Vaasan yliopisto
UNIVERSITY OF VAASA

Akseli Juslin

# Complementing a Kaplan hydropower turbine with a battery energy storage

BESS sizing for shared FCR-N market participation and reduction of turbine control movements

School of Technology and Innovations
Master of Science in Technology
Electrical Engineering

Vaasa 2021

## Acknowledgements

I would like to thank my employer VEO Oy for the possibility to be a part of this project and giving me an intriguing subject for my thesis. I have learned a lot on the way, and what a long road it has been. Several delays during the course of this project have made the writing work a struggle at times. The global COVID-19 pandemic has had its own unforeseeable impact on the progress of the whole project.

To Jukka Kelloniemi, thank you for your great expertise and knowledge that you kindly offered to me along the way.

To Janne Paavola and Juho Kaminen, thanks for your friendship during our studies together and for keeping me on track to finishing my studies one day.

To my parents, who have always supported me in my endeavours.

To Anna, thank you for being there for me all these years. Getting engaged, then married, traveling the world, buying a house, and even getting our first child. What a long time I have been at the university!

Vaasa, February 21th 2021

Akseli Juslin

**VAASAN YLIOPISTO**
**Tekniikan ja innovaatiojohtamisen yksikkö**

| | |
|---|---|
| **Tekijä:** | Akseli Juslin |
| **Tutkielman nimi:** | Complementing a Kaplan hydropower turbine with a battery energy storage : BESS sizing for shared FCR-N market participation and reduction of turbine control movements |
| **Tutkinto:** | Diplomi-insinööri |
| **Oppiaine:** | Sähkötekniikka |
| **Työn ohjaaja:** | Hannu Laaksonen |
| **Valmistumisvuosi:** | 2021 **Sivumäärä:** 60 |


**TIIVISTELMÄ:**

Pohjoismaisen sähköjärjestelmän sähkönlaatu on huonontunut viime vuosikymmenten aikana ja samalla normaalin taajuusalueen ulkopuolella vietetty aika on kasvanut. Verkkoon liittyy tulevaisuudessa entistä enemmän uusiutuvaa energiaa hydyntäviä voimalaitoksia, jotka ovat luonteeltaan epäsäännöllisiä.

Tämän työn tarkoituksena on tutkia energiavaraston asentamista Kaplan vesivoimaturbiinin rinnalle. Tämän vuoksi työssä tutkitaan olemassaolevia erilaisia teknologioita energian varastoimiseen. Näistä teknologioista valittiin yksi tähän tarkoitukseen sopiva. Energiavaraston teknologiaksi valittiin Lithium akku.

Käytössä olevan vesivoimalaitoksen Kaplan -turbiineja käytiin testaamassa useampaan otteeseen. Näiden testien tarkoituksena oli muun muassa energiavaraston koon mitoittaminen, turbiinisäätimen parametrien testaus ja hienosäätö.

Akkuihin perustuva energiavarasto voisi vähentää turbiinin ohjaustarvettu sen osallistuessa taajuusohjattuun käyttöreservikauppaan. Uusi ohjain, joka vastaisi kuorman jakamisesta energiavaraston ja turbiinin välillä on kehitteillä VEO:lla. Tässä työssä ehdotetulle ratkaisulle saatiin arvioitua noin 5 vuoden takaisinmaksuaika investoinneille.

**AVAINSANAT:** Energiavarasto, Kaplan turbiini, taajuussäätö

**UNIVERSITY of VAASA**
**School of Technology and Innovations**

| | |
|---|---|
| **Author:** | Akseli Juslin |
| **Thesis title:** | Complementing a Kaplan hydropower turbine with a battery energy storage : BESS sizing for shared FCR-N market participation and reduction of turbine control movements |
| **Degree:** | Master of Science in Technology |
| **Programme:** | Electrical Engineering |
| **Supervisor:** | Hannu Laaksonen |
| **Year of graduation:** | 2021 **Sivumäärä:** 60 |


**ABSTRACT:**

The frequency quality of the Nordic power system has deteriorated over the last decades. The number of minutes outside the normal frequency band area has increased. Furthermore, an oscillating behaviour of the grid has been observed with a growing amplitude. This oscillating behaviour increases the control work carried out by the hydro-power turbines. One of the main reasons for this development is the growing amount of power generation that is coming from intermittent energy sources, such as wind and solar.

The objective of the thesis is to explore the possibility to combine an electrical energy storage to an operational Kaplan turbine hydropower plant. To fulfil the objective, background work on different energy storage technologies was carried out by reviewing different technologies against each other for the sake of finding the most fitting technology for the purpose. A battery energy storage was chosen as the technology for the proposed application.

Measurements were made on operational Kaplan turbines to narrow down the scale of needed energy and power output for the electrical energy storage. Tests were carried out on different turbine governor models to find an optimal control scheme for the turbine.

A BESS could reduce the control movements of a Kaplan turbine operating in frequency control mode. A new controller that would share the primary frequency control regulation between the turbine and BESS is under development at VEO Oy. The payback time for an investment was found to be approximately 5 years.

**AVAINSANAT:** Electrical energy storage, Kaplan turbine, primary frequency control

## Contents

## List of Figures

## List of Tables

## Abbreviations

| | |
|---|---|
| ***aFRR*** | Automatic Frequency Restoration Reserve |
| ***CAES*** | Compressed Air Energy Storage |
| ***BESS*** | Battery Energy Storage System |
| ***BMS*** | Battery Management System |
| ***DoD*** | Depth of Discharge |
| ***EES*** | Electrical Energy Storage |
| ***FCR*** | Frequency Containment Reserve |
| ***FCR-D*** | Frequency Containment Reserve for Disturbances |
| ***FCR-N*** | Frequency Containment Reserve for Normal Operation |
| ***FFR*** | Fast Frequency Reserve |
| ***HVDC*** | High-Voltage Direct Current |
| ***IGBT*** | Insulated-Gate Bipolar Transistor |
| ***mFRR*** | Manual Frequency Restoration Reserve |
| ***PHS*** | Pumped Hydroelectric Storage |
| ***PLC*** | Programmable Logic Controller |
| ***PWM*** | Pulse-Width Modulation |
| ***SOC*** | State Of Charge |
| ***SMES*** | Superconducting Magnetic Energy Storage |
| ***UPS*** | Uninterruptible Power Supply |
| ***VSC*** | Voltage Source Converter |

# 1 Introduction

The increasing amount of intermittent renewable energy sources and a more complex structure of power systems is contributing to the growing demand and importance of primary frequency control of hydropower plants. This is also creating problems for the turbines by increasing their wear and tear. (Yang, Norrlund, Saarinen, Yang, Guo & Zeng 2016: 88.)

