before. The hour based system has proven to be a solid way of handling the power markets, but as the forms of consumption change and the production changes more and more intra hour, due to VRES, the hour based system has shown some weaknesses. There has been larger intra hour imbalances in the market, as the production sold for specific hour might change due to weather conditions and consumption changes due to new consumer habits. These situations create an unwanted market condition in which the demand for intra hour reserve capacities are needed to correct the fault in the market. Also, the change of an hour has proven to be an unwanted market condition, as the prices do not express just the balance between production and consumption, as an ideal market should, but the prices have much more variables and play in them. These kinds of challenges can be seen to arise purely from the market. (Statnett et al. 2016, p. 29-30.)

The difference of power grid and power market is good to understand, as the grid as well as the market pose challenges to the power system. However, the power grid and power market go also hand in hand and the affects in other is always casted to the other.

2.3.4 Inertia

As discussed above, system frequency is an indicator for the state of the power system. Large, fast or common deviations of the frequency indicate of poor frequency quality. One factor affecting especially to the size and speed of the deviations is the power grid inertia. Notable is also the connection between inertia and frequency quality, as the inertia decreases, the frequency deviations grow, posing a higher pressure to the frequency control units, such as hydro power.

Inertia is a term that can be used also in other contexts. The basic definition of inertia is “the resistance of a physical object to change its state of motion” (Statnett et al. 2016, p. 35). Inertia represents the amount of energy stored in kinetic form in to the object. As the Nordic power system is synchronous, the generators producing electricity run at synchronous speeds. The rotational speed of turbine-generator system depends on the structure and electrical demands of the generator, but the rotational speed and grid frequency are always directly connected (Eq. 1). (Mathur et al. 2011, p. 50.)

$$Rotational\ speed = \frac{Grid\ frequency}{2 \cdot No.of\ poles} \tag{1}$$

As there is a direct relation between the grid frequency and the rotational speed of the turbine-generator (TG) system, it can be seen that the rotational speed of the TG system affects to the grid frequency and vice versa. Of course, in this case the Nordic power grid is so vast compared to the generator that the affect to the grid frequency by a single TG unit is nominal, but the grid frequency still affects to the rotational speed. When the grid frequency deviates quickly, faster than the generator governors can react, the rotational speed of the generators does not deviate as quickly, because of the inertia stored in the rotating TG unit which has a certain mass.

The value of inertia itself can be calculated using the mass, m, radius, r, and angular velocity, ω, of the rotating object. The kinetic rotational energy, KE, here referred as inertia, can be calculated using Eq. 2. (Georgia State University, 2016.)

$$KE = \frac{1}{2} \cdot I \cdot \omega^2 \tag{2}$$

In which the rotational inertia, I, can be expressed as (Eq. 3). (Georgia State University, 2016.)

$$I = m \cdot r^2 \tag{3}$$

From the Eq. 2, the kinetic rotational energy can now be calculated when the mass, radius and rotational speed of the TG system is known. The amount of kinetic energy stored to the rotating TG system is also the amount of energy that will be dispatched to the power grid when power grid frequency drops, as the rotational mass releases its kinetic energy, or inertia to the power grid as it slows down. From the equations, it can also be seen that when grid frequency rises, the rotational speed of the TG system will change, but that change requires energy in same relation as the kinetic energy difference between different rotational speeds.

This amount of kinetic energy, either released or stored in power grid frequency deviations is referred as inertia.

As the physics behind the term inertia partly explained, the inertia truly describes the resistance of a physical object to change its state of motion, and in this context, it also describes the resistance of a TG system to change its rotational speed with the power grid frequency. This ability allows the TG systems connected to the power grid to regulate the grid frequency and to cut down high frequency deviations.

A good example of the affects of inertia in power system is illustrated in Figure 3, where the deviations of frequency and power are shown in a case of a large generator disconnection from the power grid. One factor used to describe the changes is RoCof, the rate of change of frequency. (Statnett et al. 2016, p. 35.)

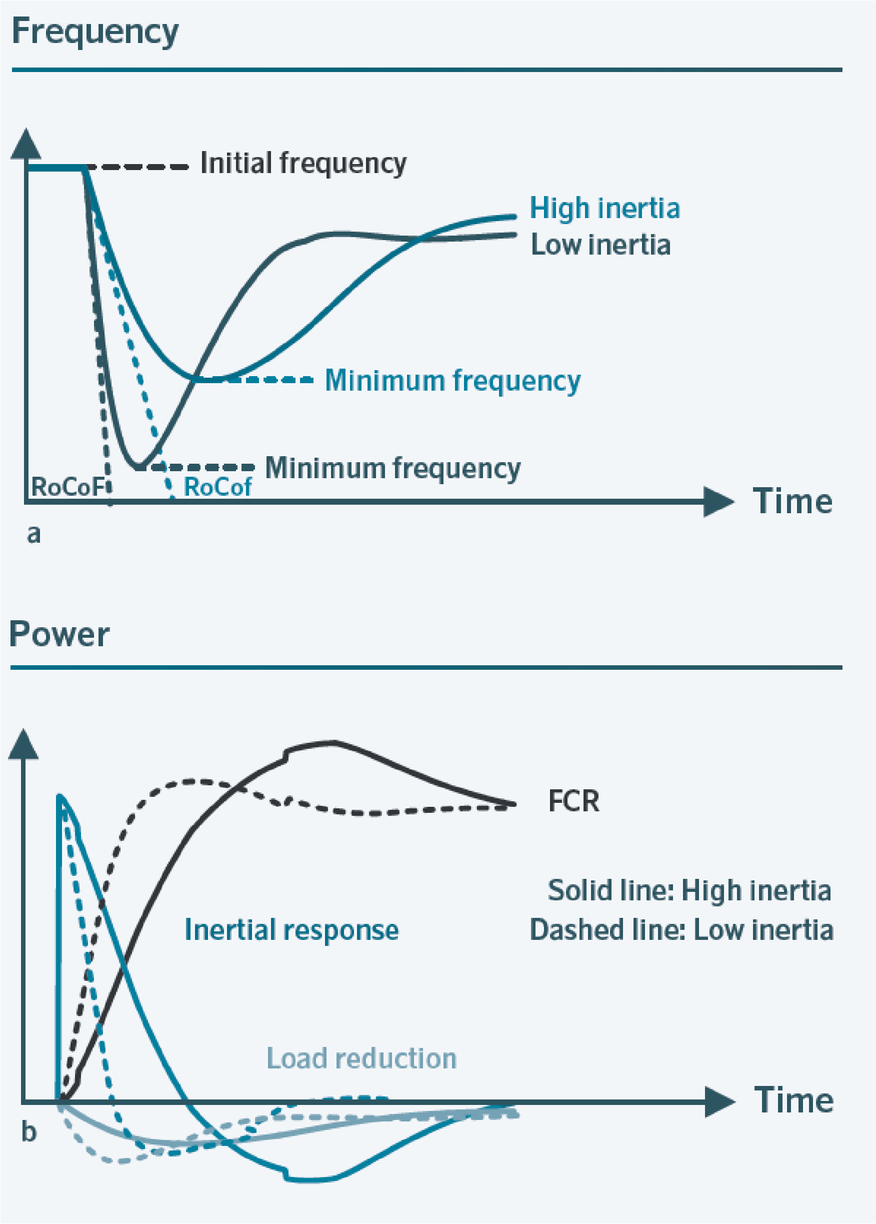

Figure 3. The differences in system frequency and TG system power output with high and low inertia after a generator trip (a) and different types of power responses with high and low inertia, with FCR products, Inertial response (kinetic energy) and Load reduction (b) (Statnett et al. 2016, p.35.)

One of the critical points of the Nordic power system frequency is considered to be 49.0 Hz. The highest load-shedding step occurs at 48.8 Hz, when the largest units will drop out of the power grid to save all electrical components, causing a total blackout, and the 49.0 Hz is seen to be the lowest point with a small margin still to the ultimate load-shedding. The system inertia helps preventing spikes in frequency not to reach these load-shedding values. As seen from the Figure 3 the grid frequency behaves a certain way in the moment of large generator disconnection. The lowest value of grid frequency is quite quickly surpassed as the power grid control systems such as FCR-N and FCR-D start working, but there is always a delay in these systems, which enables the frequency value to spike downwards. This is enough to trigger the load-shedding. (Statnett et al. 2016, p. 35-36.)

As seen from the equations described earlier, the mass and rotational speed of the TG system determines the inertia, and that is one of the key reasons the inertia is at stake. As the megatrends continues to affect on energy policies, the amount of VRES in the Nordic power system will continue to increase, which will reduce the amount of inertia connected to the power grid. Conventional PV solar power naturally has zero inertia due to the fact it has no system which would resist the change of frequency. Wind power however does have a rotating turbine, but the turbine is often connected to the grid via power converters, which eliminates the possibility for actual inertia. The wind turbines connected directly to the grid are capable of producing inertia (Muljadi et al. 2012). The affect of VRES and HVDC import energy to the system inertia can be seen from Figure 4.

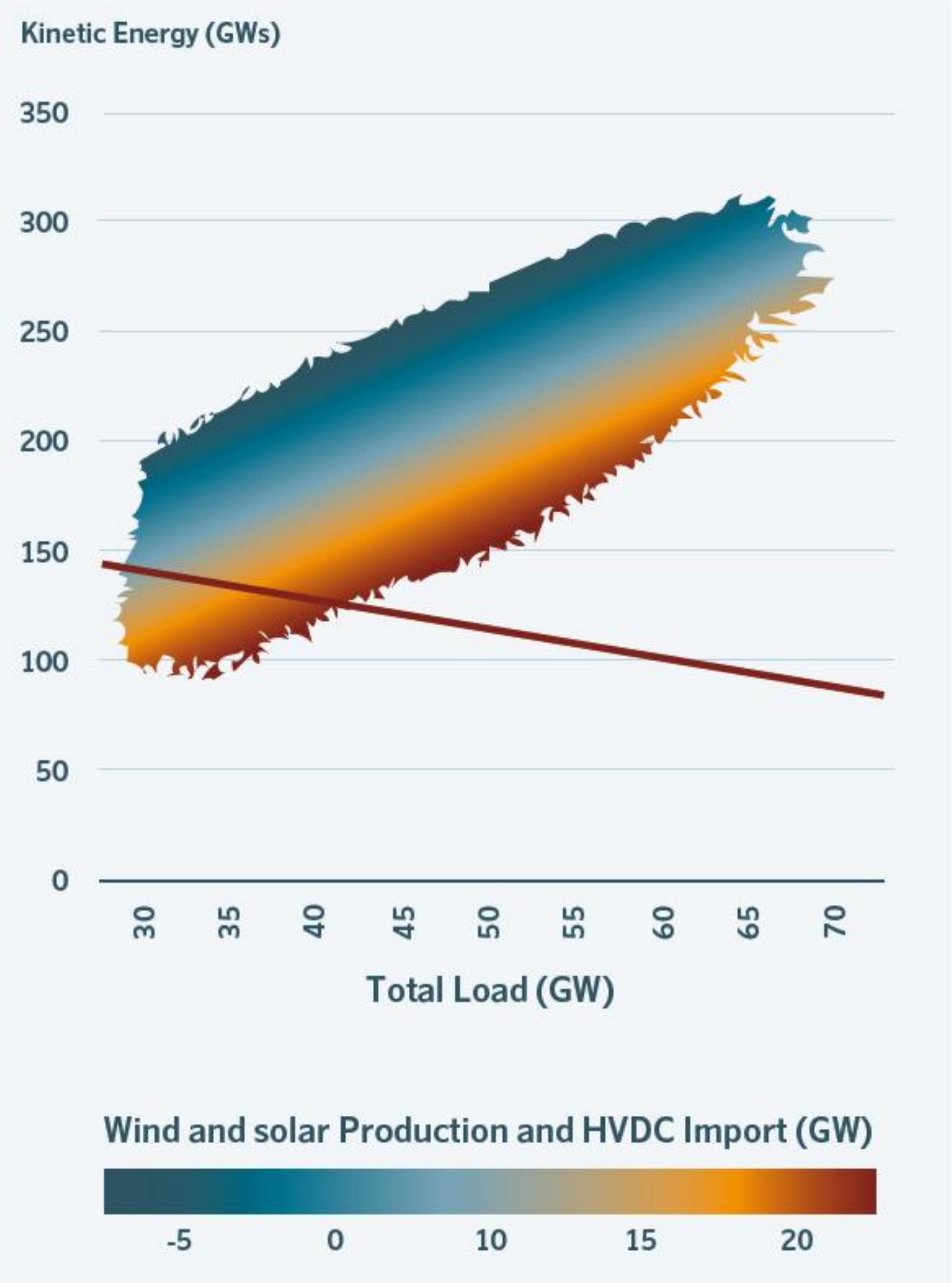

Figure 4. The estimated amount of kinetic energy, or inertia, in 2025 as a function of total load in the Nordic power system. Red line describes the required amount of kinetic energy required by assumptions by Statnett et al. (Statnett et al. 2016, p. 38).

The most dangerous points for power system tripping due to load-shedding are summer days. During summer the energy consumption is small, which leads to low energy prices and energy production with VRES such as PV solar power and wind power. The part of solar and wind power in production capacity can grow to be significant. At this point the inertia of the power system is at its lowest point, and a relatively small disconnection can trigger the load-shedding. (Statnett et al. 2016, p. 36-39.)

2.3.5 Transmission adequacy

The European Energy Union has set a target for interconnection capacity between countries. This interconnection capacity is measured in relation to the national production, and the target value has been set to 10%. The target value has been achieved by the Nordic countries (Statnett et al. 2016, p. 42). However, the congestion is a major problem in the Nordic power system. In the Nordics, there are different types of bidding zones, with some of bidding zones having a major energy over production and some bidding zones a major energy consumption.

This leads to large quantities of energy transfer between bidding zones and thus congestions. In Figure 5 the transfer links are illustrated with the congested hours annually. From Figure 5 it can be seen that on some years the most congested transfer links are under a heavy load for a major part of the year. The long periods of inter Nordic power link congestion leads to a situation, where the flexibility of the power system is crippled. The incapability of providing excess power to a certain bidding zone in the case of fault in power system, means that some of the bidding zones are experiencing a higher risk of a blackout (Figure 5).

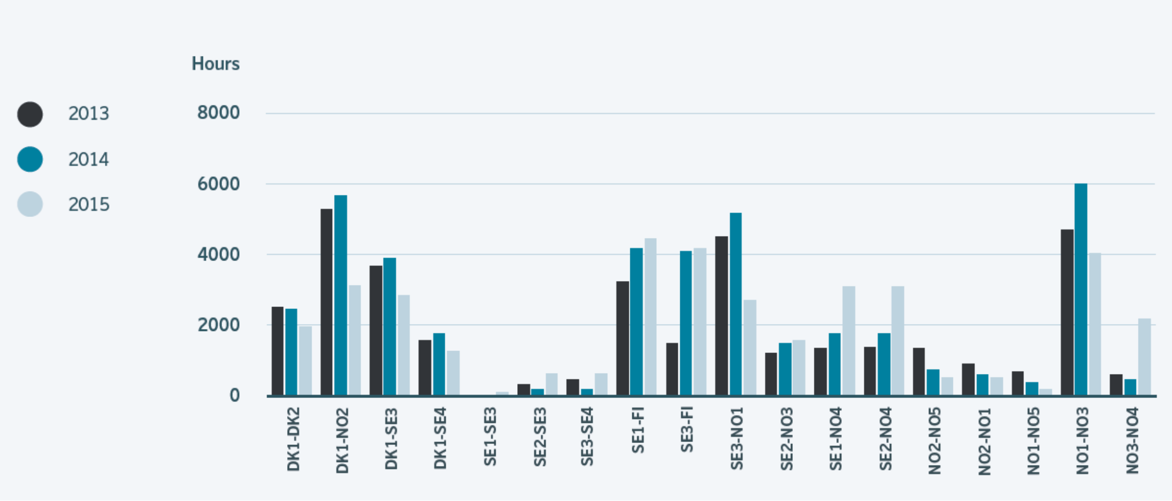

Figure 5. The inter-Nordic power system transfer link congestion hours. (Statnett et al. 2016, p. 43).

In multinational joined and co-owned power system, the transmission of electricity plays a major role. As the places of electricity production and consumption varies a lot in the Nordic countries, due to large power plant spread to areas of less inhabitation, the transmission system can be under a lot of stress. The generalized idea is that the power is produced in the northern part and consumed in the southern part of Scandinavia. Due to the nature of the Nordic power market, the countries have been divided to bidding zones. Each bidding zone has its own market price for electricity, and the prices differ because of the transmission capabilities. In an ideal market condition, all the bidding zones would have the same market price. In this case, there would not be any transmission restrictions or congestions. The different bidding zones are illustrated in Figure 6. (Statnett et al. 2016, p. 40.)

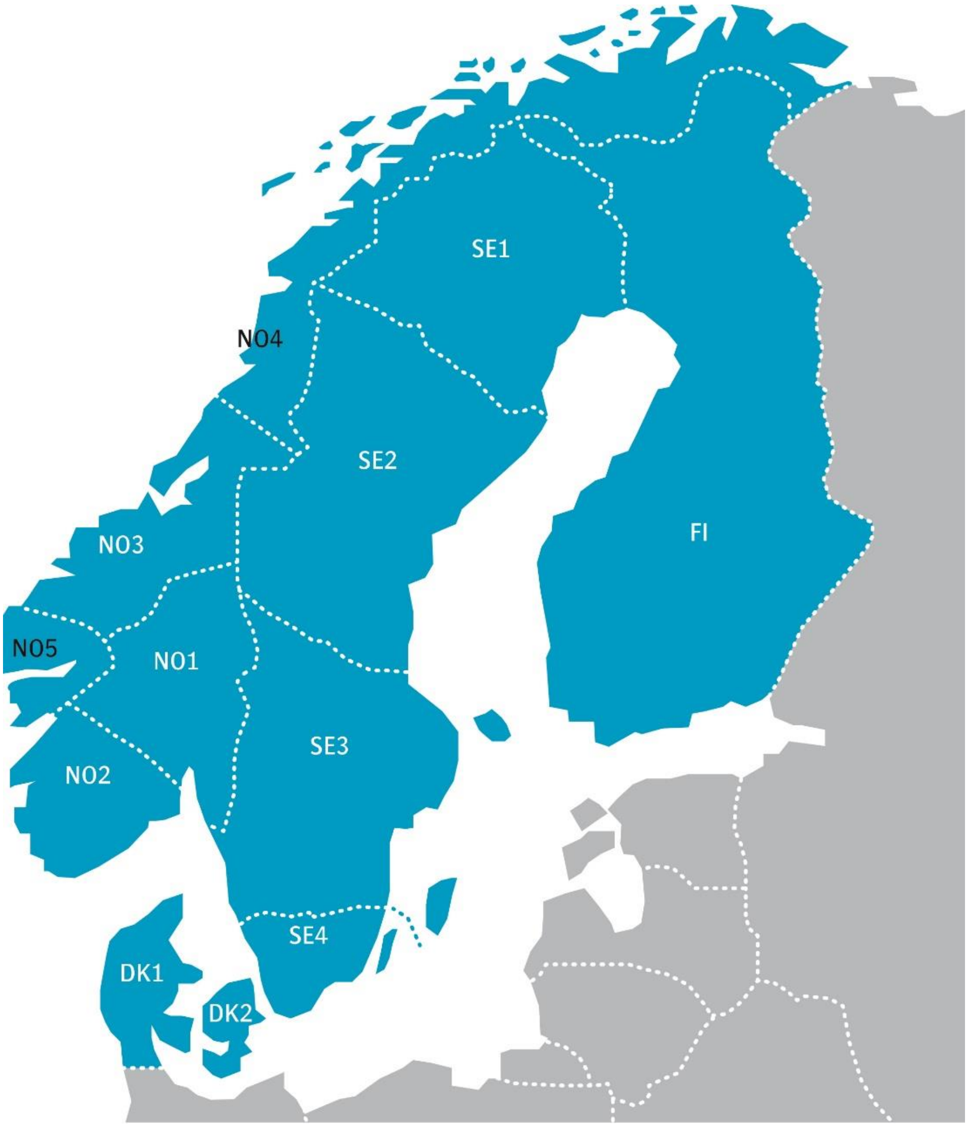

Figure 6. The Nordic power market and different bidding zones. (ResearchGate, 2016)

2.3.6 Solutions offered

The solutions offered for these challenges can be divided in to two categories. The first category is focused on the electricity markets and solving the issues by using different kinds of market incentives and products, to achieve wanted state. The second category is more technical, and the solutions are often based on technical development or new technical ways of power grid management. Both solutions need also political support, as the price formation and technical changes are usually controlled by the existing grid and market, which is already heavily influenced by policies.

The updating of FCR test demands and product specification is one solution to presented challenges. However, the updating of test demands and product specification cannot tackle all the challenges, and in some cases the solution is diverse, and requires actions from multiple different perspectives. Many of the presented challenges pose an indirect need for more precise and controlled FCR products. As the type of demand and production change, it is increasingly difficult for the demand and production to be planned with such accuracy that they will always meet, this means in practice that there will be more demand for frequency control products. This types of challenges and some direct solutions offered are presented below.