The electricity market is undergoing a transformation that will eventually lead to 15-minute periods in electricity trading (Fingrid 2019: 8). The FLEXIMAR research project carried out by VTT and Vaasa University is finding new ways for smaller loads and power generation units to be implemented into the reserve markets. This would mean that one may participate in the frequency containment reserve markets with a smaller power and energy capacity.

The Nordic transmission system operators are responsible of maintaining the grid frequency and voltage close to their nominal values. To maintain a balance in the power system, the operators procure ancillary services, such as frequency control, from the electricity market bidders. Frequency under normal operation is referred to as normal band, and it is restricted to the range of 49.9 – 50.1 Hz. Unfortunately, the frequency quality of the Nordic power system has deteriorated over the last decades. The number of minutes outside the normal frequency band area has increased. Furthermore, an oscillating behaviour of the grid has been detected, these oscillations have a period of 40 – 90 seconds and their amplitude has grown. This oscillating behaviour increases the control work covered by the hydropower turbines. (Olsson 2017: 1.)

The purpose of this master's thesis is to research background information for a hybrid solution where a battery energy storage system is connected to a hydropower plant. What are the criteria and demands for such a system? What could be the benefits of this system compared to a stand-alone hydro power plant? These are the kind of the questions I will try to answer in this thesis.

The benefits such a system might have on the operation of a hydropower plant are assumed to be the following. Using the battery energy storage as a buffer for the primary frequency control of the turbine could lengthen the maintenance intervals of the turbine and decrease the effects of wear and tear, possibly cavitation as well. When the frequency deviation from 50 Hz is small, the batteries will inject or absorb power from the grid and in this way decrease the need to constantly change the output power of the turbine.

Chapter 2 reviews different energy storage technologies. Several different technologies are presented shortly, and their characteristics and some key properties are evaluated. In addition, different applications from the grid point of view are explained. Chapter 3 continues from here by presenting an overview of the chosen technology.

In chapter 4, some of the main components of Kaplan hydropower turbines are briefly explained. Information about turbine control, wear and tear, cavitation and frequency control of the turbine will be included. Chapter 5 consists of an overview on the reserve electricity markets in Finland.

Chapters 6 introduces an operational hydropower plant which is the case study behind this master's thesis. Unfortunately, a lot of information could not be shared in order to protect the intellectual property of VEO Oy and the power plant owner. Chapter 7 will continue from here by introducing a proposed system for a hybrid application. Finally, in chapter 8 the conclusions of the study will be presented.

## 2 Energy storages in power grids

The conventional power grid structure is shown in figure 1. It consists of large centralized power plants, transmission and distribution systems and consumers. Power flow is uni-directional and there is little or no storage facility. As a result, power generation and consumption must be equal at all times, even though the demand for electricity varies considerably during the day and seasonally. Consequently, the power generating capacity needs to correspond to the peak demand of electricity that may only last for a few hours per year. This leads to building expensive plants that may only be in use for a short period in any given year. Electrical energy storages (EES) enable power generation to be de-coupled from the consumption. (Chen, Cong, Yang, Tan, Li, & Ding 2009: 292.)

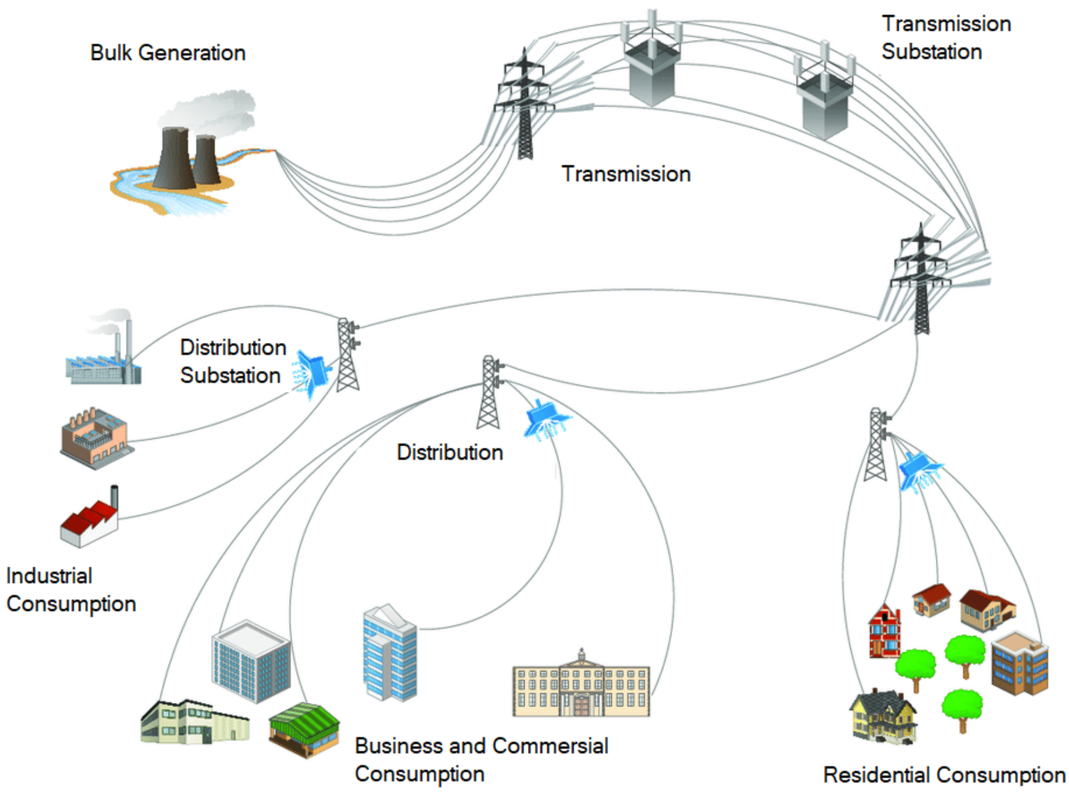


**Figure 1.** Conventional power grid structure.

Electrical energy storage can have many attractive functions for power network operation and load balancing. Such functions include (Luo, Wang, Dooner & Clarke 2015: 511-512):

- Helping in meeting electrical load demands during peaks, while also decreasing the electrical energy import,
- Providing time varying energy management,
- Ease the irregularity of power generation from renewable sources,
- Improvement of power quality and reliability,
- Helping the management of distributed and standby power generation,
- Supporting the actualization of smart grids.

Currently installed capacity worldwide is at least 140 GW of large-scale energy storages. The majority of the capacity (99%) consists of pumped hydro storages and the remaining 1 % is a mix of battery, compressed air, flywheel, and other storage technologies. (IEA 2014: 16.)