The challenges with system flexibility are considered to take care of itself to some extent. The market based solution relies on the fact that the increased short term price volatility and higher prices in balancing markets provide enough incentives that the producers will follow the market trend and the flexibility will increase. However, as there is always some uncertainty how the market will behave and how the future electricity production will be divided between flexible and inflexible power production, also technical solutions have been offered. For example, the more efficient utilization of transmissions capacities and more controlled HVDC linkages are possible solutions for flexibility dilemma. (Statnett et al. 2016, p. 20.)

The generation adequacy dilemma discussed in chapter 2.3.2 is a good example of a challenge, the solution of which requires assistance from Nordic or European level. The tools the TSOs have at use, are mainly developing the market to a way that allows higher participation of consumers to adequacy through incentives like supply security, and the development of inter Nordic transmission links to create a more supporting system leading to better generation adequacy at Nordic level. The long-term solutions however need the right policies and incentives from Nordic or European level. The main drivers for decreasing generation adequacy are the high volumes of VRES to the Nordic system, which has so high subsidies that it forces the conventional energy production out of the market. To overcome challenges like this, new policies should be made and the overall energy policy should be driven into direction that takes in account also the arisen challenges in the Nordic power system. (Statnett et al. 2016, p. 27.)

There are multiple ways of improving the frequency quality. Some of them are market driven and some more technical development and regulation. An example of market and technology driven solution is achieving the adequacy of frequency control and reserve capacity. To achieve the sufficient capacities, the market should drive producers into providing capacity by offering a new market for control products or by offering incentives high enough. On the other hand, technology is keenly present as new methodologies for producing frequency regulation are developed (Statnett et al. 2016, p. 32-33). This thesis will go into further detail about the new frequency quality improvement project by the Nordic TSOs. This project renews the old regulations and demands for frequency containment reserve production, thus changing the way the power plants will operate (ENTSO-E, 2017). This good example of technology driven solution to improve the frequency quality will be thoroughly explained in the chapter 4.1.

As mentioned before for the system flexibility, same kind of issues are also in the background of inertia dilemma. The inertia is decreasing due to legislation oriented development in the power system and the short-term options for increasing inertia are not that viable. If the current policies hold, and the development continues as the current trend shows, the options for upcoming the inertia challenge should be planned and executed during a longer time period. Some considerable ideas are the adding of additional inertia through usage of synchronous condensers and the usage of synthetic inertia. These could be genuine solutions with which the inertia level of the power grid could be raised to adequate level. However, more research needs to go into the solving the existing amounts of inertia and the actual need, before any long-term actions are taken. (Statnett et al. 2016, p. 40-41.)

Even though the transmission adequacy challenge affects to the need of FCR products, the challenge should be dealt with annual investments to the power grid. In addition to this further analysis and modelling of the power grid could lead to enhanced transmission situation. (Statnett et al. 2016, p. 49.)

2.4 60 second oscillation

In addition to the challenges the Nordic power system is facing, there is a completely different type of challenge, which lies under these previously mentioned challenges. As stated, the frequency quality of the Nordic power grid is deteriorating. The frequency control products (Chapter 2.2) are used in normal operation to maintain the nominal frequency value of 50.0 Hz. This is done mainly using hydropower.

In 2010 the Nordic TSOs formed a work group to find out if there would be a need for a new control product, aFRR. It was known due to testing done before, that the whole Nordic power system is oscillating at a 60 second time period. After the control product research, more attention was paid to oscillations to enhance the power grid frequency. TSOs were familiar with different types of oscillations in the power system, as at some cases the frequency could oscillate between different countries due to generator groups oscillating between each other, but this was found out to affect the whole power system in every Nordic country. (Kuivaniemi et al. 2018.)

In further research conducted by the Nordic TSOs, it was concluded that some hydropower plants in the Nordic countries providing the frequency control products have such turbine control settings that they in fact cause frequency deviations instead of providing frequency control. However, this was pointed out to be partly faulty information, as the finding of these unwanted hydropower plants turned out to be a hard task. At the same time, it was revealed that in fact the Nordic TSOs had slightly different types of interpreting the set regulation for existing FCR products, which had led to different types of hydropower plant control systems. (Kuivaniemi et al. 2018.)

This problem had lied beneath the previously presented challenges as the solution, the control product, was found to be broken. This can now count as a challenge for the Nordic power system, and the solution is to unify and remake these FCR products. To some extent corrective actions on this problem will affect on every challenge listed in previous chapter. The full explanation on the process, changes and goals is provided later in this thesis in chapter 4.1.

3 HYDROPOWER PRODUCTION

To fully understand the methods used in the Nordic countries to produce frequency regulation, it is important to understand the process behind the power production. Understanding the hydropower process also enables further analysis on the upcoming change in the FCR regulation.

Power derived from running water is among with fire the oldest ways of producing energy. Hydropower plants have developed into massive facilities producing some 16% of world's total electricity, and in some areas hydropower can cover up to 100% of electricity production, like in Norway (Mathur et al. 2011, p. 13). Hydropower plays a major role in the fight against climate change, providing the crucial balancing electricity production for the demand created by other more variable renewable energy sources (VRES) like wind and solar (Endegnanew et al. 2013, p. 62-63). In this chapter, the basic hydropower plant types are described and the basic components of hydropower plant defined.

3.1 Presentation of hydropower plant types

Hydropower plants are divided in three different ways using either the size of the power plant measured in megawatts (MW), the type of the power plant or the type of turbine in use at the power plant. In Figure 7 power plants are divided by the type of the power plant. The three main types of hydropower plants are run-of-river power plants (RoR), storage power plants and oceanic power plants (Mathur et al. 2011, p. 6). This thesis focuses on Finnish hydropower plants so only RoR and storage power plants are analyzed. As seen in Figure 7 the turbine types used in RoR and storage power plants are Kaplan, Francis, Propeller (or bulb) and Pelton turbines. These turbine types have different qualities and some of them are more used with high flowrates and small elevation drop, and other with small flowrates and high elevation drops (Figure 9).

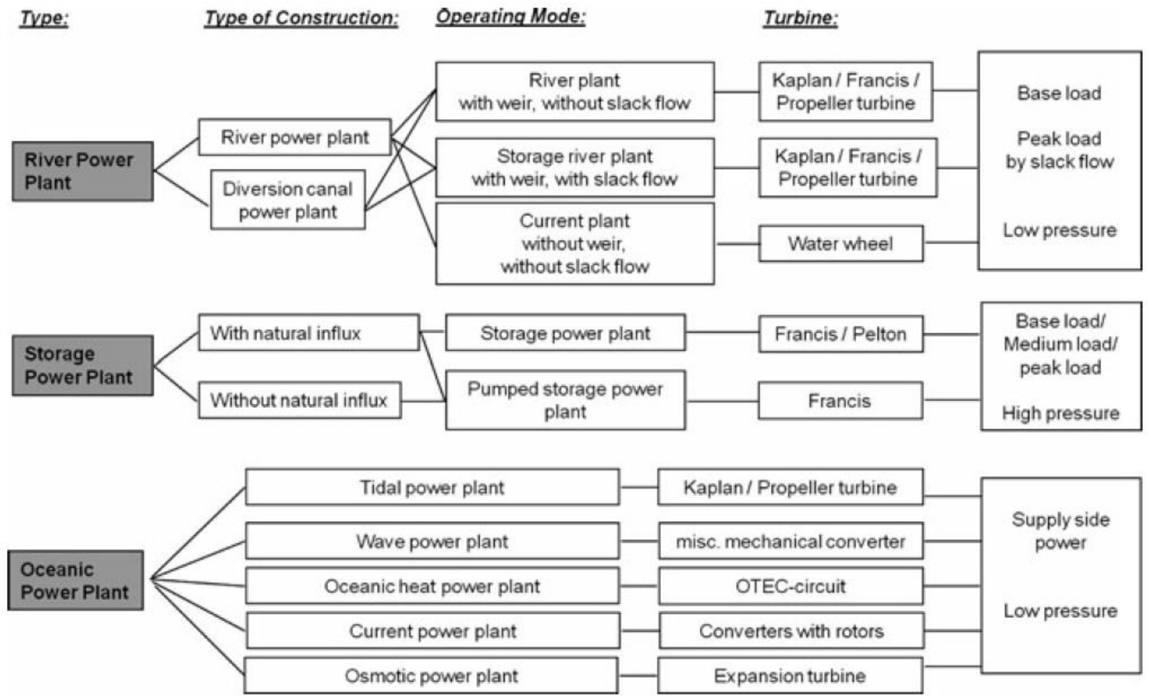

Figure 7. The different hydropower plant types divided by the type of construction, operating mode and turbine (Mathur et al. 2011.)

In Finland, all hydropower plants either owned or operated by Fortum have bulb-, Kaplan- or Francis turbine installed. This thesis in focused on Kaplan turbine powered hydropower plants. As can be seen from Figure 9, the turbine type scrutinized in this thesis have a high correlation with elevation drop, also called as hydraulic head or head, which allows operation in different types of locations.

The location of hydro power plant affects on the structure of the power plant. Almost all existing hydro power plants are different and tailor-made to match the current location. This creates a large variety of different types of power plants, even though the main principle might be same (IEA, 2012 p. 11). The location, riverbed and elevation changes are features that make hydro power possible, but these features also restrain the possibilities.

3.1.1 Run-of-river power plants

Run-of-river power production is located in a river, which creates usually a stable flow rate and elevation drop for the power plant. There are three different options for a RoR type power plant, which are determined by the surroundings. As seen in Figure 7 RoR can operate as *river plant*, *storage river* plant or as *flow current plant*. In the first example river plant has a structural weir or a dam, but the surrounding environment or regulation does not allow building up a storage. The constructed dam allows the hydro power plant to gain a little amount of hydraulic head as the level of the river rises upstream of the power plant, but to keep the water level at safe or regulated limits, the flowrate must be high enough at all times. (Mathur et al. 2011, p. 5-6.)

Another type of RoR power plant is the storage river plant in which the regulations or environmental aspects allow the hydropower plant to build up some storage upstream the power plant. This storage allows the hydropower plant to work more flexibly, but in most cases storage in RoR plants is not significant. Last type of RoR power plants is the flow current plant, which lacks the whole dam structure, thus making it possible to only exploit the natural flowrate and hydraulic head of the river. (Mathur et al. 2011, p. 5-6.)

Sometimes it is possible and feasible to build a cascading system to a river. Cascading system consists of several smaller hydropower plants which can be operated separately. This is likely to increase yearly energy production capacity of downstream power plants and this can help power output speed when operating the cascading system as a whole energy production entity (IEE, 2012 p. 13). The nominal output power of RoR power plants can vary a lot. In Finland there is RoR power plants ranging from output power of 192 MW, Imatra hydropower plant owned by Fortum, down to hundreds of kilowatts. (Fortum, 2018; Pohjois-Karjalan Sähkö, 2018). The advantages of RoR is that the environmental impact is usually quite small. Storage power plants usually needs a lot of land area for the storage lake, but RoR operates in natural riverbed. Disadvantages are that when operated in natural riverbed and relatively small rivers, factors like climate affect a lot in power output and for example the amount of rain does not correlate with the power demand, making the RoR somewhat variable source of energy. (Mathur et al. 2011, p. 6-7.)

3.1.2 Reservoir power plants

Storage power plants, or *reservoir* power plants, are the other hydropower plant type that is widely used. Storage power plants can be constructed to operate with natural influx of water or with artificial influx, or with combination of these two. Natural influx type is most common type, where the hydropower plant operates between water reservoirs with different altitude to form a hydraulic head. Artificial dam creates a large storage area or there can be even artificial lake upstream of the power plant. Natural influx brings water to this reservoir from smaller rivers, from melting snow or by other means. Natural influx storage plants can be constructed to an existing river, and then create the storage upstream, or in some cases if local conditions allow, the power plant can be constructed so that there is a lake upstream acting as a reservoir. (IEA, 2012 p. 12.)

Storage power plant can also be constructed without natural influx of water. These types of power plants usually require large hydraulic head, because the upper or lower storage is usually artificially constructed and thus has a rather small volume to store the water. When lacking natural influx of water, the influx has to be also artificial and it is done by pumping. These types of storage power plants without natural influx are called pumped storage plants or PSPs. In this type of energy production, the storage of energy is more important than base load production. (IEA, 2012 p. 14.)

3.2 Components of a hydropower plant

The hydropower plants can be divided into subcategories based on the water system they are located, as seen in the previous chapter. The hydropower plants can be divided further in specific hydropower plant components, which are all needed to form a solid hydropower production process.

To understand the function of a hydropower plant component, it is important to understand the physics behind the function. By understanding the basic physics of the hydropower process, further analysis can be done on each component and its affect to the end result of the power producing process and effect in frequency regulation.

3.2.1 Hydropower physics

Hydropower is based on two energy sources of water, kinetic and potential energy of water (Mathur et al. 2011, p. 41-45). Kinetic energy can be described as energy due to movement of water, also known as water flow. Water flow rate Q is a physical quantity measured in cubic meters of water per second. Water flow, or flow rate, is defined by measuring the velocity of flowing water, v, through a pre-determined area, A (Eq. 4).

$$Q = v \cdot A \tag{4}$$

As described, the two quantities affecting the flow rate are velocity and cross-sectional area of flow. Eq. 4 determines the volumetric flow rate which does not count in the density, ρ, or the mass, m, of flowing material, so to accurately describe water flow rate instead of using volumetric flow rate, Q, mass flow rate, $\dot{m}$, must be used (Eq. 5). (Oertel, 2010, p. 60.)

$$\dot{m} = \rho \cdot Q \tag{5}$$

Potential energy E_{pe} is best described as the energy stored due to elevation or height difference. In this case, as water is up stream in reservoir or in river it has a potential energy as described in Eq. 6, where g equals as acceleration due to gravity and Δh as height difference between water at highest and lowest point of interest.

$$E_{pe} = \rho \cdot g \cdot \Delta h \tag{6}$$

Potential energy transforms to kinetic energy when descending from highest point of interest towards the lowest point of interest. At lowest point of interest all of the potential energy has transformed to kinetic energy. (Eq. 7).

$$\rho \cdot g \cdot \Delta h = \frac{1}{2} \cdot m \cdot v^2 \tag{7}$$

The combined affect of kinetic and potential energy can be expressed with Bernoulli's equation (Eq. 6). In the Bernoulli's theorem, the law of energy conservation, incompressibility of non-viscous fluid and steady flow are taken in account to define an equation in which the kinetic, potential and pressure, p, energies per unit volume are constant at any point (Eq. 8). (Oertel, 2010, p. 62-63.)

$$\frac{v^2}{2} + \frac{p}{\rho} + gh = constant \tag{8}$$

The maximum power that can be generated, P, can be calculated from Eq. 9

$$P = \eta \cdot \dot{m} \cdot g \cdot h \tag{9}$$

where η is the overall efficiency of the power station. (Mathur et al. 2011, p. 40-45).

From Bernoulli's equation (Eq. 7) and the incompressible nature of water, a continuity equation (Eq. 10) can be obtained.

$$v_1 A_i = v_2 A_2 = v_3 A_3 = constant \tag{10}$$

From continuity equation (Eq. 10) it can be seen that as the cross-sectional area of flow decreases, the velocity of flow must increase to fulfill the principle of energy conservation. This is a vital equation when considering the components of a hydropower plant. As the potential energy transforms to kinetic energy, the relative amount of kinetic energy increases, this is important because hydro turbine generates rotating movement from kinetic energy, which can be later turned into electricity.

3.2.2 The penstock and waterways

The penstock, or waterways, play a vital role when the potential energy of reservoir or upstream has to be converted to kinetic energy. Penstock (Figure 8) is a built channel for water to enter the turbine, and it acts as an element which steers the water to right way, and by gradually decreasing in cross-sectional area it also accelerates the moving mass of water, as expressed in the previous chapter in the form of continuity equation. Other important function of the penstock is to guide water flow in such manner that every part of the round inlet of the turbine gets the same amount of water inflow. This ensures the even distribution of water and thus stress. (Mathur et al. 2011, p. 45; 58-59.)

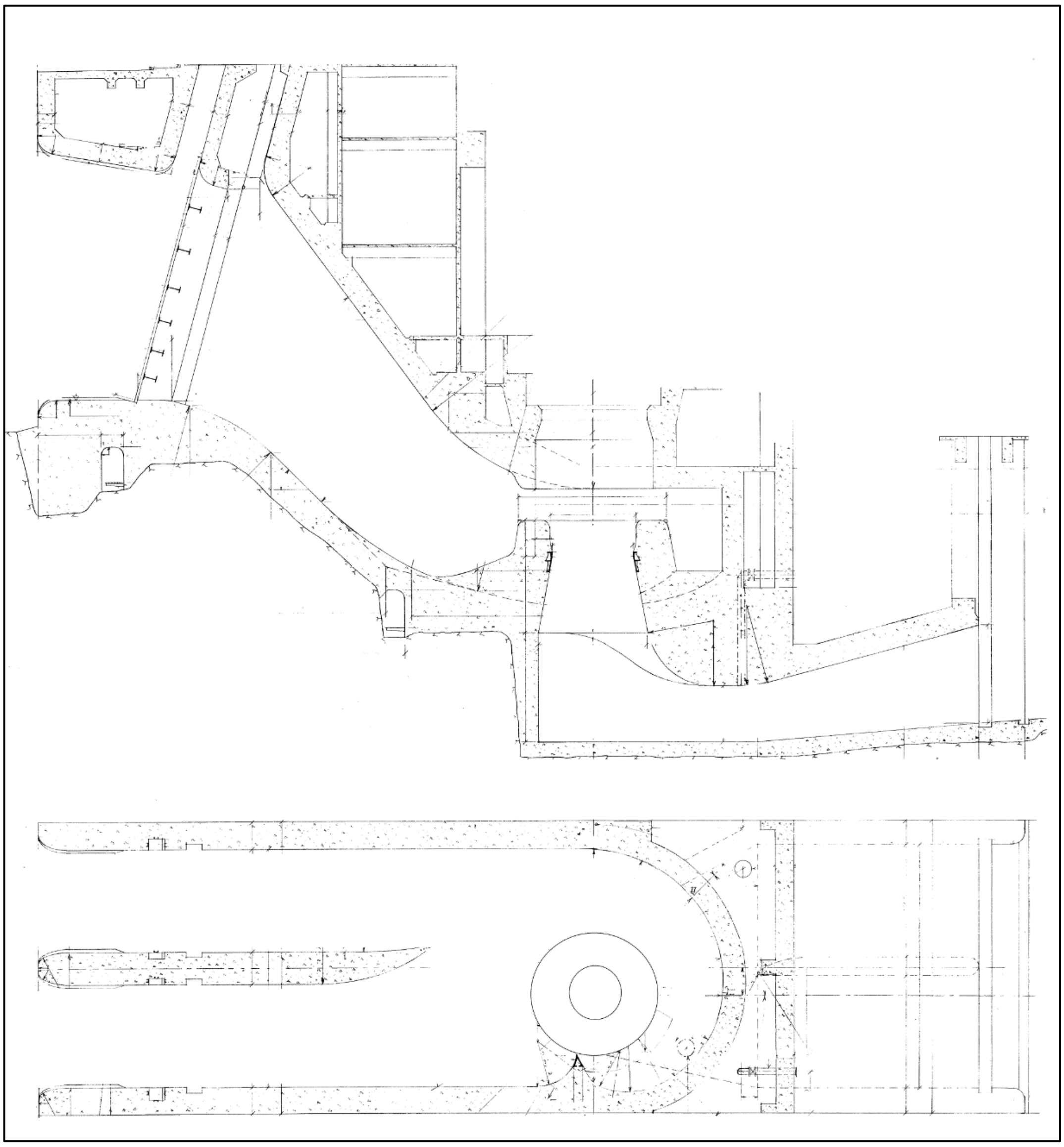

Figure 8. A figure of a hydropower plant penstock. Figure features vertical and horizontal cross sections.

3.2.3 The guide vanes and distributor ring

From penstock water is led to turbine using guide vanes. Guide vane system includes distributor ring, guide vanes, stay vanes and stay ring. Guide vanes are installed in spherical form around the turbine pit. Each vane has individual shaft which connects to stay ring at the bottom, and to distributor ring at the top. Distributor ring is fixed to each guide vane with linkage arms, and as the distributor ring is turned with hydraulic cylinders, the guide vanes turn also in fully synchronized method. Between stay ring and distributor ring there is also some fixed vanes. Guide vanes and fixed vanes form a closed sphere when fully turned, preventing the water from flowing to turbine, thus allowing for example to run the turbine to complete stop. With guide vanes, the amount of water entering the turbine can be accurately controlled. (Mathur et al. 2011, p. 66-70.)

3.2.4 The turbine types

The most notable feature, which also has the largest impact on hydropower plant behavior, is the turbine, also known as *the runner*. There are several types of turbines used in hydro power production, the most common being; Francis turbine, Kaplan turbine and its variations and Pelton turbine, all named after their inventors. The main differences between these different types of hydro turbines are the operating points. As seen in Figure 9 some turbines perform better on low head and high flow rate and some vice versa. The conditions which lead to choosing a specific turbine type comes with the location of the power plant, but there is also some exceptions. As seen in Figure 9 there is overlapping zones between the runner types. In addition to different operating zones hydro turbines have also differing features which can be used to advantage when choosing between two overlapping turbine types. (Mathur et al. 2011, p. 71 – 93.)

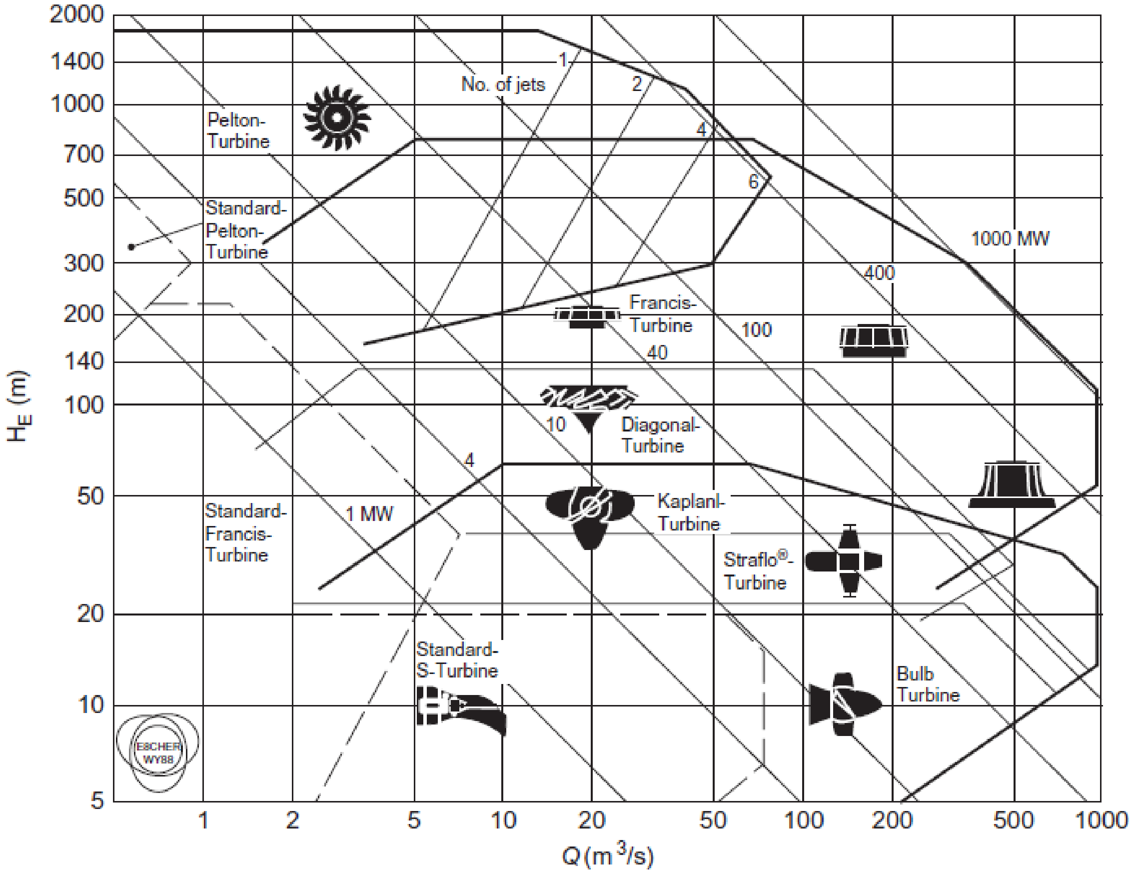

Figure 9. Turbine types presented with operating head (H_E) and flowrate (Q) (Steller, 2013).

The key difference between different turbine types is the way the water passes through the turbine, and the thus the way the energy is transferred from the water to the turbine. Most common turbine types are axial flow turbines, radial flow turbines, mixed flow turbines and crossflow turbines. (Mathur et al. 2011, p. 71 – 93.)

<u>Axial flow turbines</u>

In axial flow turbines, the water flow is in axial direction compared to the turbine. Good example of axial flow turbines is the Kaplan turbine and its applications such as the propeller turbine. The axial flow turbines are also classified as reaction turbines. Reaction turbines base on the physical phenomena in which the water travelling alongside the turbine blade profile creates a pressure difference over the blade, giving it an initial force which makes the turbine rotate. (Mathur et al. 2011, p. 71-75.)

Radial flow turbines

Radial flow turbines, are consisted basically only on Pelton turbines. In Pelton turbine, the turbine itself is usually installed in vertical position, giving it the radial direction compared to the flow. Pelton turbines are also the main type of impulse turbines. Impulse turbines differ from reaction turbines in such way, that the water pressure does not change flowing through the turbine, but only in specific type of nozzle construction. In the nozzle the water enters the atmospheric pressure, thus having only atmospheric pressure while most of the hydrostatic pressure has converted to kinetic energy. The kinetic energy is then converted to rotational energy of the turbine. (Mathur et al. 2011, p. 71 – 73.)

Mixed flow turbines

Third type of hydro turbines is the mixed flow turbines. As the name suggests the turbine is neither axial nor radial, but both. For example, in the most common mixed flow turbine, Francis –turbine, the water enters the turbine in radial direction compared to the runner, but exits in the axial direction compared to the runner. The mixed flow turbines are also a part of reactive turbines classification. (Mathur et al. 2011, p. 72.)

As mentioned earlier, these turbine types have different characteristics and thus they operate on different types of hydraulic heads and different flow rates. Sometimes however these operating areas of turbines overlap, and then the turbine type can be chosen from two different types. For example, with nominal flow of $100\ {m^3}/{s}$ and a head over 20 meters, reading from the Figure 9, both Francis and Kaplan turbines are applicable. Now the task of choosing the more favorable turbine for installation arises.

The key difference between Francis and Kaplan turbines is that Kaplan turbines provide additional adjustment to power production by having fully adjustable turbine blades in addition to adjustable guide vanes. Adjusting the blades of Kaplan turbine is done with hydraulic control unit, or the *governor system*, by feeding more oil in to the turbine and more specifically into the servo cylinder located inside the turbine housing. The *governor system* is described more in the chapter 3.2.5. By feeding more oil to the turbine, the servo cylinder extends and turns linkages, which turns the rotor blades. Vice versa by feeding oil to other side of servo cylinder the cylinder compresses and blades turn to other way. By adjusting both the guide vanes and turbine blades, higher efficiencies can be achieved with broader rates of flow rate and head. This adds up to higher investment costs, but in some cases, when the circumstances in the river or water system are not constant or there is a need for power production in broader area of inflow or head, Kaplan turbine can be the choice (Mathur et al. 2011, p. 77-82; 87-89). This thesis covers only the Kaplan turbine, as it is the most common turbine type in Finland, and it provides certain challenges on the FCR production. The next important part of hydroelectricity production is the control unit used for operating the hydro power plant.

3.2.5 The governor system

One of hydropower plants most valuable parts nowadays is the governor system. The governor system can be divided in two parts, the hydropower plant automation and the hydropower plant control hydraulics. Automation system can be considered as the brain of the hydropower plant, which by following the current measurement values of process, predicts and corrects the upcoming changes in measurement values. The correction movement is done by using the muscle of hydropower plant, the hydraulic system. Hydraulic control system acts on base of automation control and with hydraulic control system guide vanes, turbine blades and rotation speed can be altered. (Fasol, 2002, p. 68-76.)

The control operations of hydropower plant can be divided to three levels (Figure 10). Highest level of control operations is the control system level, in which the control signals are processed and control initiated, and data sent to control interface, such as HMI, human-machine-interface. Next level of control operations is the control interface level. This level works between the highest level, control system level, and lowest level, process level, as a messenger, sending the necessary control signals from the process apparatus to the control systems. This level includes different types of starters, relays, instrument transformers, transducers and such. The lowest level of this process hierarchy is the process level. This level consists of pumps, valves, control mechanisms such as hydraulic servos and other. The primary function of this level is to behave as an actuator, which executes the received signals from control interface level, originally from control system level. (IEEE, 2006, p. 6.)

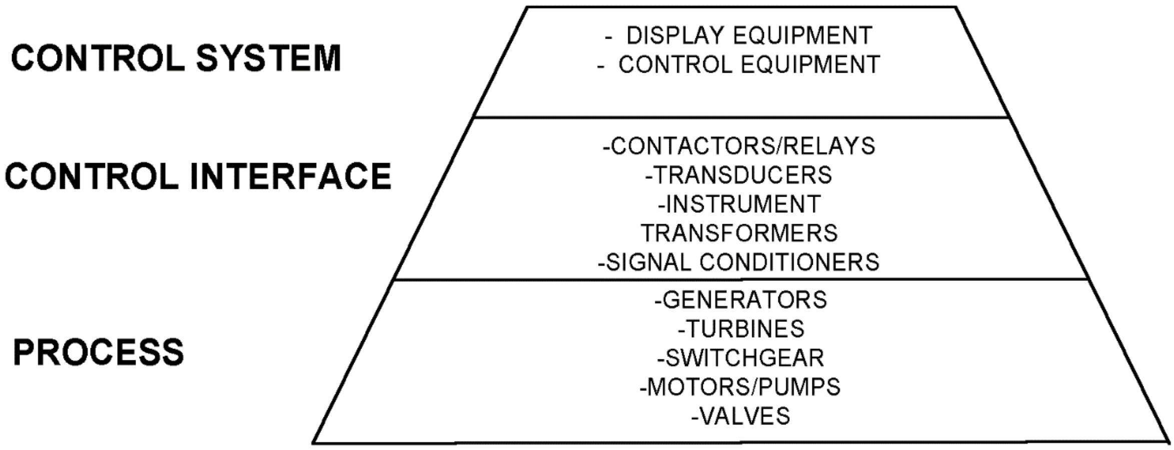

Figure 10. The Hierarchy of hydropower plant control system, stating the names of different levels and also giving examples on typical apparatus for each level (IEEE, 2006).

The control operations, adjusting power output and water flow, is actuated by the process level, which basically is an electrohydraulic governor. Electrohydraulic governor is a system which consists of hydraulic pumping unit, pressure tank, valves and hydraulic servo cylinders. The typical electrohydraulic governor operates together with hydropower plant control system level, automation system, which sends the set point values to the hydraulic governor. On the base of these set point values, hydraulic governor operates the guide vanes through distributor ring and hydraulic servo cylinder. By releasing hydraulic pressure from pressure tank to servo cylinder, the guide vanes can be closed, and by releasing hydraulic pressure from servo cylinder to pressure tank the guide vanes can be opened. The servo cylinder has a position censor, from which the automation system gets the “servo position feedback” value for additional adjustment. In hydropower plants with Kaplan turbine, same kind of method is also used to control the Kaplan turbine alongside the guide vanes. (IEEE, 2011, p. 27–29.)

3.3 Automation systems of hydropower plants

When operating in a power grid that changes all the time, with environment that changes all the time, the power output of the power plant needs to be altered as well. If considering only Francis and Kaplan –turbine powered hydropower plants, the power output correlates directly with the amount of water entering the turbine. The amount of water entering the turbine is controlled with guide vanes, which are revolved with distributor ring.

As discussed in chapter 3.2 Components of a hydropower plant, electrohydraulic governor acts in addition with automation systems as the “brain and muscle” of hydropower plant. More specifically the electrohydraulic governor is an electrohydraulic interface, which combines the automation system and hydraulic control system. The automation system acts as an operator which processes the data from different measurement points of hydropower plant, for example rotation speed of turbine, position of main servo cylinder of distributor ring and the position of Kaplan –turbine control linkage, and then compares the gained data to for example on set values or power output. This is called as a governor control system, which is based on feedback control. (IEEE, 2011 p. 2-3.)

The highest level in hydropower plant control hierarchy is the control system level (Figure 10). The typical control system level is built so that on top is the HMI, which is operated by a human operator. Below the HMI is the control system which includes both data and control. Data is gathered from the power plant and control is fed to power plant. The Figure 11 shows the typical control system arrangement, in which the interfaces and apparatus can be seen.

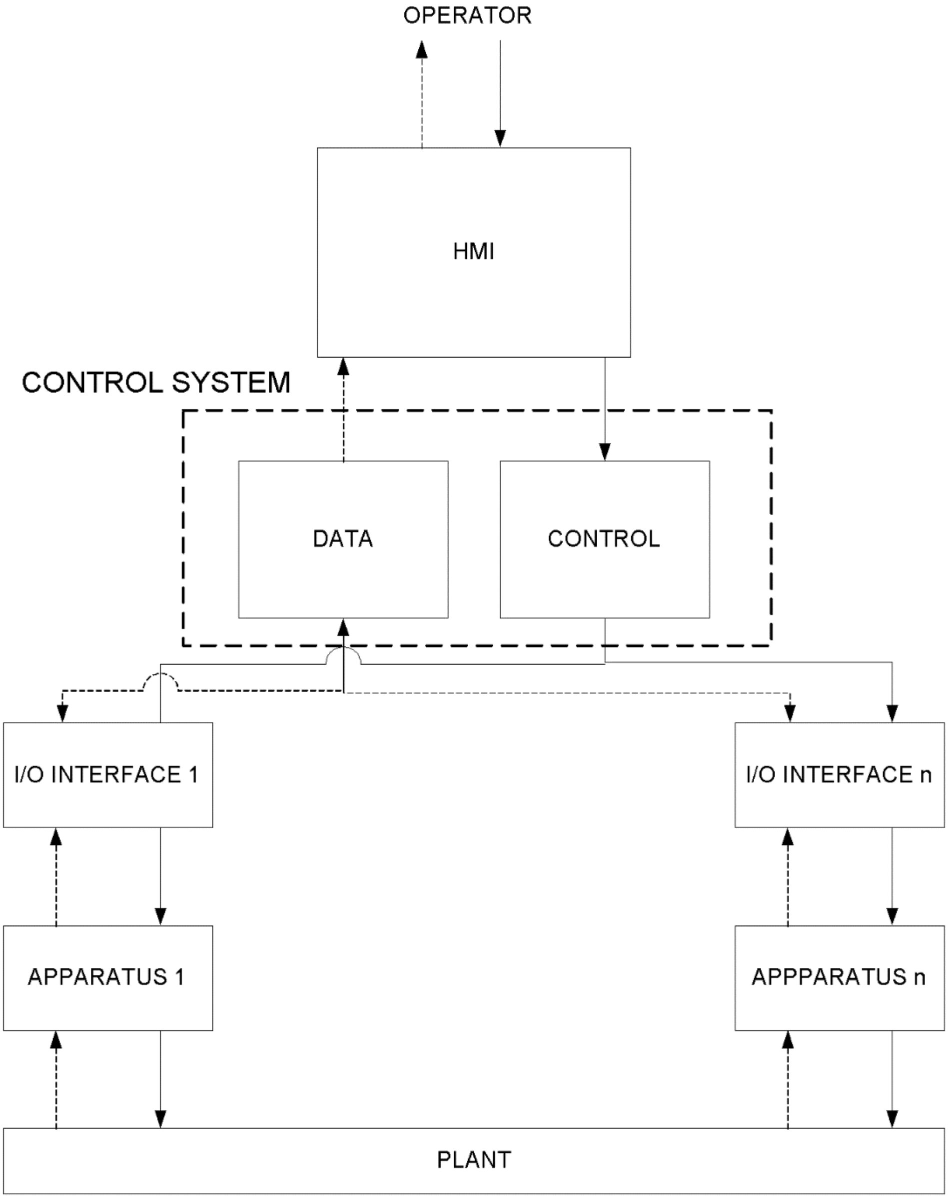

Figure 11. Typical control system arrangement and the control system components. The amount of apparatus and interfaces can change and exist on several levels (IEEE, 2006).

The main operation carried out by control system level is to balance with set points from the control interface and process system, and set points gained from the power grid connected. To operate in power grid with nominal frequency, the operating hydropower plant must operate at exact same frequency. The frequency of grid however varies all the time due to increases and decreases in demand, and therefore the control system level, or automation system, needs to give constantly control signals for the power plant to maintain the needed frequency. In addition to this variation, the surroundings of hydropower plant is varying, for example the water levels above and below hydropower plant vary due to natural in- and outflows.

As mentioned earlier, hydropower plants operate on feedback control (Figure 12), which in practice means that a set value is given, and to achieve this set value automation system sends a control signal forwards, which leads to a data signal received from different apparatuses. This process is repeated until the initial set value given from outside of the control system is received as a data signal from the apparatuses, meaning those are equal. (IEEE, 2006, p. 4-7; IEEE, 2011, p. 3-5.)

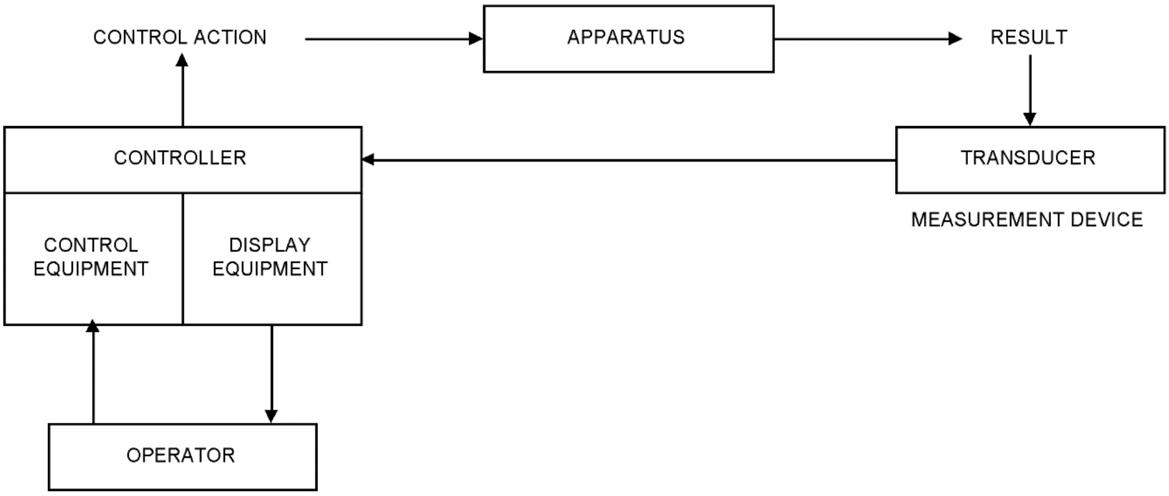

Figure 12. The closed loop feedback control system. The controller and apparatus form a closed loop, which can be influenced by operator through control and display equipment. The feedback is as a result given by apparatus, which is sent through transducer back to the controller (IEEE, 2006).

As the output power is the most valuable and frequently changed feature, and the correlation with power grid frequency is crucial, the system works directly between the frequency input (power grid frequency) and power output. The frequency of hydropower plant system is monitored and the most efficient way to adjust the hydropower plant alongside the power grid is to adjust on hydropower plant controls and monitor the affect they cast on the system frequency. There is two common ways of creating a direct control between a control signal input and frequency output. First option is to use the feedback on guide vane or distributor ring position, which indicates the amount of water flowing through turbine, and compare it to system frequency. This option is called *permanent speed droop* or simply just *speed* *droop*. Other option is to use the feedback gain from system power output and compare it to system frequency, this option is called *power droop*. (IEEE, 2011, p. 5.)

3.3.1 Droop

The droop value affects significantly to the produced power. Droop is used to describe the relation of the grid frequency deviation and hydropower plant power output deviation caused by it. This feature makes droop a control unit, which has a high impact on the hydropower plant operation.

Droop is an operator used for frequency deviation corrections in automatized governing systems. With set droop value, the control system of the hydropower plant is capable of adjusting its power output to match the deviation in the connected power grid. As mentioned earlier two types of droop exist in hydropower controlling. To define droop as an operator, it must be defined separately for both, speed droop and power droop, even though the purpose of both is the same. (IEEE, 2011, p. 6-10.)

The speed droop can be defined as the change in turbine-generator rotation speed, as a percentage of rated rotation speed, divided by the change in guide vane opening, as a percentage of distributor ring position (Eq. 11).

$$Speed\ droop = \frac{\Delta\ speed\ [\%]}{\Delta\ distributor\ ring\ position\ [\%]} \tag{11}$$

The turbine-generator rotation speed is directly connected to the power grid frequency as stated before.

The speed droop is best described as an example in which a hydropower plant operates in an ideal power grid. The ideal power grid is a power system in which there is a large interconnected power system, in which the output of single unit cannot have a significant impact on the system frequency. Now as the speed droop feedback loop (Figure 13) has been added to control system and given a set value of 4% droop, it can be defined that a 1% change in speed (which is 0.5 Hz on a Nordic 50 Hz power system) leads to a 25% change in load, which leads to 25% change in power production and thus in distribution ring position. (IEEE, 2011, p. 6.)