## 2.1 EES applications

The possible applications for EES can be divided in four subgroups that are (1) generation, (2) transmission and distribution, (3) energy service and (4) renewable energy. Below are listed some applications and they are numbered according to the four groups (Chen et al. 2009: 293) (IEA 2014: 10):

- **Commodity storage**: Storing bulk energy during the night and releasing it during peak demand hours of the day enables to arbitrage the price of production of these two periods and guarantees a more constant load factor for generation, transmission and distribution. (1)

- **Contingency service**: In case of a power facility falling off-line, contingency reserves are needed to supply power to the customers. (1)
- **Area control**: Preventing unplanned power transfer between utilities. (1)
- **Frequency regulation**: Load variations affect the frequency of the grid. EES can help balance out these variations and maintain frequency equilibrium. (1)
- **Black start**: Able to start up on their own in case of a black-out, help to re-energize the transmission system and other units to start-up and synchronize to the grid. (1)
- **System stability**: Synchronous operation of all system components on the same transmission line and the ability to maintain this operation. (2)
- **Voltage regulation**: Keeping voltages between each end of all power lines stable by injecting or absorbing reactive power. (2)
- **Congestion relief and asset deferral**: Using EES to defer the need for new installations and investments for transmission and distribution grids infrastructure. (2)
- **Energy management**: Enables customers to peak shave by time-shifting their energy demand from peak hours to other hours of the day. May reduce costs for consumer. (3)
- **Power quality and reliability**: Providing electricity to customers without oscillations, dips, spikes or harmonics in the voltage and capability to ride-trough power disruption, uninterruptible power supply (UPS). (3)
- **Transmission curtailment**: In cases when the production of intermittent power generation exceeds the transmission grids capacity. (4)
- **Time-shifting**: Storing excess power generated during peaks and using it during periods of less generation. (4)

In addition to applications listed above, there are applications that can solve problems faced in the intermittent renewable energy production (e.g. wind, solar and wave) and their widespread deployment in the future. Forecast hedge, grid frequency support and fluctuation suppression are, in their core, applications for diminishing the negative effects the intermittency of renewable power generation has on power grids and profitability while maximizing the energy output from renewables. (Chen et al. 2009: 293-294.)

Besides listing possible applications for EES there is need for differentiating the applications by their characteristics or prerequisites. This is done in table 1 where applications are listed in terms of different requirements, such as size (MW), discharge duration, typical cycles and response times. From table 1 we can see that when the size of the storage system grows larger, the discharge duration becomes longer, but the response time required from such a system is prolonged. For an energy storage system that has a capacity of a few MW and a response time in the timescale of seconds, we can see that there are several possible applications: frequency regulation, load following, voltage support, black start and demand shifting and peak reduction.

**Table 1.** Key characteristics of storage systems for chosen applications. (IEA 2014, 9.)

| Application | Output | Size (MW) | Discharge duration | Cycles (typ-ical) | Response time |
|---|---|---|---|---|---|
| Seasonal storage | electricity, thermal | 500 to 2 000 | Days to months | 1 to 5 per year | day |
| Arbitrage | electricity | 100 to 2 000 | 8 hours to 24 hours | 0.25 to 1 per day | >1 hour |
| Frequency regula-tion | electricity | 1 to 2 000 | 1 minute to 15 minutes | 20 to 40 per day | 1 min |
| Load following | electricity, thermal | 1 to 2 000 | 15 minutes to 1 day | 1 to 29 per day | <15 min |
| Voltage support | electricity | 1 to 40 | 1 second to 1 minute | 10 to 100 per day | millisecond to second |
| Black start | electricity | 0.1 to 400 | 1 hour to 4 hours | <1 per year | <1 hour |
| Transmission and Distribution (T&D) Congestion relief | electricity, thermal | 10 to 500 | 2 hours to 4 hours | 0.14 to 1.25 per day | >1 hour |
| T&D infrastructure investment deferral | electricity, thermal | 1 to 500 | 2 hours to 5 hours | 0.75 to 1.25 per day | >1 hour |
| Demand shifting and peak reduction | electricity, thermal | 0.001 to 1 | Minutes to hours | 1 to 29 per day | <15 min |
| Off-grid | electricity, thermal | 0.001 to 0.01 | 3 hours to 5 hours | 0.75 to 1.5 per day | <1 hour |
| Variable supply resource integration | electricity, thermal | 1 to 400 | 1 minute to hours | 0.5 to 2 per day | <15 min |
| Spinning reserve | electricity | 10 to 2 000 | 15 minutes to 2 hours | 0.5 to 2 per day | <15 min |
| Non-spinning reserve | electricity | 10 to 2 000 | 15 minutes to 2 hours | 0.5 to 2 per day | >15 min |

Spinning reserve and non-spinning reserve are also mentioned in table 1. These refer to the reserve capacity of electricity supply that can be utilized during rapid, unexpected loss of generation and their task is to keep the system balanced. They are classified according to their response times: under 15 minutes for spinning reserve and over 15 minutes for non-spinning reserves. (IEA 2014, 11.)

## 2.2 Key factors in assessment and comparison of EES

In order to compare different energy storage technologies and explore the ones that meet the demands of purposed application, there needs to be selection criteria for characteristics of the storage technologies. The more obvious criteria are the type (portable or permanent storage), storage duration (short or long term) and the maximum power needed. There are several other important factors that play an important role in the selection and they need to be analysed when selecting a storage technology. Some of these will be discussed next. (Ibrahim, Ilinca & Perron 2008: 1237.)

### 2.2.1 Storage capacity, duration, available power and discharge time

Storage capacity is the total energy stored in the energy storage system after charging. Discharge from a storage system is many times incomplete which results in the energy available to be retrieved from the storage being lower than the total energy stored. The maximum depth of discharge (DoD), in other words the minimum charge state of the storage, limits the usable energy available. (Ibrahim et al. 2008: 1237.)

Storage duration is another factor that impacts decisions concerning the storage technology selection. Storage duration exhibits the amount of stored energy that can be retained by the storage system over a period of time. Duration is affected by another important factor which is self-discharge rate. Self-discharge refers to dissipation of the amount of stored energy over time. For long term storage applications, the storage systems with a very low self-discharge rate are generally suitable. (Aneke & Wang 2016: 367.)

Available power is a determining factor for a storage system. It depicts the maximum power of charge or discharge of the storage system. It is usually expressed as a peak value and an average value. The discharge time, on the other hand, is the period of time the storage unit can be discharged at maximum power. The discharge time depends on the power output and DoD. (Ibrahim et al. 2008: 1237-1238.)

### 2.2.2 Round trip efficiency, durability and response time

Round trip efficiency can be calculated by dividing the output of electricity from the energy storage system with the electricity input during one whole charge/discharge cycle (Aneke & Wang 2016: 369). In order to get a realistic efficiency factor, the measurement or calculation should take into account the practical usage of the energy storage system (Ibrahim et al. 2008: 1238.)

Durability refers to the number of total charge/discharge cycles the energy storage system can manage and still be able to release the amount of energy it was designed for. All energy storages wear out over time and usage. The amplitudes of the charge/discharge cycles and the average state of charge are strongly linked to the fatigue of energy storage systems. Therefore, the total amount of cycles varies depending on usage. This is why total cycles given for a storage system represent orders of magnitude not absolute values. (Ibrahim et al. 2008: 1238-1239.)

Response time describes how fast the energy storage system can supply power. A fast response time, in order of milliseconds, is paramount for applications like power quality, rapid voltage drops and reducing flicker (other applications do not require as fast response times as can be seen from Table 1). (Aneke & Wang 2016: 369.)

### 2.2.3 Lifetime, costs and technological maturity

Lifetime of the storage system is also an important factor in deciding on a storage technology for a given application. A technology with a longer lifetime is more likely to be invested upon than an otherwise equal technology with shorter lifetime. This makes sense from an investment point of view; longer lifetime contributes to better return on initial investment. Battery based systems generally have a shorter lifetime due to chemical decay over time as opposed to mechanical storage technologies that may have a lifetime of up to 60 years. (Aneke & Wang 2016: 367.)

Probably the most important factor in choosing an energy storage system will evidently be the cost. Any technology, if not commercially viable, will not be deployed on a large scale. Cost analysis should include capital costs and operating costs in order to be able to calculate the possible feasibility of the energy storage system for any given application. The operation costs include operation, maintenance, disposal and replacement costs. The auxiliary components needed for some storage technologies add to the capital costs of the storage system so they will only be sensible above certain power output and energy content. There are different ways to express the costs of an energy storage system, for instance, cost per kWh, per kW and per kWh/cycle. (Aneke & Wang 2016: 367.)

Technological maturity is another factor affecting the choice between different energy storage systems. The more mature the technology is, the more there is experience and expertise in operating such a system. It also influences costs; the maturity of the technology drives down the costs and therefore makes it a more compelling option. (Aneke & Wang 2016: 369.)

## 2.3 EES technologies and classification

Electrical energy cannot be stored directly to energy storage systems in an alternating current grid and therefore it has to be converted into other forms of energy. These include electrochemical, magnetic and mechanical energy storage technologies. (Boicea 2014: 1778.)

A more visual presentation of energy storage technologies classification is given in the book Energy Storage in Power Systems (Sumper, Gomis-Bellmunt & Díaz-González 2016: 94) which I have reproduced in figure 1. The figure also shows timescales for each technology and adds a fourth class named thermal storage. As can be seen from figure 2, there are a lot of different energy storage technologies and choosing the right technology for the right application entails knowledge of the planned usage and its requirements, furthermore knowledge of the proposed EES technology.

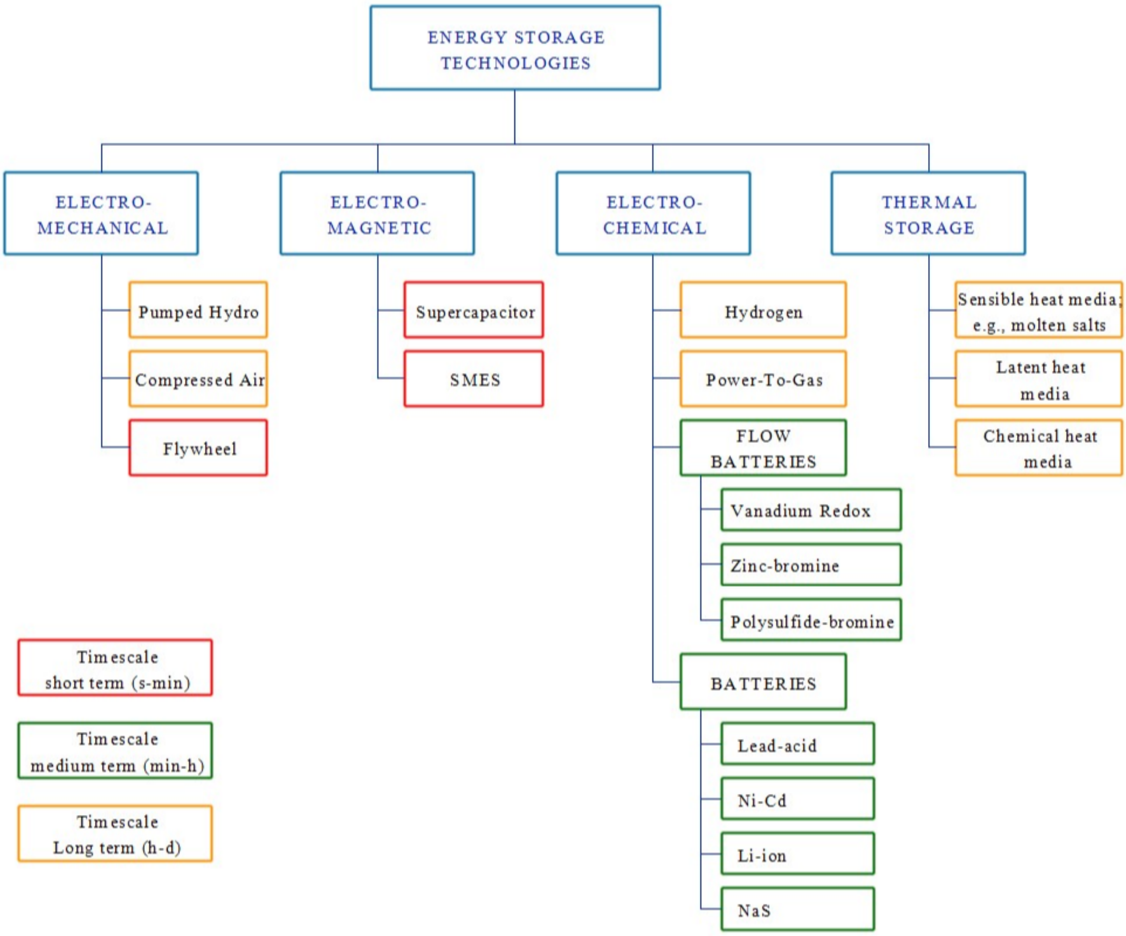


**Figure 2.** A catalog of energy storage technologies.

### 2.3.1 Electromechanical energy storage systems

Pumped hydroelectric storage (PHS) is the most used and most mature energy storage technology for high power applications. Its operating principle is fairly straigthforward: during periods of low demand the excess energy is consumed from the grid and it is used to pump water from a lower reservoir to an upper reservoir. This process is then reversed in times of high demand of electricity and power is injected to the grid. The stored energy is based on the gravitational potential energy of water. (Sumper et al. 2016: 94.)