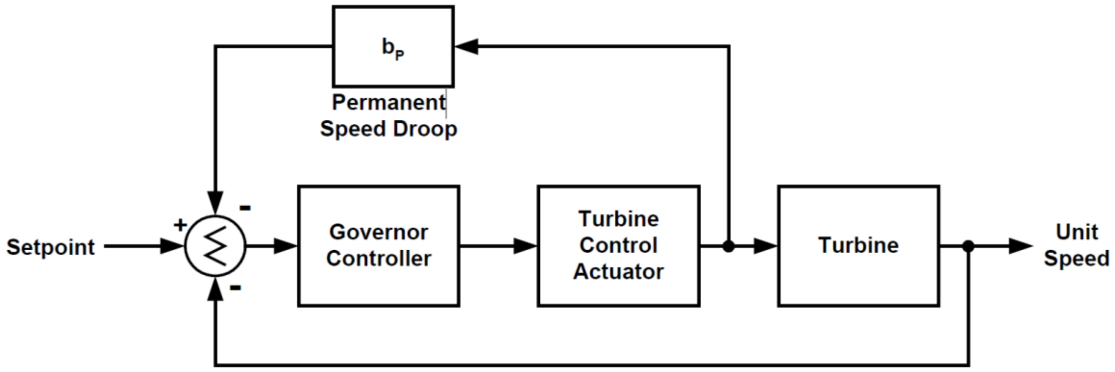

Figure 13. A permanent speed droop (speed droop) feedback loop added to a hydropower plant control system (IEEE, 2011).

As seen in the Figure 13, the control system needs a set point value, from with to operate the speed droop. The set point value can be for example set so that the system starts to react when a frequency deviation of +0.1% or -0.1% is achieved. The set point value can be used to control a large amount of hydropower plants, so that they will start operating gradually as the frequency deviates. Notable is however, that a hydropower plant fleet with speed droop operation, cannot restore the power system to way it was after a system disturbance. Speed droop helps to control the disturbance and to settle the frequency on power grid, but it won’t be able to set the frequency on same value it was before the disturbance on its own. (IEEE, 2011, p. 7.)

The power droop works with same principle idea than speed droop. The equation for power droop can be expressed as follows (Eq. 12):

$$Power\ droop = \frac{\Delta\ speed\ [\%]}{\Delta\ output\ power\ [\%]} \tag{12}$$

The power droop application works well if the output power is desired to keep constant while the circumstances like hydraulic head changes. This type of control allows also an accurate power output at desired time, but when operating in small grid or in an isolated system, the power droop setting can destabilize governor operation. (IEEE, 2011, p. 9.)

In Figure 14 the governing system with power droop setting is displayed in a block diagram. From this it can be seen that the working unit behind the power droop is actually a speed regulation unit, from which the power output is derived. As the power droop is based on power output value, synchronizing of this kind of unit can prove to be a difficult task, as the system cannot get a reference value on generated power, because its rotation speed does not match the power grids frequency, and does not produce any power to the power grid. It is quite common in this type of applications to run normal speed droop when synchronizing the generator and when producing a power output to power grid, changing the speed droop to a power droop. (IEEE, 2011, p. 9-10.)

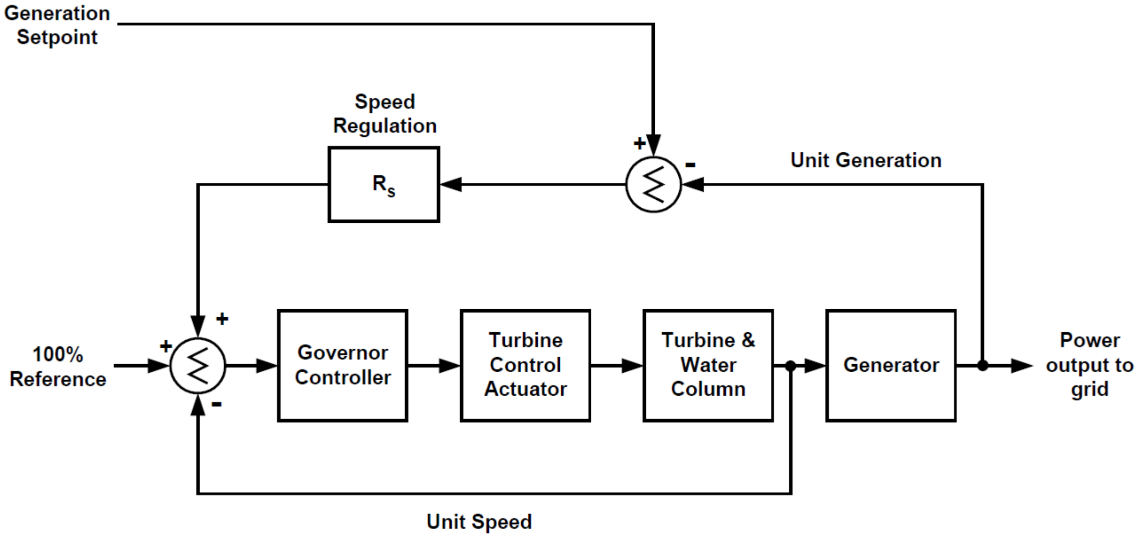

Figure 14. A speed regulation, also known as power droop, governing system as a block diagram (IEEE, 2011. p. 9).

3.3.2 PID -controller

As the basic physics and control mechanisms of hydropower plant have already been explained and established the only interesting unit left is the PID –controller. As the physical elements and hydropower plant components set the frame where and how the hydropower plant can operate, the PID-controller and its modifications and tuning set the actual way the hydropower plant completes its process of producing a certain power output.

To understand the operations needed, and the possibilities at hand when tuning the PID – controller for different types of operating situations, for example frequency control production, it is crucial to understand the mechanisms and algorithms which the PID –controller bases on.

The controller referred in this thesis is a proportional-integral-derivative –controller, also known as PID –controller. The PID –controller has been in use from the beginning of 20th century and has already a long history, but as the development of digital technology and software packages grow, there has been a significant amount of research also for new PID – controller applications. The PID –controller consists of three separate terms, which all process error input values to a command signal in different ways. (Visioli, 2006, p. 3.)

The proportional term produces a control action, which is proportional to the control error. (Eq. 13) The proportional control action can be described with a factor K_p, which is called a proportional gain. Proportional control action is an immediate response to a control error input, which is a positive ability. The proportionality provides also a benefit of avoiding excessive control. The proportional control has also drawbacks, which is why it often is seen combined with integral and derivative factors, main drawback is that proportional controller alone produces a steady state error. (Visioli, 2006, p. 4.)

$$u(t) = K_p e(t) + u_b \tag{13}$$

The term u_b refers to a bias term, which is used to model the steady state error. The u_b value can be set to a fixed level, or it can be adjusted manually until the steady state error is reduced to nothing. (Visioli, 2006, p. 4-5.)

The integral term of PID –controller produces an action which is proportional to the integral value of the control error. As in Eq. 13 the affect of integral action can be described with following equation (Eq. 14).

$$u(t) = K_i \int_{o}^{t} e(t)dt \tag{14}$$

In Eq. 14 the sub index of K_i refers to an integral gain. The past values of control error affect to the integral action. This feature allows the integral action to set automatically to the correct value of u_b, which reduces the steady state error to zero. Now with the proportional part and integral part, a PI –controller can be formed. In this setup, the integral part is also called as automatic reset, due to its action nature and ability to set the correct value for u_b. A basic concept of PI –controller is shown in Figure 15. (Visioli, 2006, p. 5-6.)

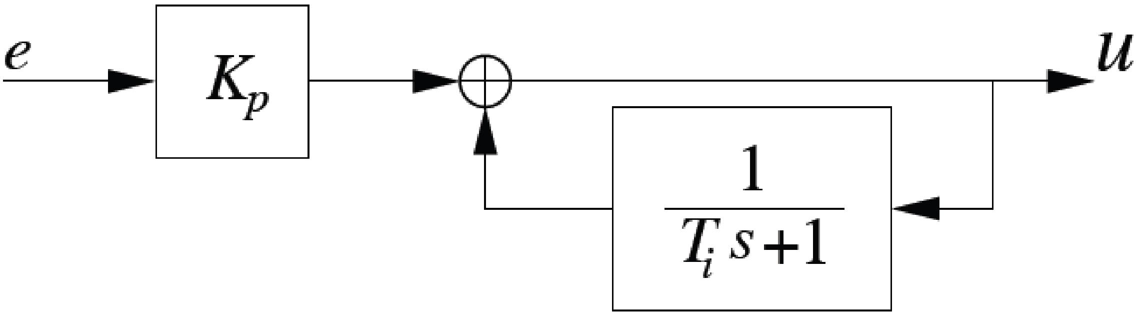

Figure 15. A typical PI -controller with automatic reset configuration (Visioli, 2006).

The derivative term is a bit more complex. Although the derivative term can have a great potential of improving the control performance, its complexity and few critical issues make it unsuitable for some practical cases (Visioli, 2006, p. 6). Derivative term can be used in fine tuning, or in cases where special attention is needed, but not usually in the basic models of hydropower controllers. (Byström, Interview, 22.2.2018.)

The derivative term can be described as following (Eq. 15)

$$u(t) = K_d \frac{de(t)}{dt} \tag{15}$$

Where the term K_d refers to a derivative gain. The deeper understanding of derivative action requires the understanding of Taylor series and the expansion of the control error at time T_d ahead (Eq. 16).

$$e(t + T_d) \simeq T_d \frac{de(t)}{dt} \tag{16}$$

And thus a control law proportional to this expression can be described as (Eq. 17)

$$u(t) = K_p \left(e(t) + T_d \frac{de(t)}{dt} \right) \tag{17}$$

which creates a link between proportional controller and derivative controller, forming a PD –controller. In this equation (Eq. 17) the control variable u at time moment t is based on the predicted control error value at time moment $t + T_d$. (Visioli, 2006, p. 6.)

Full PID –controller is illustrated in Figure 16 with K_i and K_d values in addition to K_p.

All of the proportional, integral and derivative parts can also be modelled with controller transfer functions and expressed with the proportional term K_p (Eq. 18, Eq. 19 and Eq. 20). (Visioli, 2006, p. 5-7.)

$$C(s) = K_p \tag{18}$$

$$C(s) = \frac{K_i}{s} = K_p\left(1 + \frac{1}{T_i s}\right) \tag{19}$$

$$C(s) = K_d s = K_p\left(e(t) + T_d\frac{de(t)}{dt}\right) \tag{20}$$

When modelling the function of the combined proportional, integral and derivative terms, the combined controller transform function (Eq. 21) describes the ideal, or non-interacting form. In this equation (Eq. 21) the proportional term is modelled with the proportional gain factor, K_p, the integral term is modelled with integral time constant, T_i, and the derivative term is modelled with derivative time constant, T_d. (Visioli, 2006, p. 7.)

$$C(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{21}$$

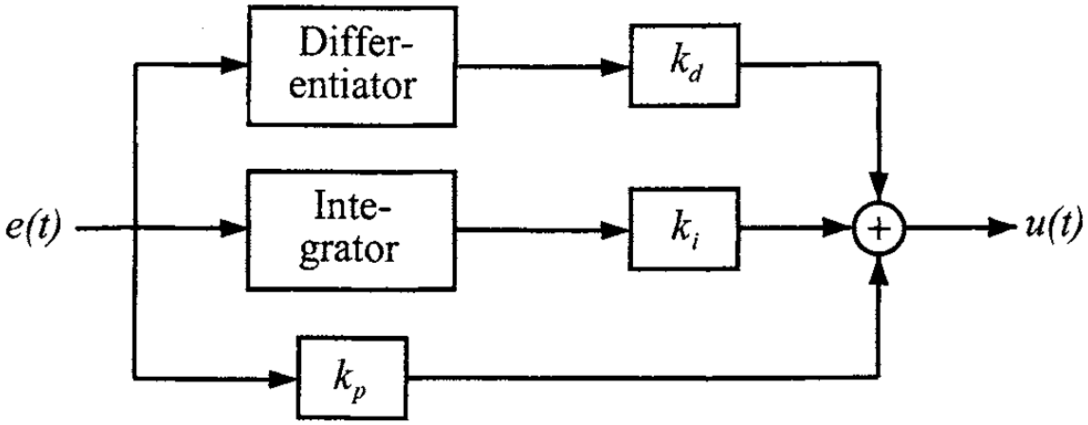

Figure 16. A full PID -controller illustrated as a block diagram. From the figure, it can be seen how all of the P, I and D components form the corrective signal u(t) (Silva et al. 2005).

The PID –controller system should be tuned before commissioning. The tuning is quite simple because all of the three values, P, I and D have a very distinct affect to the process. However, the balancing of these three values to gain the best possible process efficiency and accuracy can be tricky. Increasing of the P value, also known as gain, affects the most on bandwidth of the system and the increase in response speed, but also increase in the oscillatory factor of the system. Increasing the I value, also known as integration time, decreases the response time, but in the same time the system becomes more stable. Increasing the derivative time, or D value, gives the system a damping feature, but a too big D value will result in unstable system. As seen the tuning can also be tricky, and sometimes not all of the PID –values are even needed. Most common combinations on the PID –controller field are P, PI, PD and PID –types of controllers. To gain the highest cost-effectiveness only required amount of parameters should be added to the controller. In some cases, only the P -controller is sufficient, but as stated before, in most cases the fact that the P –controller carries a steady state error makes it insufficient choice. The PI –controller has a much more variability and an ability to set automatically the steady state error to zero. Therefore, the PI –controller is the most adopted controller in industrial context. The PI –controller is also in most cases a sufficient choice for hydropower governors. (Visioli, 2006, p. 15-16; IEEE, 2011 p. 15; Byström, Interview, 22.2.2018.)

4 FREQUENCY CONTROL USING HYDRO TURBINES

Frequency control in joined power systems consists of multiple different levels, or products. First level is the primary frequency control, called Frequency Containment Reserve (FCR), which reacts to frequency deviations in power grid. FCR principle is that power generating stations, which have sold a share in this product to the TSO in charge, provides additional energy output or reduced energy output proportionally to the frequency deviation, thus trying to maintain the nominal value of power grid frequency. The second level is the secondary frequency control, which is centralized and controlled by the TSO instead of independent energy producers. The secondary frequency control products are known as, Automatic Generation Control (AGC), Load Frequency Control (LFC) and Frequency Restoration Reserve (FRR). Main task of TSO controlled secondary frequency control is to restore the frequency back to its nominal value. (Saarinen, 2017, p. 14.)

As stated earlier in this thesis the VRESs are creating a growing need for power system balancing products. With the usage of PI and PID –controllers, Nordic hydropower plants have taken over of the most of responsibility for frequency control in the Nordic power grid, as the demand for power system balancing has grown. Hydropower provides a completely renewable option for frequency control, which can be carried out with higher efficiency than most other power sources. The installed capacity of hydropower in Nordic countries also provides large capacities for frequency control products, and the ramping speed of hydropower is faster than most other power sources. (Saarinen, 2014 p. 9.)

4.1 Present TSO requirements vs. new TSO requirements

As stated in the previous chapter 2.4, the Nordic TSOs are carrying out a change to the regulation and demands towards FCR-N and FCR-D frequency control product producers. Nowadays there is an almost unified set of regulatory tests which has to be completed to gain the permission to provide frequency control products. The tests determine if the TG system at hand is capable of frequency control, and to what extent, by also determining the capacity the TG system can offer to the TSOs. This chapter is going to analyse the present and new TSO FCR- production requirements and the changes between the requirements.

4.1.1 The present version of frequency control requirements

The present FCR tests are highly focused on power output capabilities. The mainline of the test is that the power output capacity sold, should be activated during a certain time with a certain rate. The third factor that is observed, in addition to power output and time, is the control dead band.

The dead band is used to limit the excess control movement of the turbine runner during FCR-N and FCR-D production. As described in chapter 3.3 the power plant control system works by measuring the power grid frequency and adjusting the power output accordingly. The grid frequency is in constant movement so one can imagine that the power plant control equipment such as hydraulics, would be under a constant stress. Dead band can be defined as a certain amplitude of power grid frequency deviation, to which the control system will not react. This allows the control system to rest in certain position and only react to a proper frequency deviation, which prevents the excess control movement. The excess movement is known to cause wear and tear on the control mechanics (Byström, 2018. Riikonen, 2018). The dead band maximum value is controlled by Fingrid to ensure the sufficient frequency control properties of a power plant. The maximum value of dead band is 50 ± 0.01 Hz (Fingrid, 2018d.)

FCR-N

The demands for FCR-N under the Fingrid transmission system in the year 2018 are straightforward. The power plant at hand shall adjust the power output linearly on the frequency zone of 49.90 – 50.10 Hz. The other main demand is that the full power output capacity sold to the TSO shall be activated fully as a result of 0.10 Hz deviance in 3 minutes. (Fingrid, 2018d.)

The accuracy used when delivering the FCR-N or FCR-D power output offer is 0.10 MW. Another piece of information the TSO needs from the FCR producer is the available capacity. Due to external factors, such as water inflow and the level of the reservoir the capacity of FCR product may deviate and this has to be informed to the TSO. The real-time capacity available, $c_{FCR-N,2018}$, can be calculated from Eq. 22. (Fingrid, 2018d.)

$$c_{FCR-N,2018} = \max[\min(P_{max} - P_{sp}, P_{sp} - P_{min}, c_{test}), 0] \tag{22}$$

The factors are defined as follows:

P_{max} is the maximum power output capacity of the power plant at the moment

P_{sp} is the power output at the set point value of the power plant at the moment, indicating the current power output.

P_{min} is the minimum power output capacity of the power plant at the moment

c_{test} is the capacity proven by the FCR tests

To find out the capacity that can be offered to the TSO at a certain moment, the normal capacity has to be determined by TSO provided capacity tests. The time and place for the tests, in addition to the testing plan and basic operation principle of the control system has to be informed to the TSO, which is allowed to send its own employees to monitor the tests. The tests has to be documented. Lack of proper documentation might lead to rejection of the offer. The total error of the tests must be less than 10% and the register frequency for the documentation must be less than 0.2 seconds. (Fingrid, 2018d.)

The actual test is conducted as a step response test, where the power grid frequency input value is disconnected and new value is fed in using the testing equipment. The frequency is set to 50.0 Hz and then deviated + 0.10 Hz to value of 50.10 Hz. The power output is monitored for five minutes and the measurement for maximum power output is taken at three minute mark. After this the same procedure is done with decreasing the frequency value by 0.10 Hz to the value of 49.90 Hz. (Fingrid, 2018d.)

The tests are conducted with three nominal power output values, with which the power plant is capable of producing frequency control. Power output values are, $P_{\mathrm{min,o}}$, for the minimum power operating value when the FCR is desired to be offered. $P_{max,o}$, for the maximum power operating value when the FCR is desired to be offered and $P_{50\%,o}$ for the third value between the *min* and *max* values, which can be calculated with Eq. 23. (Fingrid, 2018d.)

$$P_{50\%,o} = P_{min,o} + \frac{P_{max,o} - P_{min,o}}{2} \tag{23}$$

With these power output values the tests can be finished and the result is three different operation points according to the nominal power output and two values for each power output for high and low frequency situations. After this power curves are drawn, which show the power increase in relation to the frequency decrease and vice versa. (Fingrid, 2018d.)

FCR-D

The frequency containment reserve for disturbances is tested in somewhat similar way. The deviation, or step, inserted to the frequency system in FCR-D test is -0.50 Hz so that the value of the frequency is set to 49.50 Hz. The deviance in power output is monitored for two minutes and power output is registered at 5 second mark and 30 second mark. The FCR-D shall remain active after the 30 second mark. The demands are that the power output activates in somewhat linear way on the frequency area of 49.90 Hz to 49.50 Hz. (Fingrid, 2018d.)

The real-time available capacity can be calculated with the Eq. 24 and must be provided to the TSO. (Fingrid, 2018d.)

$$c_{FCR-D,2018} = \max[\min\left(P_{max} - P_{sp} - c_{FCR-N,2018}, c_{test}\right), 0] \tag{24}$$

The testing for disturbance is only done in downwards in frequency value, as this is the realistic situation if a large generator drops off the power system.

4.1.2 The upcoming version of frequency control requirements

As stated before, the frequency quality of the Nordic power system has been decreasing and as the challenges listed by the TSOs show, the frequency is going to undergo even bigger deviations. The future predictions show that the need for frequency control is going to increase while the capacity for frequency control is decreasing. The efficiency of frequency control has to be increased to maintain sufficient power grid frequency quality.

Also one major issue driving towards new and more efficient frequency control methods is the 60 second oscillation found in the Nordic power system. The oscillation is claimed to be caused by hydro power plants with poor frequency control abilities. This means that the hydropower plants have been sufficient in frequency control by the testing done by present test methodologies. There are however factors in frequency control that the present tests fail to take in account, leading to poor control, which actually amplifies different types of oscillatory deviations in frequency value.

The process of renovating the FCR products started as TSOs came in to the conclusion that in order to reduce the oscillatory movement of the power grid frequency, the regulation needs to be corrected and further unified. The implementation of new FCR demands has two main drivers; the first is that a large scale process, which affects every hydropower plant producing FCR products, enables the elimination of old regulations. Old set of regulations had evolved in to an unwanted state, as the multiple interpretations of the regulations made the demands unfair between countries. The second driver is that the new regulations are planned so that the regulations guide the hydropower plant owners in to a more reasonable turbine control settings. The new settings will allow the hydropower plants to act more precisely in oscillatory situations. One of the ground rules of the new demands is that the power plant power output must be able to follow sinusoidal frequency deviations. (Kuivaniemi et al. 2018.)

However, the fact that the Nordic hydropower has the feature of producing oscillatory frequency deviations will not be eliminated with these new regulations. It is in the nature of the hydropower plant that it will always have some, inevitable delay in the power output. The new regulation set is implemented to decrease oscillatory movement drastically, but not to eliminate it. The schedule for implementing the new regulations are yet to be finished. (Kuivaniemi et al. 2018.)

The application for FCR has to be done every five years. The application shall include all items listed in the format created by ENTSO-E. (ENTSO-E, 2017a.)

FCR-N

The definition of FCR-N has remained the same. The frequency range in which the operation takes place is the same as present, 49.9 Hz to 50.1 Hz, and the capacity production must achieve 100% in both ends of the frequency range. (ENTSO-E, 2017a.)

The new test set can be divided in two subcategories, the performance tests and stability tests. The present tests do not take in account the impact of the stability factor to the frequency, but in the new test set there is a way of testing the stability of the power capacity release. (ENTSO-E, 2017a.)

The performance tests begin with a stationary performance requirements. The stationary performance requirements determine the overall capability of power plant for FCR production. The requirements are that in stationary state at 50.0 Hz, 0% of FCR capacity shall be in use. At 49.9 Hz 100% of capacity upwards shall be in use and at 50.1 Hz 100% of downwards capacity shall be in use. In the frequency area of 49.9 Hz to 50.1 Hz the control should be proportional to the deviation of the frequency change and thus somewhat linear. (ENTSO-E, 2017a.)

The next part of the testing is the dynamic performance tests. The base of the test is a sine form frequency input, which the power plant has to compensate as efficiently as possible. The sine tests include 10 different time periods for the sine wave, 10, 15, 25, 40, 50, 60, 70, 90, 150 and 300 seconds. Figure 17 illustrates the test procedure. The power plant stays synchronized to the grid during the testing. (ENTSO-E, 2017b.)

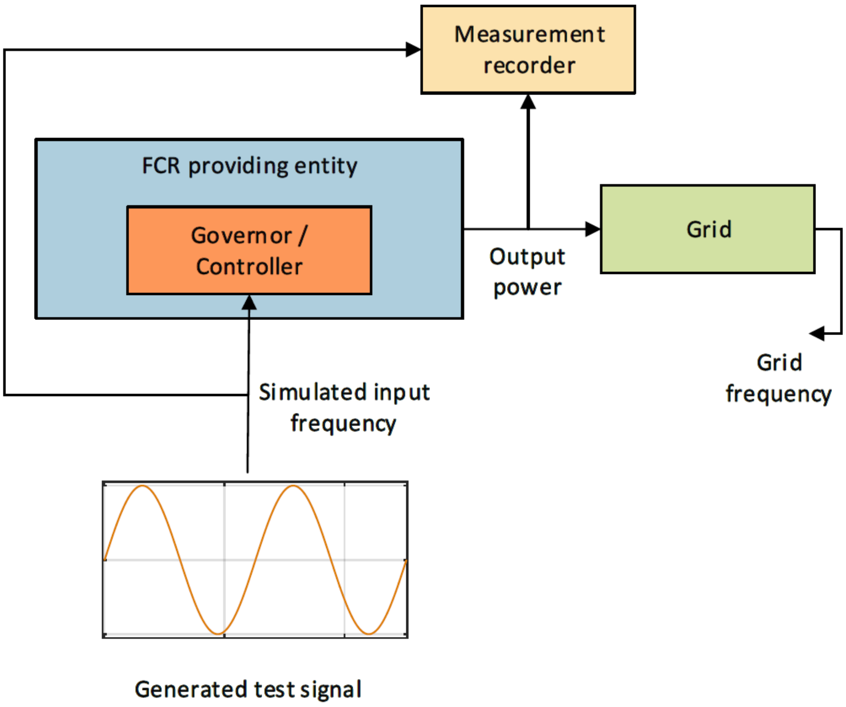

Figure 17. The new test procedure for FCR testing including the sinusoidal test signal input (ENTSO-E, 2017b).

As the test includes various different time periods for the sine wave, there must be a transfer function which to use as a base. “A transfer function value (transfer function evaluated for a certain time period / angular velocity) is defined as the gain that describes the magnification of the output and the phase that describes the phase shift of the output, relative to input signal”. (ENTSO-E, 2017b) The transfer function is dependent on the angular velocity and time period, which both are affected by the sine wave time period. (ENTSO-E, 2017b.)

The angular velocity, ω, with a certain time constant, T, can be calculated from Eq. 25.

$$\omega = \frac{2\pi}{T} \tag{25}$$

With the angular velocity the non-normalized gain for the transfer function can be calculated with the amplitude of measured sinusoidal power signal, a_p, with the angular frequency, and with the amplitude of the input sinusoidal frequency deviation, a_f (Eq. 26). (ENTSO-E, 2017b.)

$$|FCR(j\omega)| = \frac{a_P}{a_f} \tag{26}$$

As now the amplitude is affected by the FCR capacity of the entity, the non-normalized transfer function must be transformed to normalized transfer function. The normalization is defined as the static gain being equal to 1 per unit, pu. (Eq. 27).

$$|FCR(j0)| = 1{,}00\ pu \tag{27}$$

Now the normalized gain for the transfer function with specific angular velocity can be expressed with the normalization factor, n. (Eq. 28) The normalization factor can be obtained from a step response test. (ENTSO-E, 2017b.)

$$|F(j\omega)| = \frac{|FCR(j\omega)|}{n} \tag{28}$$

The step response test is done by inserting a set of frequency deviations to the frequency input, which is followed by power deviations by the TG system. Ideally the deviation in power output should be proportional to the deviation of the frequency input, but this is not the case. The main function of the step response test is to do a set of frequency variations upwards and downwards (Figure 18) and let the power output settle down to a specific value, before inserting the next frequency deviation. Before the set of deviations, a small deviation, sized half of the nominal deviation of 0.1 Hz, is entered to clear the effect of backlash. (ENTSO-E, 2017a) After the set of larger deviations, which add up to 0, meaning the starting frequency, the power output should ideally be also the same as at the beginning. From the differences in power output compared to the frequency deviation, the normalization factor can be calculated using following steps. (ENTSO-E, 2017b.)

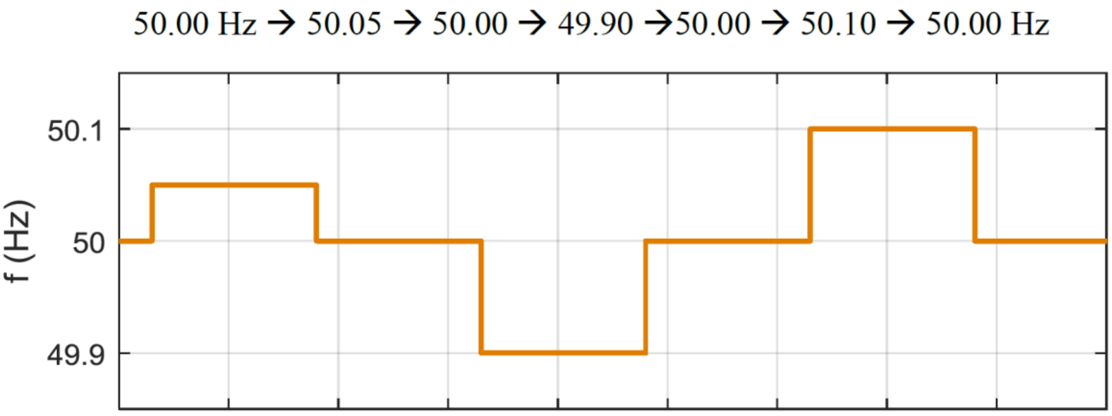

Figure 18. The step response test procedure used in the normalization factor calculation (ENTSO-E, 2017a).

The frequency deviation illustrated in Figure 18 is inserted as input value for the frequency. As the power system follows the frequency deviations and the data is collected, a curve of the power output can be illustrated (Figure 19).

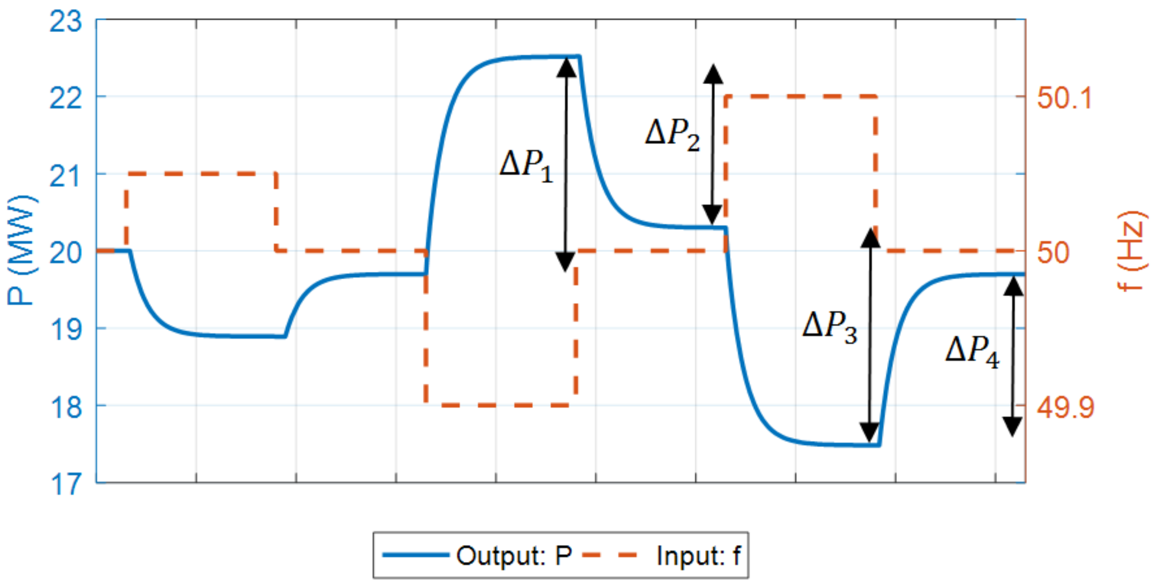

Figure 19. The power curve combined with the frequency deviations (ENTO-E, 2017b).

In the Figure 19 the power deviations are presented as $\Delta P_1, \Delta P_2, \Delta P_3$ and ΔP_4. To define the normalization factor, a backlash for the TG system has to be calculated. The backlash is a factor that describes the error in power output after the step response test. (ENTSO-E, 2017b.)

First, the average of the active power step response without backlash is calculated using the power deviations gained from the step response test (Eq. 29).

$$\Delta P_{no\ backlash} = \frac{|\Delta P_1|+|\Delta P_3|}{2} \tag{29}$$

Now the total backlash factor, $2D_{pu}$, can be calculated using Eq. 30. The backlash is expressed in per units.

$$2D_{pu} = \frac{||\Delta P_1| - |\Delta P_2| + |\Delta P_3| - |\Delta P_4||}{2 \cdot \Delta P_{no\ backlash}} \tag{30}$$

The first restriction applies in this section of the FCR testing. The total backlash factor gained from the step response test and equations should be less than 0.3 pu. The backlash scaling factor, H, can be obtained by using the total backlash. (ENTSO-E, 2017b.)

The scaling procedure can be found in the “Supporting Document on Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area” by ENTSO-E. (ENTSO-E, 2017b.)

As the scaling factor is obtained the normalization factor can be calculated by using the Eq. 31

$$n = \frac{H \cdot \Delta P_{no\ backlash}}{A_{step}} \tag{31}$$

where the factor A_{step} has the value of 0.1 Hz due to frequency deviation.

The phase of the transfer function, φ, for a certain time period can be calculated from Eq. 32, using the time difference, Δt, of the input signal and power output signal.

$$\varphi = Arg\big(F(j\omega)\big) = \Delta t \cdot \frac{360°}{T} \tag{32}$$

Now the different time constant sinusoidal frequency deviations can be inserted to the TG system and the measurement can be done. After the measurement period one should have 10 different time constants with a gain and phase value for each. The next step is to form FCR vectors that are plotted in complex plane having an imaginary y-axis and real x-axis. The vectors start always from the origin point, (0,0), and the length of the vector illustrates the gain, while the direction and angle of the vector illustrates the phase. The functions used for calculating the x-coordinate and the imaginary y-coordinate are presented below (Eq. 33, Eq. 34). (ENTSO-E, 2017b.)

$$x = |F(j\omega)|\cos[Arg\big(F(j\omega)\big)] \tag{33}$$

$$y = |F(j\omega)|sin[Arg\big(F(j\omega)\big)] \tag{34}$$

Now the vectors of different time constants can be drawn. The actual dynamic performance test is to compare these FCR vectors to individual circles, drawn in the same coordinate system with the FCR vectors. The vector may cross the line of the individual test circle, but the vector may not end inside the circle, or the result reads as a failure. This test provides one with ten different coordinate systems, each with one FCR vector for a certain time constant and an individual test circle to illustrate the limits. Example of this kind of result is presented as an appendix (Appendix I). (ENTSO-E, 2017a.)

The stability test is somewhat similar to the dynamic performance test. In the stability test the same FCR vectors are used, meaning the stability will also be tested on ten different time constants. This time however all of the test values are plotted in to same coordinate system. The coordinate system features a Nyquist point (-1,0) (ENTSO-E, 2017a), and around the Nyquist point a stability margin circle, predetermined to have a radius of 0.411 pu. (ENTSO-E, 2017b.)

All of the FCR vectors are multiplied with the grid transfer function, (Eq. 35)

$$-\frac{600\ \mathrm{MW}}{0{,}1\ \mathrm{Hz}} \cdot \frac{f_0}{23\ \mathrm{GW}} \cdot \frac{1}{2\frac{120\ \mathrm{GWs}}{23\ \mathrm{GW}} \cdot s + K_f \cdot f_0} \tag{35}$$

in which the

f_0 is 50.0 Hz

K_f is 0.005 (The load frequency dependence)

s is the Laplace operator

By multiplying the FCR vectors are modified to form a series of coordinate system points, which will form a curve. This curve must evade the Nyquist circle from the right hand side and it may not cross the circle at any point for the test result to be positive. An example of partial test result is illustrated in Figure 20. (ENTSO-E, 2017a.)

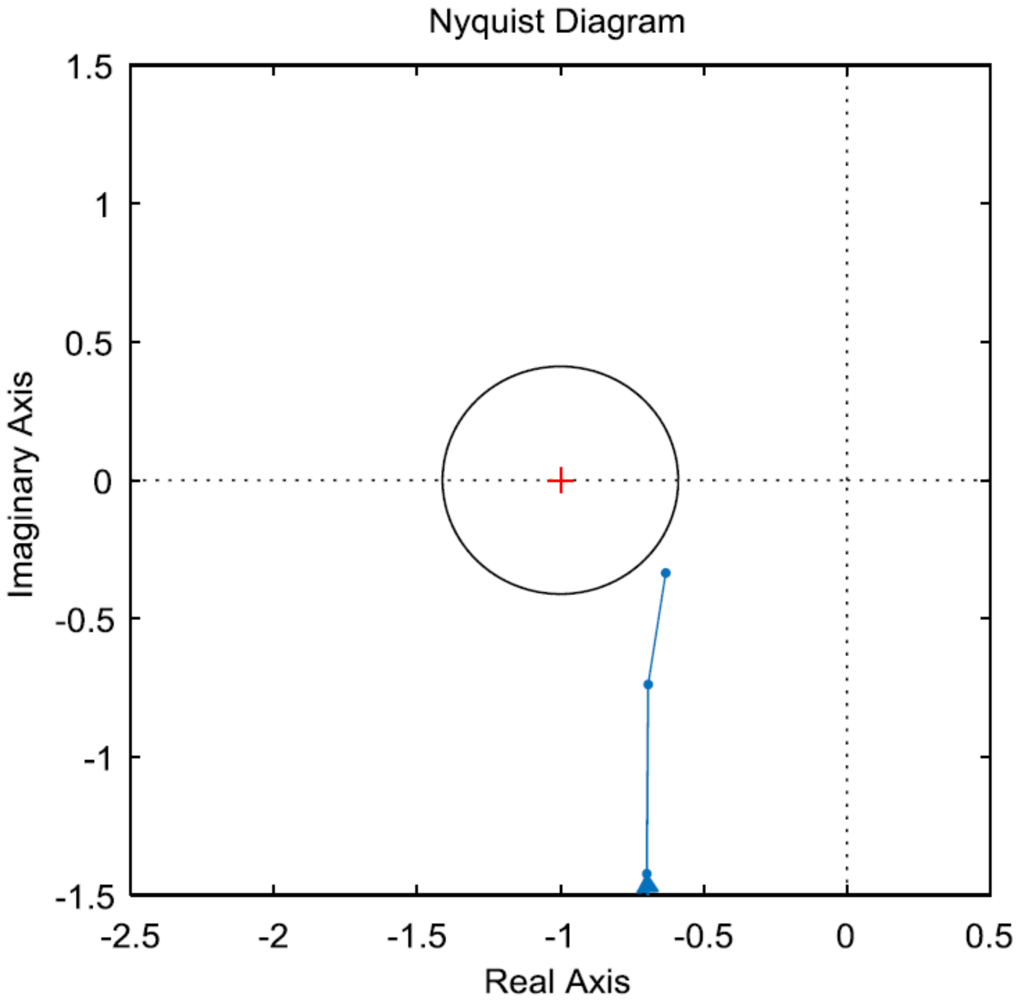

Figure 20. The Nyquist point and stability margin circle presented along with a partial FCR stability test result.

For the FCR-N capacity measurement the total backlash needs to be calculated from Eq. 36

$$2D = \frac{\left||\Delta P_1| - |\Delta P_2|\right| + \left||\Delta P_3| - |\Delta P_4|\right|}{2} \tag{36}$$

After the total backlash is calculated an Eq. 37 is introduced for the prequalified FCR-N capacity, $c_{FCR-N,pq}$.

$$c_{FCR-N,pq} = \frac{|\Delta P_1| + |\Delta P_3| - 2D}{2} \tag{37}$$

After this is done with all tested power output set points, a curve can be defined based on different capacities on different power output values. (ENTSO-E, 2017b.)

The prequalified FCR-N capacity is used to calculate the prequalified real-time FCR-N capacity, $c_{FCR-N,pq}(P_{sp})$. Prequalified real-time capacity can be calculated using Eq. 38, by inserting the maximum, P_{max}, and minimum, P_{min}, power output values at that moment. From the prequalified maximum, $c_{max,pq}$, and minimum, $c_{min,pq}$, capacities the prequalified real-time capacity can be determined as follows. (Eq. 38, Eq. 39).

$$c_{FCR-N,pq}(P_{sp}) = c_{min} + (c_{max} - c_{min}) \frac{P_{sp} - P(c_{min})}{P(c_{max}) - P(c_{min})} \tag{38}$$

$$c_{FCR-N,pq}(P_{sp}) = 0 \; if \begin{cases} P(c_{max}) > 1{,}05 \cdot P_{sp} \\ P(c_{min}) < 0{,}95 \cdot P_{sp} \end{cases} \tag{39}$$

The prequalified real-time capacity is used to calculate the maintained FCR-N capacity, c_{FCR-N}. The maintained capacity depends on the setpoint values and has to be recalculated, when the setpoint values are altered during operation of the hydropower plant. Maintained FCR-N capacity is a calculated real-time data which shall be sent to the TSO. The maintained capacity can be calculated with Eq. 40.

$$c_{FCR-N} = \max[\min\left(P_{max} - P_{sp}, P_{sp} - P_{min}, c_{FCR-N,pq}(P_{sp})\right), 0] \tag{40}$$

FCR-D

The stationary performance requirements for FCR-D have undergone one major change. Before the FCR-D product was only offered as an upwards control product, meaning the FCR-

D frequency was decided to be 49.50 Hz to 49.90 Hz. In the new regulation, the FCR-D is divided to two products, FCR-D upwards and FCR-D downwards. The frequency areas and power output capacity activation is determined as follows. (ENTSO-E, 2017a.)