Compressed air energy storages (CAES) basic principle is also simple. Electrically driven compressors are used to compress air and the pressurized air is stored in any kind of volume, for example underground caverns. Energy is converted from electrical energy to potential energy of the pressurized air. Energy can be released back to the grid by expanding the air through an air turbine. A large variety of different concepts of the CAES technology exist today. (Budt, Wolf, Span & Yan 2016: 253.)

Flywheels are essentially cylinders coupled to the shaft of an electric motor-generator. The system stores energy kinetically in the rotating cylinder and it is charged when the system is used as a motor and discharged when it is used as a generator. Nowadays the systems use magnetic bearings and they are placed in a vacuum in order to reduce friction and wind shear. Flywheels are only suitable for short term storage applications as their self-discharge rate is about 20 % of the stored energy per hour. (Sumper et al. 2016: 114-116.)

### 2.3.2 Electromagnetic energy storage systems

Supercapacitors consist of electrochemical cells that have two electrodes (anode and cathode), an electrolyte and a porous membrane. The membrane allows ions to transit between the electrodes. The layout is similar to the electrochemical cells in batteries, but there are no chemical reactions occurring in supercapacitors and the energy is stored in the cell electrostatically. The anode is negatively charged, the cathode is positively charged, and the electrolyte has both negative and positive ions. When a voltage is applied over the electrodes an electrical double layer phenomenon occurs near the electrodes as they interface with the electrolyte. These double layers form the electric field where the energy is stored. (Sumper et al. 2016: 120-125.)

In the case of superconducting magnetic energy storage (SMES) the energy is stored in a magnetic field. The magnetic field is generated by a direct current flowing through a coil made from superconducting material. In order to maintain the superconducting state, the coil needs to be cooled to very low temperatures using liquid nitrogen or liquid helium. Since superconductors offer no resistance to current the energy losses are close to zero apart from the cooling system. (Hall & Bain 2008: 4355.)

### 2.3.3 Electrochemical energy storage systems

Hydrogen energy storage systems are based on producing hydrogen with an electrolyzer when there is excess energy. The hydrogen is then stored and afterwards fed to fuel cells for electricity production when power is needed. (Agbossou, Kolhe, Hamelin & Bose 2004: 633.) Hydrogen is part of the power-to-gas concept that also includes mak-ing synthetic methane. Gases that are produced with excess power available can be used in many different applications such as gas grid, gas powered vehicles and industry. (Sumper et al. 2016: 127.)

Energy storage systems with conventional batteries and flow batteries are based on the conversion of electrical energy into chemical energy and back. The reactions happening in the battery cell are reduction and oxidation, also known as redox. Batteries have the following components: the two electrodes (anode and cathode), an electrolyte, a separator and a container. The anode is the negative electrode and the cathode is the positive elec-trode. The electrolyte is a substance that enables the redox reactions to happen between the two electrodes and ions to exchange between the electrodes. The electrolyte is an electronically insulating substance. A separator is used to prevent an internal short circuit of the battery and a container is used to pack the battery cells into a closed and controlled environment. (Sumper et al. 2016: 97-99.)

### 2.3.4 Thermal energy storage systems

Thermal energy is often stored directly in the moment of being produced. This is done in order to avoid energy conversion losses. Thermal energy storages are therefore explained as systems that absorb, store and release thermal energy in a controllable way. Molten salts are used in solar power plants as sensible heat media. The molten salt is heated with heat from the sun gathered by the solar field. The hot molten salt is then used to warm up a heat transfer fluid via heat exchanger, and the heat transfer fluid is used to run the turbine which is connected to a generator. Thermal storage can be used for instance to time-shift the energy production so that even when there is no sun the turbines can run from the heat stored in the molten salt. (Sumper et al. 2016: 125-127.)

# 3 Chosen technology: Lithium battery energy storage

The previous chapter focused on providing a more profound picture on the existing energy storage technologies and their characteristics. This work allowed to narrow down the possibilities for an energy storage technology that might be used together with a hydro power plant.

The requirements were established by measurements carried out at Hydropower Plant 1., the results of which are explained in chapter 6. The requirement for the physical size of the storage system was determined by the available space in existing electrical rooms at Hydropower Plant 1. An existing spare cubicle in the low voltage switchgear was considered as a connection point for the storage system as this would reduce costs. Different energy market participation options were considered for the energy storage system. FCR-N market place was chosen for the application presented in this thesis. The key requirements for the proposed application were then specified and their rough estimates were the following: electricity output, energy storage size in the region of 80 – 200 kWh, discharge duration between 1 second to 1 hour and a response time in the region of millisecond to seconds.

The best alternative was determined to be a battery energy storage. Lithium-Ion batteries were chosen as the technology for electrical energy storage. Lithium-ion batteries are superior compared to other battery chemistries in terms of cycle efficiency. This can be seen in figure 3 where different storage technologies are compared against each other. Self-discharge losses are not considered in this comparison. Lithium-ion batteries have a very high cycle efficiency of over 90 %. It makes sense to choose a technology that has less losses during operation.

A comparison of life expectancy and energy efficiency of different technologies is given in figure 4. This also supports lithium-ion as the most fitting technology for the proposed application. Compared to other batteries it has the highest efficiency and longest life expectancy.