At power grid frequency 49.90 Hz 0% of FCR-D upwards capacity shall be activated. At power grid frequency below or equal to 49.50 Hz 100% of the FCR upwards capacity shall be activated. Also at grid frequency of 50.10 Hz 0% of the capacity shall be activated and on frequencies above or equal to 50.5 Hz 100% of the capacity shall be activated. The activation between initial FCR-D start, being 49.90 Hz or 50.10 Hz, and nominal value for 100% activation, being 49.50 Hz or 50.50 Hz, should be somewhat linear. (ENTSO-E, 2017a.)

The FCR-D dynamic performance requirements differ from the FCR-N performance requirements. For the FCR-D dynamic performance test frequency ramp test and step tests are used, as the prequalified FCR-D capacity, $c_{FCR-D,pq}$, has to be calculated. From the data of the frequency ramp test, illustrated in Figure 21, the prequalified FCR-D capacity can be calculated using Eq. 41

$$c_{FCR-D,pq} = min\left(\frac{\Delta P_{5s}}{0,93}, \Delta P_{ss}, \frac{E_{supplied}}{1,8\ s}\right) \tag{41}$$

In this equation ΔP_{5s} is the activated power 5 seconds after the initial of the frequency ramp. ΔP_{ss} is the steady state of power output value after the frequency has been deviated from 49.90 Hz to 49.50 Hz or from 50.10 Hz to 50.50 Hz. $E_{supplied}$ is the amount of energy produced during the first five seconds of the frequency ramp. This value can be calculated as (Eq. 42).

$$E_{supplied} = \int_{t}^{t+5s} \Delta P(t)dt \tag{42}$$

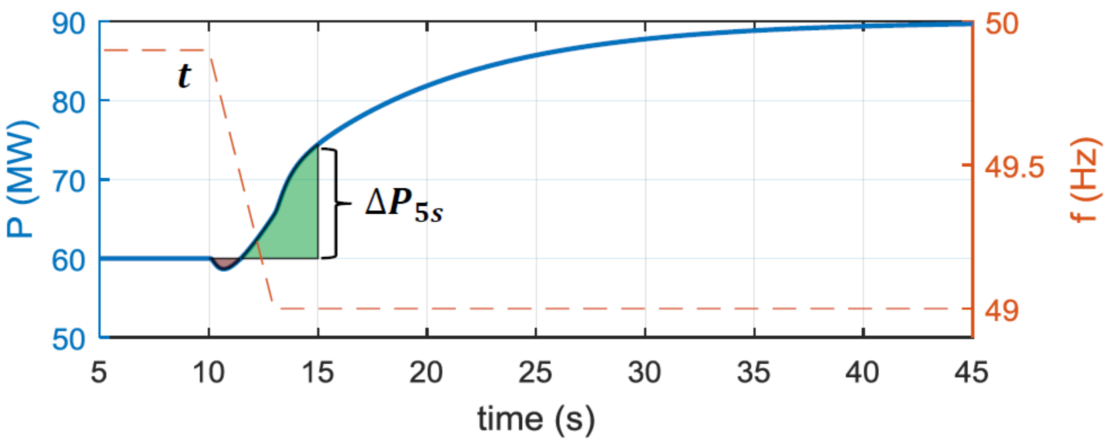

Figure 21. The FCR-D upwards frequency ramp test. The frequency is deviated from 49.90 Hz to 49.00 Hz and the green area implicates the energy produced during the first five seconds (ENTSO-E, 2017a).

For the mandatory real-time data of maintained FCR-D capacity, c_{FCR-D}, the capacities for upwards and downwards regulation must be calculated as follows, (Eq. 43, Eq. 44). (ENTSO-E, 2017a.)

$$c_{FCR-D,up} = \max[\min\left(P_{max} - P_{sp} - c_{FCR-N}, c_{FCR-D,pq}(P_{sp})\right), 0] \tag{43}$$

$$c_{FCR-D,down} = \max[\min\left(P_{sp} - P_{min} - c_{FCR-N}, c_{FCR-D,pq}(P_{sp})\right), 0] \tag{44}$$

The stability requirements for FCR-D are the same as for the FCR-N discussed before. As the both FCR-D and FCR-N tests use the same time constants, the basic vectors are the same, however the grid transfer function has been altered to following form (Eq. 45). (ENTSO-E, 2017b.)

$$-\frac{\Delta P_{ss} \cdot 1450 \text{ MW}}{c_{FCR-D} \cdot 0{,}4 \text{ Hz}} \cdot \frac{f_0}{23 \text{ GW}} \cdot \frac{1}{2\frac{120 \text{ GWs}}{23\text{GW}} \cdot s + K_f \cdot f_0} \tag{45}$$

4.2 HPPs in FCR and TSO requirements for HPPs

The new TSO requirements pose also new demands towards the physical appliances in the hydropower plants. The restricting physical factors has to be identified to have efficient ways of analyzing the possibilities to participate in FCR production. In this chapter a process is defined to find the connection between test performance and physical properties of a hydropower plant. Also some ground rules have already been set, and the few new tests conducted have also disclosed some rules of thumb, which are valuable in this process.

4.2.1 The FCR vector critical factor assessment and end component connections

The process for finding the connections between physical hydropower plant elements and FCR test results is crucial for the thesis. If the connections can be modelled with high enough precision, then the ranking system accuracy will increase to a sufficient level and the Fortum owned hydropower plants can be ranked according to the FCR capabilities.

To connect the FCR test and hydropower plant equipment, the FCR test was examined backwards compared to the previous presentation in chapter 4.1.2. Starting point for this process was the FCR dynamic performance test result. As mentioned before, the FCR dynamic performance test can be divided in to two separate parts, the vector and the circle. The vector has been calculated using various equations and tests, whilst the circle is predefined and unique for each of the time constants. From this it can be seen that the only factor affecting to the circle is the time constant, T, and the vector can be divided into two separate components, X and Y factors. The X and Y factors can still be divided in two, to the gain and the phase. (Eq. 32, Eq. 26, Eq. 28, Eq. 31)

$$\varphi = Arg\big(F(j\omega)\big) = \Delta t \cdot \frac{360°}{T} \tag{32}$$

$$|FCR(j\omega)| = \frac{a_P}{a_f} \tag{26}$$

$$|F(j\omega)| = \frac{|FCR(j\omega)|}{n} \tag{28}$$

$$n = \frac{H \cdot \Delta P_{no\ backlash}}{A_{step}} \tag{31}$$

As the tests are limited to Kaplan turbines with power feedback, the factor *n* does not play any part. The control system in power feedback is built so that it will eliminate the backlash, thus making the factor *n* obsolete. (Olenius & Riikonen, 2018.)

Closer inspection of the equations show that as the factor *n* is not counted in, and the factors a_f and *T* are purely based on the predetermined sinusoidal frequency signal, the only values which are connected to the physical hydropower plant are Δt and a_P. These values represent the time delay in the power output compared to the frequency signal, Δt, and the magnitude of the power output, a_P. As the FCR test result is based on these two values, the next goal is to define the connection with these *critical factors* and hydropower plant *end components* to find out the possible ways of affecting to the FCR test result.

Before the connection between critical factors and end components can be defined, the end components has to be specified. To specify all the end components affecting these critical factors, a meeting was held with Fortum hydropower specialists. In this meeting the process plan was presented and after that the end components were defined as follows;

- Droop value
- Proportional control value, P
- Integral control value, I
- Water time constant, T_w
- Turbine time constant, T_t
- Hydraulic time constant, T_h

- Power measurement and filtering, $T_{P,m\&f}$

The droop value is a set parameter in the hydropower plant automation controls, as well as the proportional control value and the integral control value. The D parameter of controller is not listed as PI –controller is more used than PID –controller in hydropower applications. Water time constant is a delay due to the physical properties of water and water inertia. Turbine time constant represents the inertia and limitations that the turbine blades have. Hydraulic time constant represents the limitations in hydraulic control system and power measuring and filtering represents the change in time factor due to digital measurement ant filtering process. (Olenius & Riikonen, 2018.)

These end components were chosen as they were seen as components or set values which will affect either to the magnitude of power output or to the time delay compared to the frequency signal. (Olenius & Riikonen, 2018.)

The next step is to evaluate the end components by the economic input needed to affect the result. The end components are divided in to four classes, *Can be affected with low costs*, *Can be affected with moderate costs*, *Can be affected with high costs* and *Cannot be affected*. The end component division is as illustrated below (Table 2)

Table 2. The end components ranked by the economical input needed to affect the FCR test result.

Can be affected with low costs	Can be affected with moderate costs	Can be affected with high costs	Cannot be affected
Droop	Power measurement and filtering	Turbine time constant	Water time constant
P parameter		Hydraulic time constant	
I parameter			

From the table above (Table 2) it can be seen that the most economically feasible way to affect to the FCR test result is to tune and apply different types of parameter combinations in to the hydropower plant PI –controller. The power measurement and filtering time constant can be reduced with PI -tuning combined to new hardware, but the improvement capacity varies between hydropower plants. Turbine time constant and hydraulic time constant can be reduced by renewing the existing systems with the demand for less play and delay. This is an extreme action which comes with high economical investments, and should not be used before the more economically feasible ways are exploited. The best option is to optimize the hydropower plant with the more economically feasible methods and then apply the high cost methods when the hydropower plant overhaul is planned. The least economically feasible end component is water time constant. This value is derived straightly from hydropower plant waterway structures and hydropower plant operating conditions. Altering the waterways usually leads up to altering the character of the hydropower plant at hand which cannot be considered as an economically feasible action. Thus the water time constant is considered as an end component which cannot be affected.

After the evaluation, the process can be finished by connecting the critical factors and end components. This was done in meeting and the results are presented below (Figure 22);

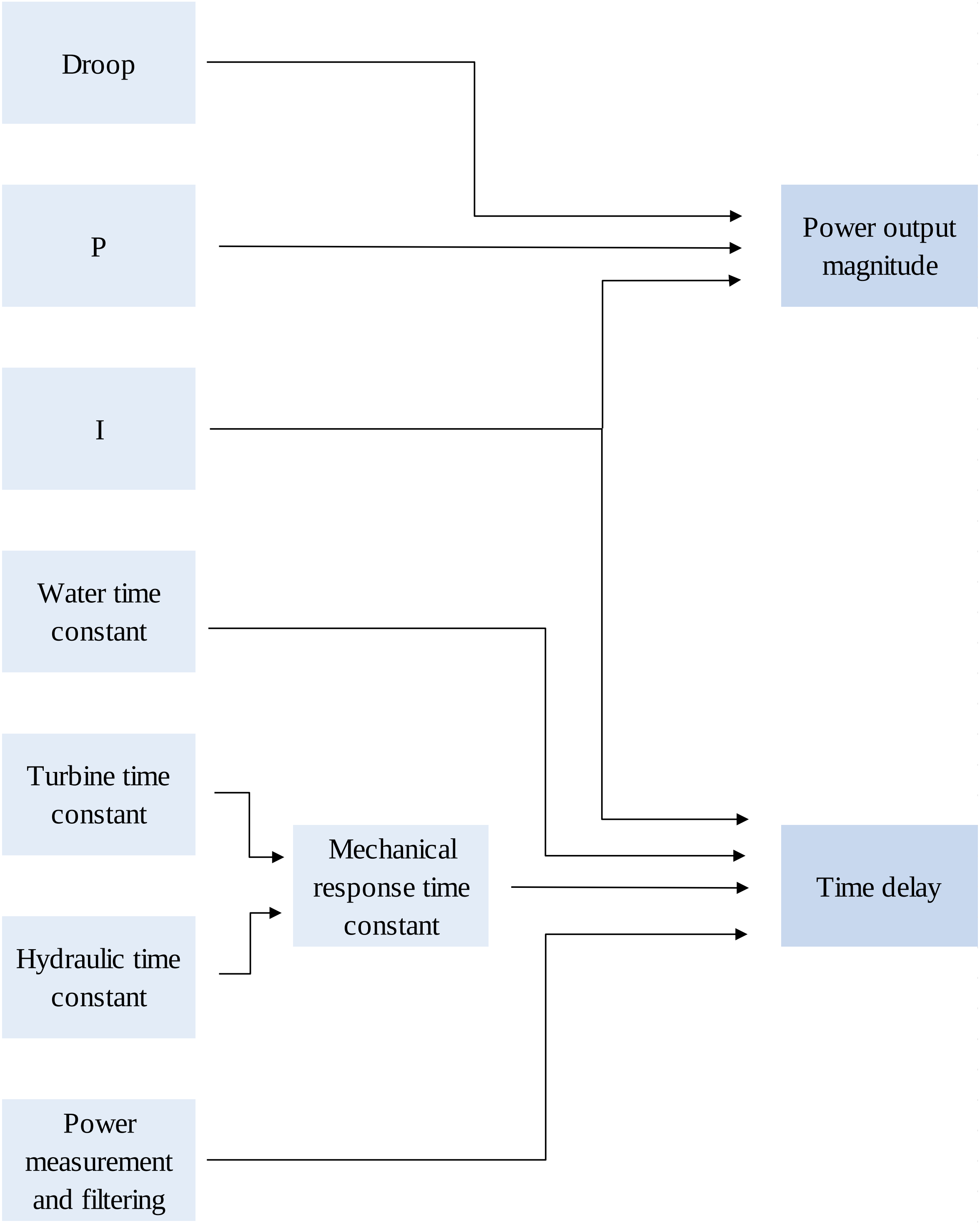

Figure 22. The hydropower plant end components connected to corresponding critical factor.

The presented figure (Figure 22) was constructed with the knowledge of Fortum specialists. The end components can be quite straightly divided into two different sub categories, to the end components affecting the power output magnitude and to the end components affecting the time delay compared to the frequency signal. (Olenius & Riikonen, 2018.)

Notable in Figure 22 is that the turbine time constant, T_t, and hydraulic time constant, T_h, form together a mechanical response time constant, T_m. The factor of mechanical response time is used, as it was noted that when defining the values for these end components, it is usually hard to separate the value for turbine and hydraulics due to measurement process.

The time delay and power magnitude can also be expressed as (Eq. 46, Eq. 47)

$$\sum \Delta t = T_w + T_m + T_{P,m\&f} + I(T) \tag{46}$$

and

$$\sum a_p = Droop(f) + P(f) + I(f) \tag{47}$$

where the factors T_w, T_m and $T_{P,m\&f}$ represent the time delay values considered to be rather constant throughout the power range. The factors $I(T)$, $Droop(f)$, $I(f)$ and $\mathrm{P}(f)$ however are considered to be dependent on other values in the process and thus can’t be treated as constants. The I value differs from other end components by affecting both of the critical values. The I value in PI control system has an affect on the PI control output value, or power output correction signal, but it also affects the time delay. While the I value can be treated as a function of the frequency signal time period, T, and a function of the frequency value, f, both Droop value and P value are functions of the frequency value.

As defined, the end component values can be divided to constants and functions. However, all of the values are unique to each hydropower plant, as is the end components. To help find out the operating points for positive result in FCR tests, value ranges should be defined to all end component values, to gain more information on possible solutions. Theoretically all factors can get values in the range of $[0, \infty]$, but the practice is different. It has already been established in previous FCR testing that in order to have a positive result in the FCR test the following should apply (Eq. 48, Eq. 49)

$$T_w < 2s \tag{48}$$

$$T_t(full) < 60s \tag{49}$$

where the factor $T_t(full)$ implements the full opening time for turbine runner blades. Of course during normal operation or in FCR tests the opening process from fully closed to fully opened is not needed, but this value is considered to be a good indicator on the performance capabilities and reaction speed of the Kaplan turbine. The opening time is also quite easily measurable, and may be even found on documentation. These restrictions of values have originated from discussions between Fortum and Fingrid after conducting tests at Pyhäkoski hydropower plant. (Olenius & Riikonen, 2018.)

Now the basic model of interaction between FCR tests and hydropower plant components is achieved. This process model can be used to model the capability of current Fortum hydropower plants when the needed information is available.

5 COMPANY HPPS AND TSO REQUIREMENTS

This chapter answers to the second research question; *how does the new requirements affect Fortum hydropower?* As the comparison between old and new requirements is made in chapter 4.1, the goal in this chapter is to implement these changes to existing Fortum hydropower fleet. To define the requirements the new FCR tests are posing on Fortum hydropower fleet, the end component values for each power plant has to be sourced. After the hydropower plant data is sourced, a full scale physical FCR test is arranged at Fortum owned Nuojua hydropower plant. The Nuojua test case will serve as a reference result to which other Fortum hydropower plants will be compared to in the FCR ranking system.

5.1 Hydropower plant data gathering

Specifying and individualizing different hydropower plants is crucial to do comparison. In chapter 4.2.1 the end components affecting the FCR test result are defined. These components are used when comparing the hydropower plants. To have a valid comparison, and thus ranking system, thorough sourcing and analysis of the data is needed.

The end component data was found to be lacking and not accurate enough to form a solid comparison. Even though the end component data per end component is lackluster, the value of total time delay can be sourced from previous test data. The total time delay is used in ranking system and it is described more accurately in chapter 5.1.2.

5.1.1 Water time constants

For the water time constant, a graphical way of integrating the water time constant through the waterways was used. The graphical integration provided accurate results, when compared to commissioning report from 2015.

There is also an older estimate on water time constants, which has been done using the previous FCR test results and general knowledge on the behavior of the TG system. These values can be considered as values of moderate accuracy. There is a slight contradiction between the mathematical model of the water time constants and the measured water time constant values. While comparing the FCR test results of Nuojua TG 3 to the mathematical estimates of the water time constants, it can be seen that as the flow rate decreases to low level, the measured water time constant does not decrease as drastically, indicating that there is a minimum value for water time constant, even though this cannot be seen from the water time constant equation (Eq. 50)

$$T_w = \frac{l \cdot Q}{A \cdot h \cdot g} \tag{50}$$

where l describes the length of the waterways, and A describes the cross-sectional area of the waterways. The comparison of mathematically calculated water time constant and is presented in the appendix (Appendix II).

5.1.2 Time constants

It is highly unlikely that a company would have a good and accurate database for different time constants for hydropower production, as this has not been seen as something worth measuring. Now as the requirements become more demanding, the time constant values are starting to have economic value. Defining the time constants with full scale testing is a large-scale project which is not economically feasible so the idea of separate time constants is discharged.

From the old FCR tests, a total time constant can be acquired using the data from step response tests. This provides a reliable data source, although not ideal one. The total time delay value is acquired by measuring the initial start and end of the measured power output value, and then comparing this value to the moment of inserting the frequency step to the control system.

5.1.3 PID -controller parameter finding

PID -controller parameter finding is done by testing different combinations of P, I and D parameters. With knowledge of controller behavior, which is discussed in chapter 3.3.2, the parameters can be altered so that the positive impact of each parameter outcomes the challenges posed by the parameter.

In addition to time constants, the PID -controller parameters affect highly on the FCR test result. During the testing the other end components cannot be altered. The PID -controller parameter tuning is the fastest, most cost efficient and most reliable way to affect the FCR test results.

The PID -controller parameter finding starts with initial FCR sinusoidal tests sequence run, using the existing parameters, to see how the current settings compare to the new regulation. The finding proceeds by running the FCR sinusoidal test sequences until one of the ten test sequences fail. As discussed in chapter 4.1.2 the FCR tests are done by using ten different time periods for the sinusoidal frequency signal with maximum value of 50.1 Hz and minimum value of 49.9 Hz. From the FCR test experience at Sveg hydropower plant in Sweden, the most difficult time periods are proven to be the middle range time periods of 40, 50 and 60 second sinusoidal oscillations. (Byström, 2018.)

The more accurate description and the best available testing procedure is explained more thoroughly in the next chapter.

5.2 FCR tests at Nuojua TG 3

After obtaining the critical factors, end components of hydropower plants and their values from data, and total time delay values for each hydropower plant, the next step is to validate one hydropower plant for reference object. This chapter describes the FCR testing procedure which was carried out to validate Nuojua hydropower plant as a reference, to which rest of the fleet can be compared to. Nuojua TG 3 was chosen as reference due to its young age, high pressure hydraulic governor system and fast reaction time.

5.2.1 FCR test procedure

The FCR test entity requires fast reaction from the TG system, as well as sufficient power output. The FCR test can be divided in to three different sectors. The first one is the fast sector, which includes oscillations with time period of 10, 15 or 25 seconds. From the test results and experience, it can be said that this fast sinusoidal oscillation requires fast response time from the TG system to have a positive result.

Figure 23 is an example of FCR test result with sinusoidal frequency with 10 second time period. In the figure the stability boundaries, performance boundaries and an example of test vector, combining time delay and power output amplitude, are illustrated. The time delay is illustrated with the angle of the example vector, while the power output amplitude is illustrated with the length of the vector. This example case would pass the test with the 10 second time period.