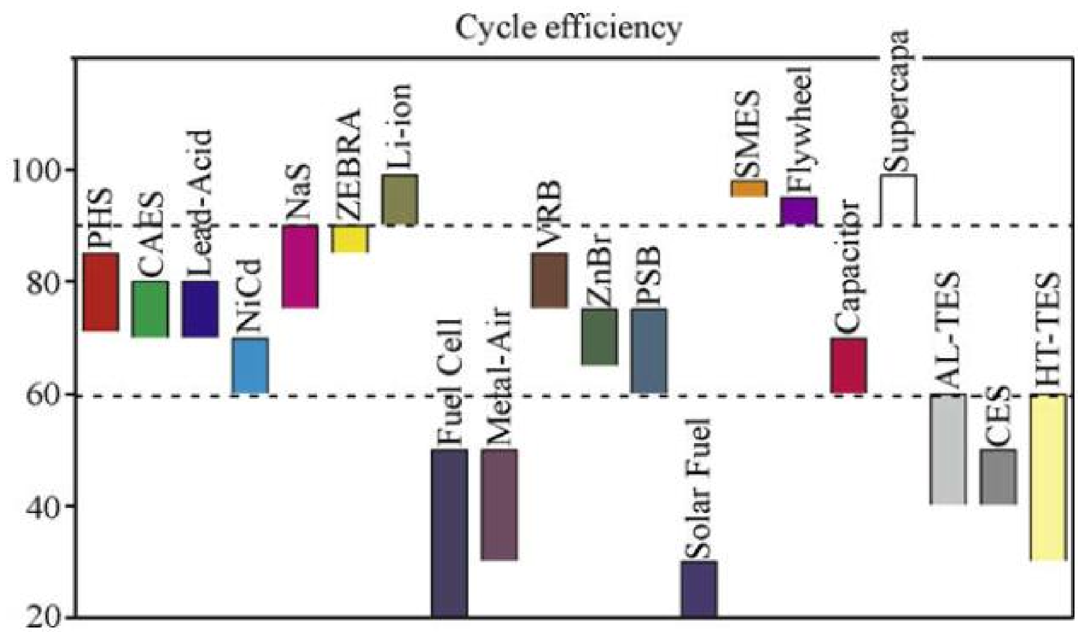


**Figure 3.** Cycle efficiency of EES systems. (Chen et al. 2009.)

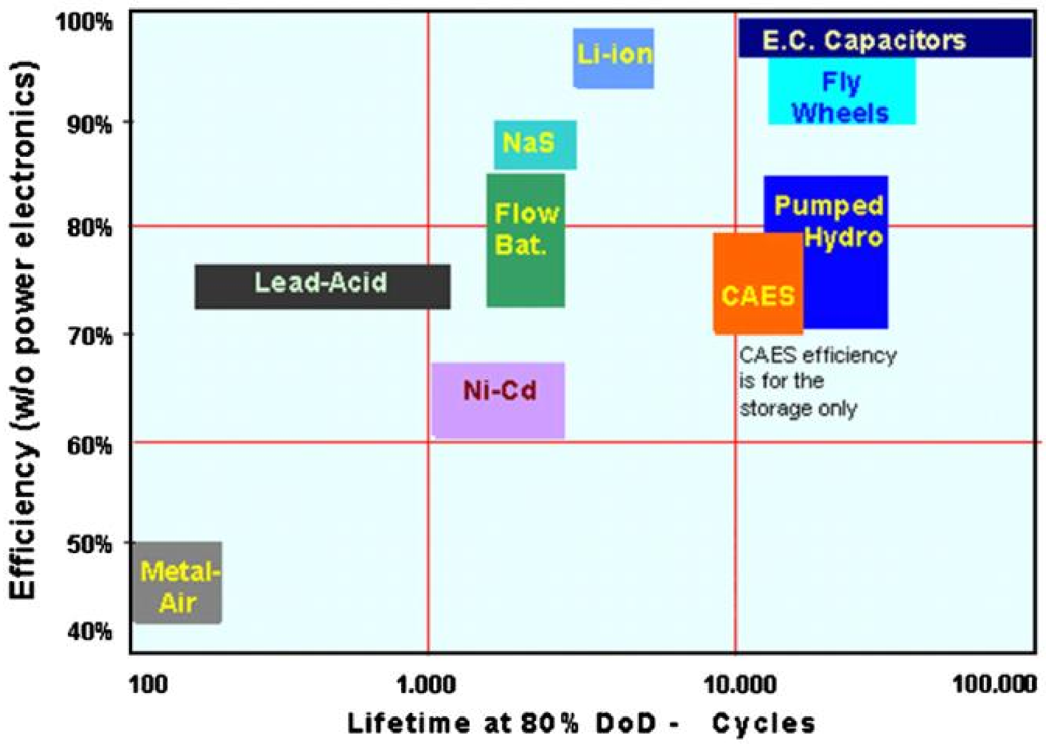


**Figure 4.** Distribution of storage technologies as a function of energy efficiency and life expectancy. (Ibrahim et al. 2008.)

Another factor influencing the decision was the price of the technology. Lithium-ion battery prices have been on the decline for almost three decades now. And the trend is most likely to continue as production quantities are rising. In figure 5 you can see the price of Lithium-ion batteries over the course of 25 years. On the Y-axis is the prize of in USD per kWh and on the X-axis is time. Utility scale projects have been mapped from the year 2000 to 2017. During this time period the price for utility scale batteries have fallen from 4285 USD/kWh to 1568 USD/kWh. This is 63 % reduction in overall prize per kWh over the course of 18 years.

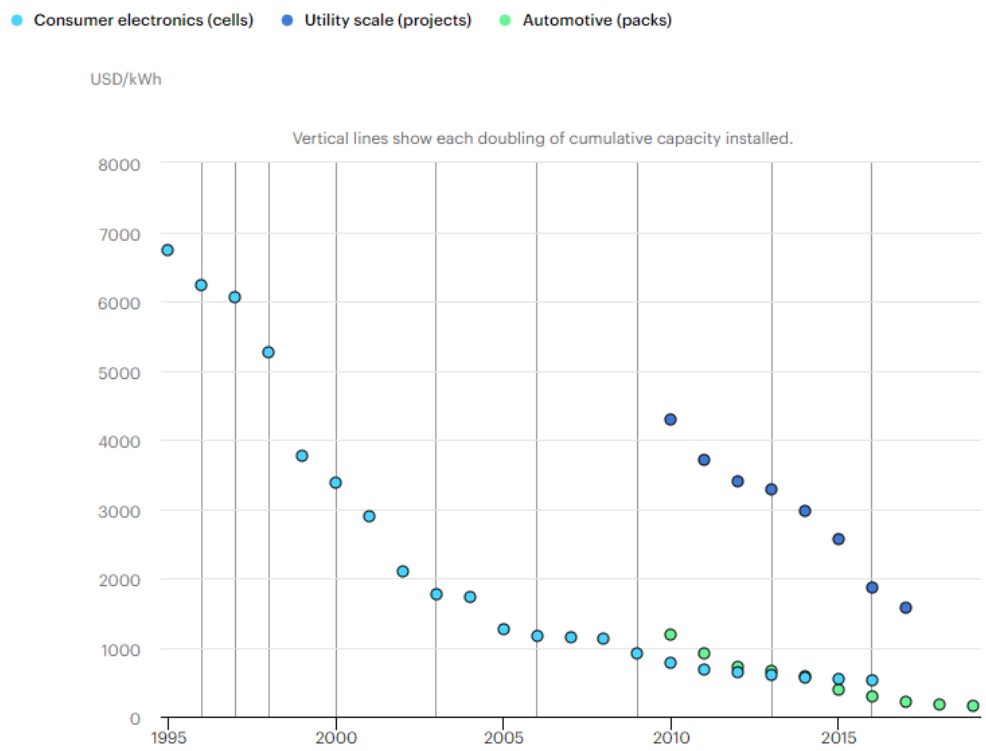


**Figure 5.** Evolution of Li-ion battery price, 1995-2019. (IEA 2020.)

Self-discharge, which is the energy dissipation from the energy storage system during storing periods is of medium ratio in Lithium-ion batteries. This means that they are suitable for applications where the storage period does not exceed a period of ten days. In the case of primary frequency control this is not a problem as the storage periods are short. (Chen et al. 2009.)