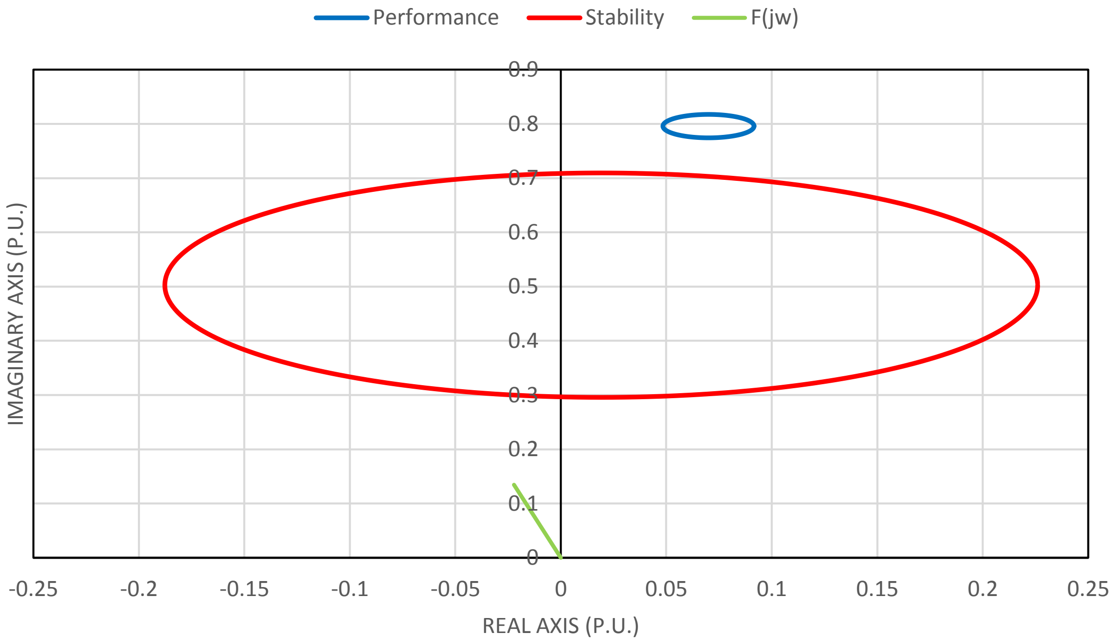

Figure 23. 10 second time period sinusoidal oscillation FCR test result

The middle sector composes of 40, 50 and 60 second time period oscillations. Figure 24 presents the FCR test with 50 second time period in the sinusoidal frequency oscillation. By comparing these figures, it can be seen that the impact of performance in the test result has grown significantly, while the impact of stability is decreasing, when testing the longer time period oscillation.

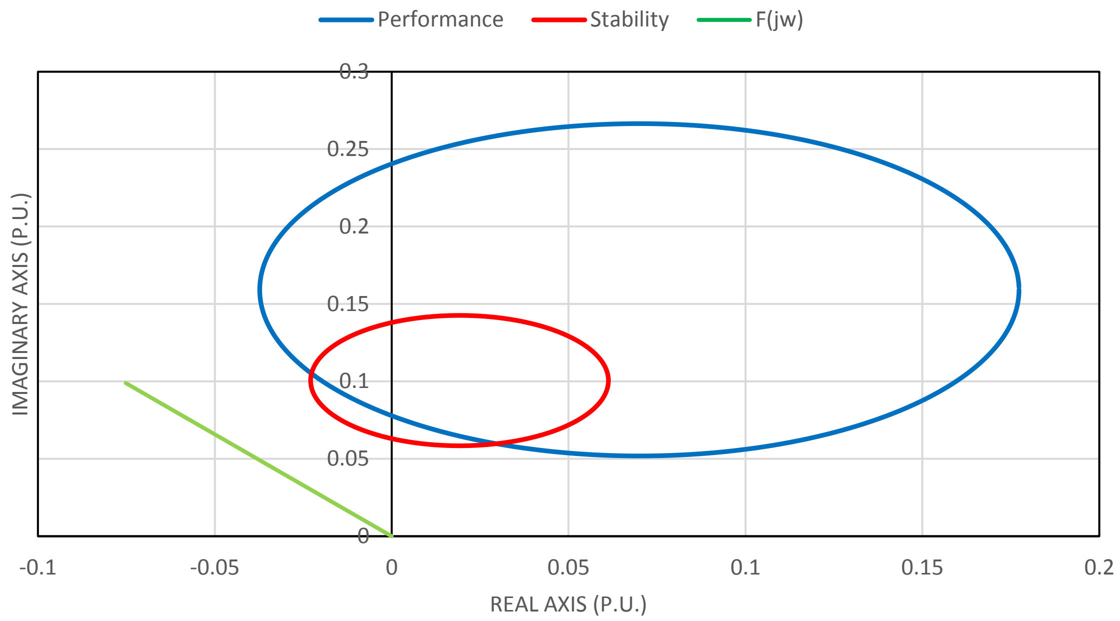

Figure 24. 50 second time period sinusoidal oscillation FCR test result

As the test figures show, the performance and stability boundaries have much more higher value on the imaginary axis on the 10 second oscillation than on the 50 second oscillation. This indicates that the only option for positive test result is to “avoid” the boundaries with low enough time delay, as the amplitude of the power output should be enormous to clear the boundaries with more time delay.

In Figure 25 slow sector oscillation with 150 seconds’ time period is shown. The slow sector composes of 70, 90, 150 and 300 second time periods. Notable feature in the slow sector is that the performance boundary is now the directive boundary, and that it cannot be “avoided”. The only option to pass the slow sector is that the power output amplitude is high enough.

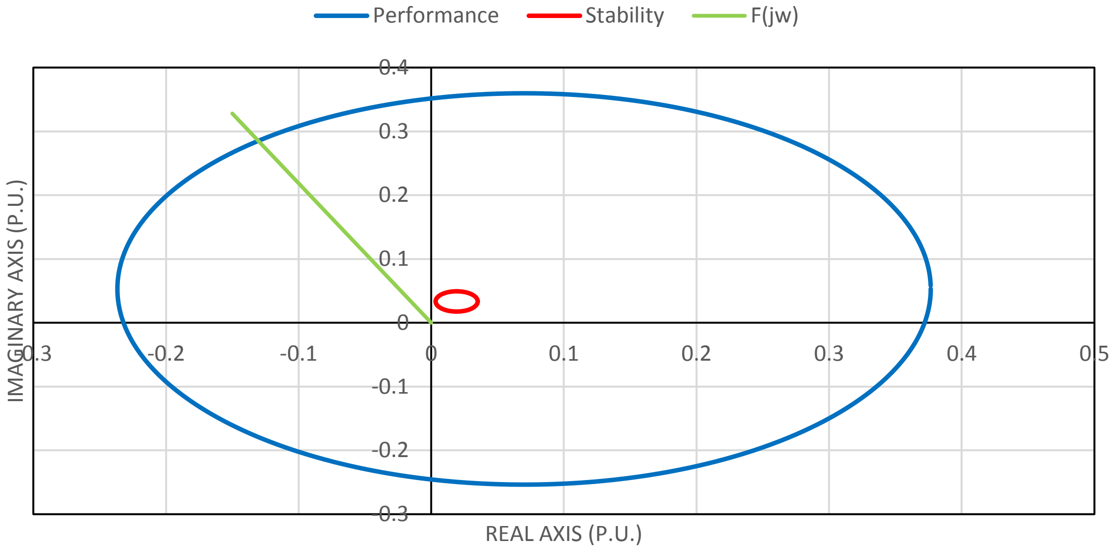

Figure 25. 150 second time period sinusoidal oscillation FCR test result

To have a positive FCR-N test result all of the 10 different time periodic tests has to be passed with constant PID -parameters.

In addition to dynamic performance and stability circles illustrated above, the combined performance and stability of the power plant is also measured with the Nyquist curve. The Nyquist curve uses the same test data, but the main function is to also depict the relations between the different test sequences. The Nyquist curve results positive if the figure drawn from test data avoids the stability boundary, and does not cross the boundary at any point. Below is illustrated an example of the Nyquist plot (Figure 26). This example results positive in Nyquist criteria.

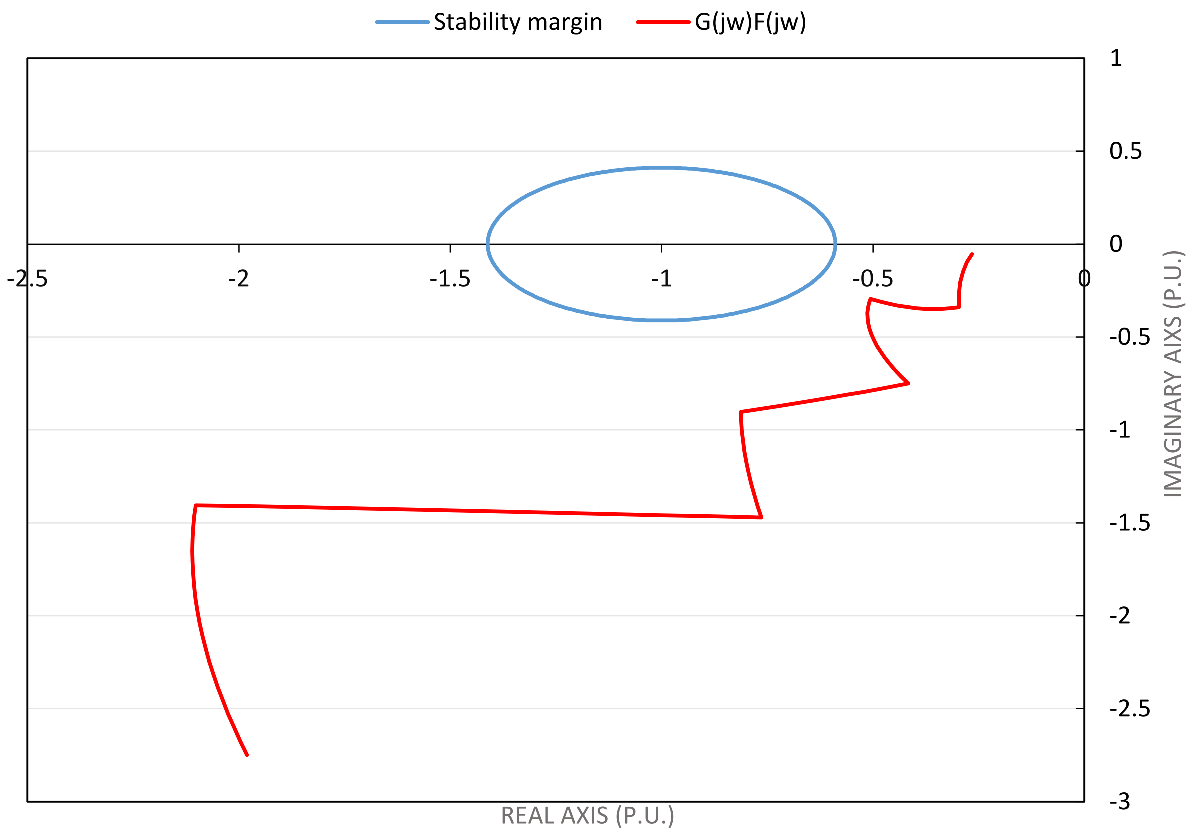

Figure 26. Nyquist plot illustrating the Nyquist criteria in the FCR test result

5.3 FCR test results

Nuojua TG3 passed the FCR-N tests at preliminary inspection. The PID -controller parameter finding proved to be a time-consuming task, as it was also during Sveg FCR tests. The fine tuning of P and I -parameter relation in addition of usage of short derivative time provided the wanted result, in which the amplitude of power output is kept low on the fast oscillating test sequences, while growing enough for slow oscillating test sequences.

5.3.1 FCR-N result and upcoming FCR test demands

The test provided multiple results; firstly, preliminary inspection indicates that the FCR-N test result was positive. Some data analysis and test data further inspection is needed to confirm the result, as the test data has a quite strong noise in it, complicating the inspection.

Secondly, although the test result is positive, during the pretest preparation the FCR test was underrated. Nuojua TG3 is considered to be one of the best Kaplan machines in the Fortum's Finnish hydropower fleet, and the early modelling of the unit indicated that the FCR test will not prove any difficulties. Testing of the unit required however a significant amount of time, taking five days in addition to pretest preparations. The PID -parameter combination was also found to be delicate, and acquiring the final parameter combination proved to be a hard and time consuming task.

5.3.2 Test preparations and testing technique

Thirdly, as the Nuojua TG3 did not perform as well as expected and significant amount of time was needed for a positive test result, the modelling tool was found lacking in performance. To correct the FCR test expectations for individual hydropower plants, a more accurate modelling tool is needed. A more accurate modelling tool could also provide a better baseline for the FCR tests as the PID -controller parameters could be sourced more definitely beforehand, which could reduce the time required for full scale FCR tests significantly.

One important result from the Nuojua FCR tests was also the testing technique and testing order validation. As the test sequences were required to be repeated due to resulting in failure, the fastest testing order was discovered. The preferred testing order starts with the middle sector and 50 second oscillatory frequency signal. From the result, it can be seen if the required time delay is achieved and if the power output amplitude is high enough. This result also indicates the result for the remaining sequences, if the first test provides a positive result with a low marginal in either power output magnitude or in time delay, the whole test sequence is highly unlikely to provide a positive test result. After the first middle sector sequence is passed, a fast sector oscillation is tested. For example, an oscillation with 15 second time period will display the time delay produced with current parameter settings more clearly than middle or slow sector test sequences. If the fast sequence is also passed, then a test sequence from slow sector will be tested.

The slow sector affects highly on the time used for the tests, as it takes few full oscillations of the frequency to settle the TG system to a constant state, which is required for reliable test results. 90 second oscillation is used to the test the slow sector as it provides a challenge for the power output amplitude, but does not consume as much time as 150 second oscillation. The 70 second oscillation does not provide as high challenge for the power output amplitude alone. If a test set of one fast, one medium and one slow oscillatory frequency deviation is passed, then the test can proceed to remaining sequences to test for the boundary conditions between the sectors.

6 LIST OF HYDROPOWER PLANTS AND FCR CAPABILITY RANKING SYSTEM PRESENTATION

Scope of this thesis covers only the Kaplan turbine hydropower plants in Finland, which are owned by Fortum. The goal in this chapter is to rank these hydropower plants by their expected capability to perform in the new FCR tests. The ranking is done to form a larger picture of the FCR capacity the hydropower fleet can provide, and to ease the revision planning in the future, as the weakest links of the fleet are revealed.

6.1 Fortum hydropower fleet

The Fortum hydropower fleet covers numerous hydropower plants, powered by numerous TG systems. When considering the scope of the thesis, the number of hydropower plants is limited to 12, with total of 28 Kaplan turbine powered TG systems. These hydropower plants can be divided to three categories based on the river system they operate in. Presentation of the hydropower plants key figures is illustrated below (Table 3).

Table 3. Fortum's Kaplan powered TG systems located in Finland, listed by the water systems.

River system	Power plant	TG system	Nominal power [MW]	Nominal height difference [m]	Nominal flow $[m^3/s]$
Vuoksi					
	Tainionkoski				
		TG 1	16,5	8	250
		TG 2	14,5	8	250
		TG 3	14,5	8	250
	Imatra				
		TG 7	38	24	180
Oulujoki					
	Jylhämä				
		TG 1	17	11	150
		TG 2	19	11	164
		TG 3	19	11	164
	Montta				
		TG 1	16,5	12,2	165
		TG 2	14,3	12,2	150
		TG 3	16,5	12,2	165
	Nuojua				
		TG 1	27	22	150
		TG 2	27	22	150
		TG 3	**33**	**22**	**167**
	Pyhäkoski				
		TG 1	48,7	32,4	170
		TG 2	49	32,4	170
		TG 3	49	32,4	170
	Pälli				
		TG 1	17	13,8	150
		TG 2	17	13,8	150
		TG 3	17	13,8	150
	Utanen				
		TG 1	18	15,6	150
		TG 2	18	15,6	150
		TG 3	22,7	15,6	167
Emäjoki					
	Aittokoski				
		TG 1	44,8	29,6	171
	Leppikoski				
		TG 1	11,6	12	125
		TG 2	11,6	12	125
	Seitenoikea				
		TG 1	39	21,4	160
	Ämmä				
		TG 1	16,6	11,5	140

Notable is that those TG systems that are not within the scope, are excluded. From Table 3 it can be seen that the nominal power deviates a lot between the power plants, and also that power plants located in same river system share the nominal flow rate, with some error due to inflow between the hydropower plants. Nuojua TG 3 is highlighted as it used as a reference power plant, because the new FCR test results were positive.

The Finnish Kaplan turbine fleet illustrated above consists large variation of nominal power outputs, height differences and flowrates, indicating that the power plant behavior also changes quite drastically. This indicates that the FCR test results or FCR capability predictions are quite hard to transpose between the hydropower plants. To conduct any further research, additional information is needed.

6.2 Fortum HPP FCR technical ranking

One of the key goals in this thesis is to orientate to the Fortum hydropower fleet, to gain information about the FCR capabilities. The FCR capabilities so far have been predicted by few of the employees, who are the most acquainted with the hydropower fleet and the capabilities of the individual hydropower plants.

The foundation for ranking system was presented in chapter 4.2.1 in its ideal form. The ranking is however completed in a different way due to data availability and modelling tool accuracy. The ranking system used is presented below.

6.2.1 Presentation of the ranking system

Time delay has been proven to be the main factor defining the capabilities of FCR production. To fully understand the concept of time delay, a more specific approach to the subject must be taken. As described before (chapter 4.2.1), the time delay value composes of I –parameter of the controller, water time constant, T_w, time constant from power measuring and filtering, $T_{P,m\&f}$, and from the combined mechanical time delay in the hydraulic and turbine system, T_m. When comparing these values, the affect of I –parameter is still unclear and depends highly on the relations in the parameter settings of the controller. To gain the absolute value of the time delay, the affect casted by I –parameter should be mathematically modelled. As there are no such models available, the absolute time delay value is left out of the comparison, and the more uncertain value of time delay, the total time delay, is used.

The total time delay is composed of all above mentioned factors. The total time delay is used in the comparison as it can be easily obtained from old FCR test results, and the results provide accurate figures. The downside of the total time delay is that the controller parameter settings have a high affect to the total time delay value, thus giving results which does not necessarily correspond to the mechanical and physical properties of the hydropower plant, which are the main interests.

In old FCR tests, the time delay values come from the FCR-D capacity measurements, in which a large 0.5 Hz step in frequency is used to measure the reaction of power output of the hydropower plant. Even though the initial purpose of this step test has been different, the step test results provide important data to be used.

A typical power output curve in result of a frequency step is presented below (Figure 27. A typical power output curve of a hydropower plant in result of a step change in frequency.). The power output curve is usually shaped somewhat similarly to a hyperbolic curve. In the beginning of the curve a “dip” can be seen. This dip in power output is mainly created by the inertia of flowing water, water time constant, T_w.

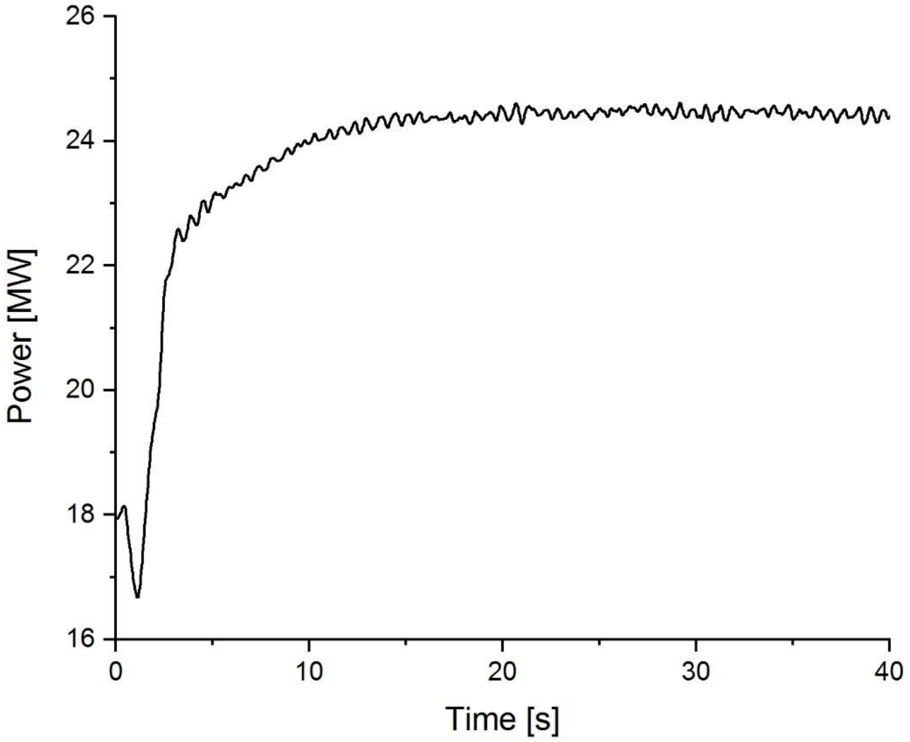

Figure 27. A typical power output curve of a hydropower plant in result of a step change in frequency.

From the figure above (Figure 27. A typical power output curve of a hydropower plant in result of a step change in frequency.) the maximum power output magnitude and 63% of the total power output can be read. The total time constant and time constant for achieving 63% of the maximum power output can be obtained when the maximum power output is known. The step deviation of the frequency takes place at 0 second mark. (Figure 28)

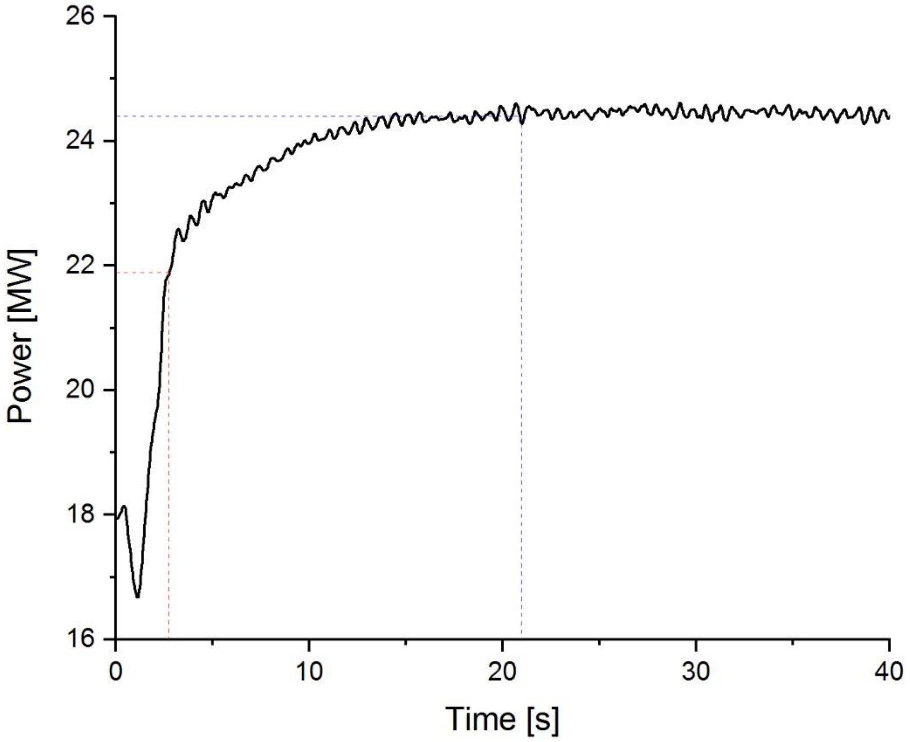

Figure 28. The sourcing of 100% of power output (blue dashed line), 63 % of power output (red dashed line) and the corresponding time delays.

In addition to these values also the maximum power output loss during the dip, and the duration of the dip can be sourced (Figure 29). The dip of power output curve illustrated above is magnified in the following figure.

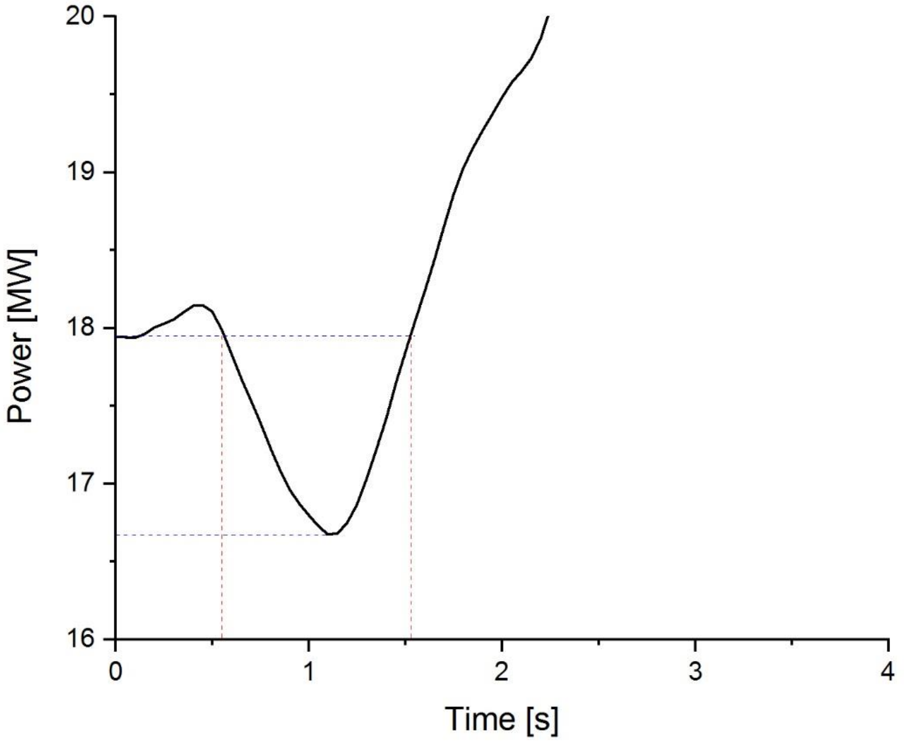

Figure 29. The sourcing of the dip of the power output value (blue dashed line) and the time delay caused by the dip (red dashed line).

In the ranking system two defining values are used; the valuation coefficient, *VC*, and the stability coefficient, *SC*. The valuation coefficient describes the monetary value in the FCR production with the TG system at hand. The valuation coefficient can be calculated using the 63% power output magnitude and the time delay from initial frequency step to the aforementioned power value as follows (Eq. 51)

$$VC = \frac{63\ \%\, power\ output\ [MW]}{Total\ time\ delay\ (63\%)[s]} \tag{51}$$

The stability coefficient describes more the FCR capability, and stability of the power output of the TG system at hand. Large dip in the beginning of power output increase indicates of large water time constant, T_w, value and may cause difficulties during the upcoming FCR test sequences due to increased time delay and uneven power output. The stability coefficient can be calculated by using the relative dip in power output and the time delay caused by the dip as follows (52)

$$SC = \frac{\frac{Dip\ [MW]}{63\%\ power\ output\ [MW]}}{Time\ delay\ (Dip)[s]} \tag{52}$$

The more recent FCR tests done at Nuojua TG 3 were conducted using manual operation mode of the power plant, which leads to bypassing the PID -controller. Due to bypassing of the controller, the total time delay results do not match, as the controller parameter factors are not accounted. Despite this, the Nuojua TG 3 remains as a reference power plant as it performed desirable on the upcoming FCR tests. The old FCR test values of Nuojua TG 3 are used in the ranking.

In the hydropower plant ranking, the *VC* and *SC* are used to rank the TG systems of power plants to three different groups; desirable performance, performance as good or better than Nuojua TG 3 and undesirable performance. Due to the uncertainty in the ranking procedure, the ranking does not provide more accurate results on the actions that need to be taken on a single power plant level, and the comparison inside the groups should be done critically and using additional information.

6.2.2 Ranking system results

The following results presented (Appendix III) are based on the previous FCR step response test results of the Fortum owned Kaplan turbine powered TG systems located in Finland. The results do not take in account the absolute time delay values of end components or the relative effect of the PID -controller parameter settings.

The ranking system defining values are composed of valuation coefficient and stability coefficient presented in chapter 6.2.1. The ranking coefficient, *RC* is acquired from equation presented below. (Eq. 53)

$$RC = \frac{VC}{SC} \tag{53}$$

The complete ranking table is presented as an appendix (Appendix III). The colour scales of the cells indicate whether the value is desirable or not, green being the most desirable and red the least desirable.

From the ranking result table presented in the appendix (Appendix III) it can be seen that Aittokoski TG 1 has the most desirable overall performance, while Tainionkoski TG 2 has the least desirable overall performance. With the ranking results the TG systems can now be divided to three groups as mentioned in chapter 6.2.1 (Appendix IV)

It is crucial to remember to always use also external information or data when comparing power plants inside the groups, as the ranking does not take every variable in to account. From the ranking table (Appendix IV) it can be seen that the most desirable performance is delivered by far the Aittokoski hydropower plant. Aittokoski features however an older version of used controller systems so the ranking value of Aittokoski TG 1 is not at that level in reality.

The light yellow sector from Pyhäkoski TG 1 to Nuojua TG 3 illustrates the group of TG systems that performed as well as or better than Nuojua TG 3 in the old FCR tests. This indicates that the TG systems coloured on light yellow or light green should be able to perform desirably in the upcoming FCR tests. From this ranking, it can be seen that only 5 TG systems out of 26 TG systems, Pyhäkoski TG 3 is not included as it had no FCR test data, should be able to pass the upcoming FCR tests without any modification, using just controller tuning.

The amount of tuning and modification needed for the remaining TG systems to perform desirably on the upcoming FCR tests is unclear, and needs further research. Some of the remaining TG systems should be capable of fulfilling the upcoming demands with just different type of controller setup, but some with lowest ranking scores might not fulfil the demands without major modifications.

7 CONCLUSIONS

The main research subjects in this thesis were the upcoming FCR requirements and modelling the affect the FCR requirements cast on the Fortum hydropower fleet. As answer to first research question; *How does the new TSO requirements compare to old ones?* it can be said that the upcoming FCR requirements are going to set higher demands on hydropower plant optimization and controller tuning. The time delay factor of power output capacity has a significant role in the upcoming requirements, whereas it has little or none impact in the current requirements.

The time delay factor has a high affect on the FCR test results, and thus should be more thoroughly researched. The time delay mechanisms are not yet fully researched, and the formation of total time delay is still unclear. These factors have to be researched to exploit the full potential of the hydropower fleet. The upcoming requirements also poses good opportunities for those who have prepared for the change. The new version of FCR requirements will hopefully increase the frequency quality and thus eliminate the unnecessary stress posed to hydropower plants. The upcoming FCR requirements are also going to clear the field and set every producer on the same line, reducing the amount of free loaders thus rewarding the producers with properly optimized power production.

The answer to the second research question; *how does the new requirements affect Fortum hydropower?* is a bit more convolute. The main goal of this thesis was to create a ranking system for the Fortum Finnish Kaplan powered hydropower fleet, from which it can be seen that a minority of the hydropower plants are capable of fulfilling the upcoming requirements according to the research done. The ranking list was created using current hydropower plant test data, which does not correspond the actual upcoming FCR testing. The controller tuning and structure was found to be a crucial factor on the success in the upcoming test set. Some of the assumptions made in the early stages of this research was partly proven to be faulty, such as that the usage of Kaplan turbine provides undesirable result as a standard. The problem was discovered to be more in the control systems than in the turbine itself.

However, the affects of this result are yet to be researched completely. In the following chapter 7.1, future research subjects are listed, which may provide the complete answer to the question of “*what are the affects of this result and what actions are needed*”.

There are two possibilities for actions needed. First one is that the FCR production is seen to have such economic value that further research is funded to fine tune the hydropower plant controllers using modelling and mathematical optimization. The second option is that the wear and tear of hydro turbines due to FCR production is researched thoroughly. This alternative may lead to a result that the FCR production is not economically feasible, in which case the action needed is to terminate the FCR production using hydropower.

This thesis does not provide the solution to this two way dilemma. The base for further research is however established and the possible outcomes are recognized.

7.1 Future research

As the research is carried through the process, new possibilities for future research are found. In this chapter the future research subjects found during the main research are listed and analyzed

7.1.1 Wear and tear in Kaplan turbines due to FCR-N and –D

One of the key questions in addition to the FCR capability is the wear and tear in Kaplan turbines caused by FCR production. This topic has arisen lately as the economic structure of FCR production has been inspected more thoroughly.

As the monetary revenue gained from FCR is determined by the capacity sold to the local TSO by bidding, it is vital to also research the cost structure thoroughly, to gain information on the actual profit made. Traditionally it has been seen that the FCR production does not have any costs, as the lost energy due to FCR is compensated by the TSOs. However, higher efficiencies are pursued in every field, and also hydropower production has been under interest. It has been suggested that the FCR production increases the wear and tear in the hydro turbines, due to mechanical wear in seals and bearings.

This topic lacks a complete research, which could set a price for FCR production. If the wear and tear proves to be significant enough to overcome the monetary revenues from FCR production, the FCR production with hydro turbines will be cancelled, which increases the FCR product demand and thus the monetary revenues.

If wear and tear proves out to outcome the FCR revenue, next dilemma arises; are the FCR requirements too demanding, thus causing excessive wear and tear, is the monetary revenues from FCR too small, or is the hydropower the best alternative in FCR production. The wear and tear research combined to the capabilities of hydropower plants when accurately optimized will prove out to be a dividing point for the conventional picture of the Nordic power grid control and hydropower usage.

The wear and tear research will also clarify, what is the technically and economically way to use hydropower in the Nordic power system. The fast ramping speeds of hydropower plants will have more value in the future, due to the challenges the Nordic power grid is facing, but it is unclear whether the ramping speeds should be used for frequency regulation or profit maximizing at the intraday power market.

7.1.2 Hydropower plant modelling tool

Hydropower production efficiency has already been increased to near theoretical maximum and the hydropower produced is traded with accurate planning and maximal profit exploitation. However, the production process itself in the Nordic countries rely heavily on experience gained before, instead of focusing on the ways new technologies could be interpreted to fine tune the system.

During this thesis research, it has been seen that the PID -controller setups and ways of thinking originate from history, when for example in Sweden only one company was in charge of determining the controller setups, while others merely followed. This provides reliable, but not necessarily the most efficient usage of PID –controllers, and more recent and sophisticated controller techniques should be researched to improve the hydropower plant handling.

Full scale hydropower plant modelling tool enables the simulated testing and also new types of optimization techniques. This could save a lot of time required for hydropower plant testing by changing TSO demands and such, but also provide additional tools for controller optimization and tuning.

The mathematical hydropower plant modelling tool enables simulated testing, which will help gather information about the hydropower plant behavior in a more economic manner. Nowadays the hydropower plant testing is done as a full scale tests, which requires lots of planning because of the long term production planning. Also, intraday markets make the full scale testing hard, and also economically quite large projects. If simulated and accurate testing could be performed, more research could be done on high efficiency and high demand operations, such as fast reaction to power grid frequency deviations or high capacity production in case of a large disturbances. More capacity could be gained, increasing the monetary annual revenues.

In addition to the simulated testing, the modelling tool would enable higher accuracy controller optimization. The controller optimization is done nowadays using either PID –controller optimization theorems, or using different test requirements to determine when the controller is sufficiently tuned. However, the controller types and structures used at hydropower plants are rather simple, due to the fact that they have been adequate in the past, and they are easier to tune. More simple structures in controller design usually limit some actions, and higher efficiencies and better performance could be reached with more complicated controller design. Tuning of these types of complicate full PID –controllers to the best performance available could be eased with the assistance of mathematical simulation and optimization.

8 SUMMARY

The main goals in this thesis were to research the main differences between the current and upcoming FCR requirements and then transpose these differences to demands casted on the Fortum hydropower plant fleet. For the scope of this thesis the hydropower plant fleet was narrowed down to applying just Kaplan powered Finnish hydropower plants as it was suggested earlier that the Finnish way of PID –controller tuning combined with Kaplan turbines would increase the difficulties.

With the help of documentation done by the Nordic TSOs in addition to the interview done at Fingrid, the differences between current and upcoming FCR requirements were defined. Also, the reason behind the upcoming change as well as a deeper understanding of the impacts casted by the change were understood.

The research done on hydropower plant automation and control systems, combined to the testing opportunities presented in Finland and Sweden located hydropower plants with some of Fortum’s hydropower specialists made it possible to allocate the demands posed by the FCR requirement change to the hydropower plant fleet, and to create a base for the FCR ranking capability system.

The FCR capability ranking system was first created on theoretical level, but the realization of insufficient and unreliable data combined to the lackluster performance of the modelling tool made it clear that the theoretical ranking could not be applied. However, the theoretical background could be used when the possible FCR capability ranking system was developed, thus gaining results but with decreased accuracy. These results however confirmed the suspicions that had arisen during the thesis research among the hydropower specialists.

The goals set in the beginning of this thesis were met, but not to the accuracy planned. However, this thesis provided a valuable list of further research projects as well as information on the hydropower plant fleet capabilities that had not been foreseen.

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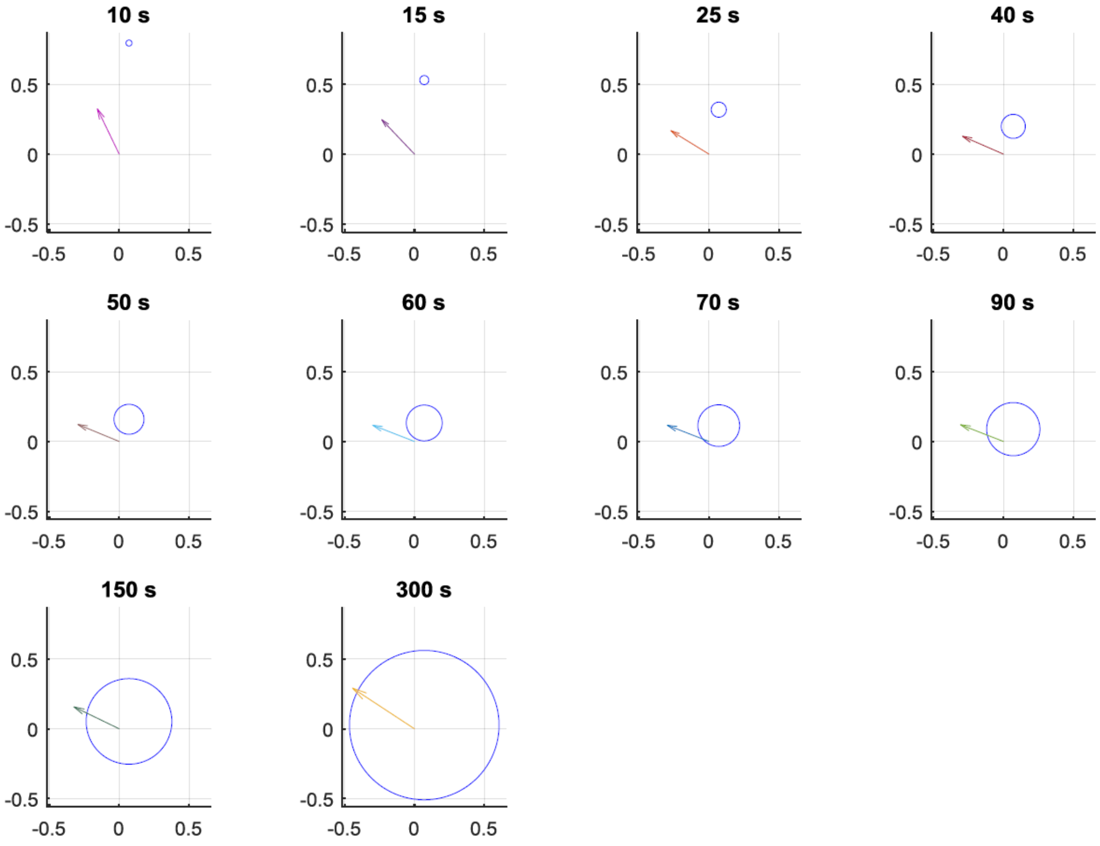
APPENDIXES

Appendix I: An example of a FCR dynamic performance test result

Time period [s]	Circle centre (x,y) [3] [p.u., p.u.]	Circle radius [p.u.]
10	(0.070, 0.796)	0.022
15	(0.070, 0.531)	0.032
25	(0.070, 0.318)	0.054
40	(0.070, 0.199)	0.086
50	(0.070, 0.159)	0.107
60	(0.070, 0.133)	0.128
70	(0.070, 0.114)	0.149
90	(0.070, 0.088)	0.190
150	(0.070, 0.053)	0.307
300	(0.070, 0.027)	0.535



Appendix II: The comparison of mathematically calculated water time constant and measured time constant at Nuojua TG 3

Test number	Power output [MW]	Flow rate [m3/s]	Height difference [m]	T_w [s]	$T_{P,m\&f}$ [s]	T_m [s]	Total time delay 63% [s]
#1	31	170	20,5	1,2	0,08	0,4	1,68
#3	28	150	20,9	1,04	0,08	0,4	2,01
#4	7	39	20,9	0,27	0,08	0,4	1,97

In this chart the test number #1 represents a commissioning test done by Andritz. Andritz provided a value for water time constant (T_w) and mechanical time constant (T_m), while time constant for power measurement and filtering ($T_{P,m\&f}$) is from the measurement device manual. The total time delay for 63% power output change has been calculated by combining the previous factors.

Test numbers #2 and #3 represent FCR tests done at Nuojua TG 3 by Timo Riikonen and Joonas Muikku (author) with two different power output values. In these cases the total time delay is measured from the test result and the water time constant has been calculated with the Eq. 50. The mechanical time constant is considered to stay same, as it is not seen been affected by power output or flowrate. The cells marked with light yellow contain self-calculated values, while the cells marked blue contain measured values.

From this chart it can be seen that the calculated time delay on small flowrate does not compare with the measured time delay

$$0{,}75s < 1{,}97s$$

which indicates that the equation used for water time constant calculation does not provide accurate results with low flow rates. There is also error on the higher power output result, but it is not as major as with the low power output result. Both of the measured values provide a different result than the one provided by Andritz.