Other factors that turned the scale in favour of this technology were: maturity of the technology, its physical size, easy to install, and the fact that expansion and updating in the future should be easy.

## 3.1 Basic battery specifications

A battery energy storage comprises of cells, modules and packs. A cell is the smallest packaged form of a battery and it has a voltage in the region between 1 to 6 volts. Several cells are combined, in series or in parallel in order to form a module. These modules are then connected again, in series or parallel to form a battery pack with a desired voltage level. (MIT 2008.)

C -rate of a battery describes the rate of discharge relative to the batterie's maximum capacity. For example, a 1C battery will discharge the entire battery in one hour. A 2C battery would be depleted in 30 minutes. E-rate (MIT 2008.)

Battery condition is described by several variables. State of charge (SOC) expresses the battery's present charge level. This is given as a percentage of the battery's maximum capacity. Depth of discharge is the opposite of state of charge. It expresses how much of the battery's capacity has been discharged. A deep discharge is referred to when the depth of discharge is at least 80 %. Terminal voltage is measured from the battery terminals when load is applied. The terminal voltage changes depending on the state of charge and charge/discharge current. Open circuit voltage in turn is measured from the terminals when no load is connected. Open circuit voltage increases with the state of charge. Internal resistance is the resistance inside the battery. When internal resistance increases, the battery's efficiency decreases because more energy is converted into heat. Internal resistance is usually different for charging and discharging. (MIT 2008.)

Technical specifications of a battery are abundant, and I will name some of them here. Nominal voltage is the reported or normal voltage of the battery. Cut-off voltage is the minimum allowed voltage of the battery which defines the empty state of the battery. Energy of the battery describes the energy capacity of the battery in Wh. Cycle life is the amount of charge/discharge cycles that can be expected from the battery at a predefined performance criteria. The operating life of a battery depends on the rate and depth of cycles, and by conditions such as humidity and temperature. (MIT 2008.)

## 3.2 Connecting a battery energy storage to the grid

A battery energy storage system (BESS) comprises of the voltage source converter (VSC) and the battery pack where the energy is stored. The rating of the converter is the determining factor for the systems operating range. The phase shifting action of the DC/AC -inverter can provide reactive power compensation from the battery to the grid, which is limited by the inverters apparent power capacity. (Adewuyi, Shigenobu, Ooya, Senjyu & Howlader 2019.)

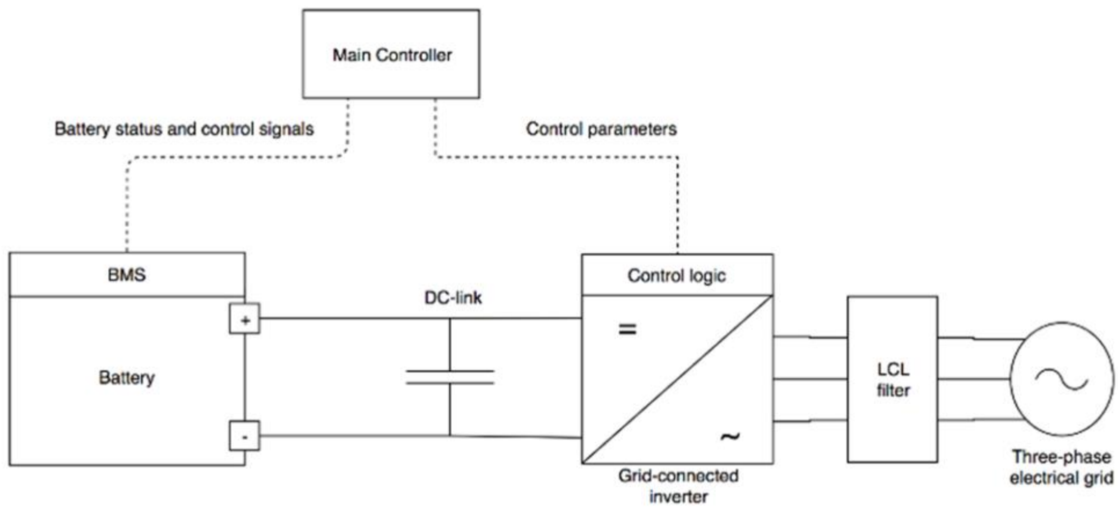


**Figure 6.** Schematic for a grid connected BESS assembly. (Ovaskainen, Öörni & Leinonen 2019.)

A grid-scale BESS has its own Battery Management system (BMS) which integrates control and protection of the battery. This enables the monitoring of the battery and ensures safe operating conditions. The battery terminals are connected to a DC-link which in turn is connected to the terminals of the inverter. The DC-link voltage is controlled by the battery and the link has a capacitor that can absorb or discharge transient currents. These transient currents are generated by the inverter when the switching action is rapid. The inverter uses power semiconductor switches that are typically Insulated-Gate Bipolar Transistors (IGBTs). A normal control method for the switches is Pulse-Width Modulation (PWM)-based. The schematic of the system described here is illustrated in figure 6. In this figure you can also see a grid-side passive filter for the inverter. This smoothens the voltage waveform and eliminates switching frequency harmonics from the output. (Ovaskainen, Öörni & Leinonen 2019.)

## 3.3 Management and control of battery energy storage system

A BESS can be used for different applications and depending on the application the control of the system also changes. Some examples for applications are black start, peak shaving, frequency regulation, and microgrid voltage and frequency control. In frequency regulation operating mode, the BESS emulates the operation of a synchronous generator. It dispatches power when the grid frequency drops below nominal and then consumes power when the frequency is higher than nominal. In microgrids a BESS can be used to form a grid. It can be controlled as a voltage source that gives other inverter connected loads a frequency reference. The other inverters can in this case be controlled as current sources. Another option is that all inverters in the microgrid are controlled as voltage sources in droop mode for automatic load sharing. (Ovaskainen, Öörni & Leinonen 2019.)

There are principally five individual control elements in BESS control. These being: frequency controller, voltage controller, Active power (P) and reactive power (Q) control, charge controller, and current controller on direct (d) and quadrature (q) axis. Frequency controller reacts on the deviation of frequency from nominal value. The droop setting limits the battery full active power activation by dividing the size of the deviation with a droop setting value. (Datta, Kalam & Shi 2019.)

The voltage controller reacts to voltage deviations from nominal value. The difference is calculated by subtracting the real voltage value from the voltage reference. BESS absorbs reactive power when this value is negative, meaning that the voltage is too high, and injects reactive power when the voltage is too low. This control also uses a droop setting. (Datta, Kalam & Shi 2019.)

The charge controller creates a charging/discharging signal based on the current SOC of the battery and the incoming current reference value of d-axis. Active power is regulated by the BESS if battery SOC satisfies the current operating conditions. This means that the battery cannot be charged if it is already at full charge or vice versa. The reactive current is not considered in charge control. A current limiter restricts the total current flowing through d and q-axis to avoid the overloading of the converter. (Datta, Kalam & Shi 2019.)

The PQ control of BESS is more complicated than the previous controllers. The active and reactive power at BESS output are compared to the reference values of previous (frequency and voltage) controllers. The active power difference is then added to the difference of charge controller input and output current on d-axis. From these inputs a PI controller generates the active power reference. Similar calculations are done for the reactive power reference. The PQ control can be tweaked by giving preferences to active power over reactive power by implementing a deadband or a lower gain for the reactive power activation. A first order low pass filter is used to smooth out the input and the time constant in this filter defines the dynamic behaviour of the output. This controller is given maximum and minimum values that are tuned by trial and error. These parameters diminish the overshoot and undershoot of frequency as well as settling time. (Datta, Kalam & Shi 2019.)

### 3.3.1 Battery degrading

One of the main factors that degrade battery lifetime is the amount of charge/discharge cycles and their DOD. Higher charge currents increase the change in DOD during the operating period and this affects the battery lifetime negatively. Fast charging/discharging cycles in frequency control reduce the lifetime of a battery. (Datta, Kalam & Shi 2019.)

The capacity of a battery changes over the course of its lifetime. The main factors of degradation can be divided into external factors such as temperature and time and internal factors such as state of charge, current and depth of discharge. Contrary to Datta et al. (2019) Mahesvari et al. claim that lower degradation of battery capacity is experienced in the range of 30-60% SOC. In lower or higher charge states the battery degrades faster. It would then make sense to optimize the battery usage so that the state of charge is most of the time inside this region. (Maheshwari, Paterakis, Santarelli & Gibescu 2020.)

# 4 Kaplan turbine hydropower plant

A hydropower machine is a machine that converts the hydraulic power of a water fall into mechanical power on the machine shaft. The hydropower machine has necessary equipment to regulate the power input and output according to conditions dictated by the variable grid load, alternating heads, and flow discharges. (Kjølle 2001: 1.1.)

The increasing amount of intermittent renewable energy sources and a more complex structure of power systems is contributing to the growing demand and importance of primary frequency control of hydro power plants. This is also creating problems for the turbines by increasing their wear and tear. (Yang, Norrlund, Saarinen, Yang, Guo & Zeng 2016: 88.)

In this chapter I will explain briefly some of the components of the Kaplan turbine. I will also have a look at how the Kaplan turbines are governed and the effects of wear and tear of the turbines as well as cavitation.

## 4.1 Brief description

The Kaplan turbine was designed by Professor Kaplan and it was patented in 1913. Shortly after that he developed the turbine further and added revolving runner blades. Kaplan turbine was a great improvement in the domain of low-pressure turbines, and it is dominant in this region even today. Kaplan turbines are utilized when there are low heads and large water discharges. They are suitable for this application due to their dimensions which are relatively small, their high rotational speeds, a large overloading capacity and their favourable progress of the efficiency curve. Kaplan turbines are axial flow machines, this means that the water flow is parallel to the axis of the turbine. (Kjølle 2001: 1.4, 8.1)

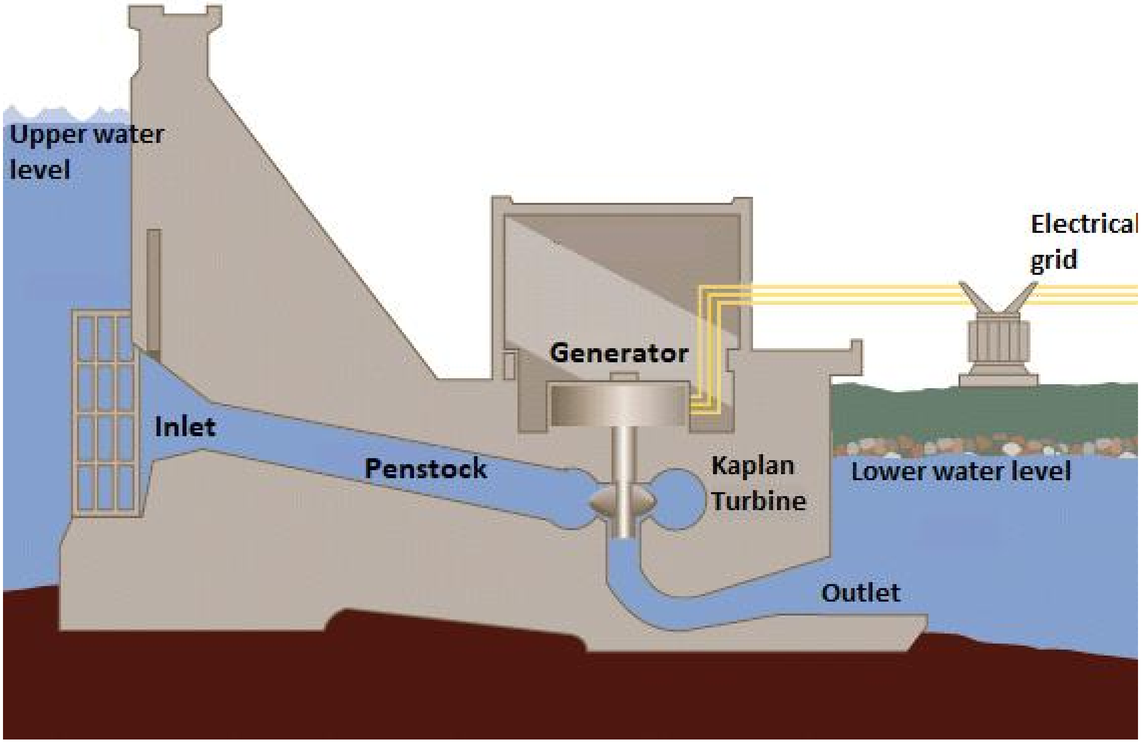


**Figure 7.** Hydropower plant with Kaplan turbine. (Gustafsson 2013.)

Arrangement of a Kaplan turbine is as follows. Water flows from the upstream basin into the scroll casing. From there the water flows via the stay ring and the guide apparatus into the runner. After the runner the water flows by the draft tube and enters the tail water basin. (Kjølle 2001: 8.1.)

The penstock transports the water from the upper water basin to the turbine. It consists of an inlet, the turbine passage, and an outlet. These parts of the hydropower plant can be seen in figure 7. The net head, which is the difference between the upper and lower level of water, dictates the largest amount of energy available for the turbine. This is only a theoretical figure as friction losses and water dynamics reduce the available energy. An interesting phenomenon happens when the wicket gates are opened more to increase the power output. This in turn will increase the water flow but the pressure on the inlet side will drop for a short period of time. This creates a voltage drop in the turbines out-put during fast up-regulation of the turbine power output. (Gustafsson 2013: 9.)

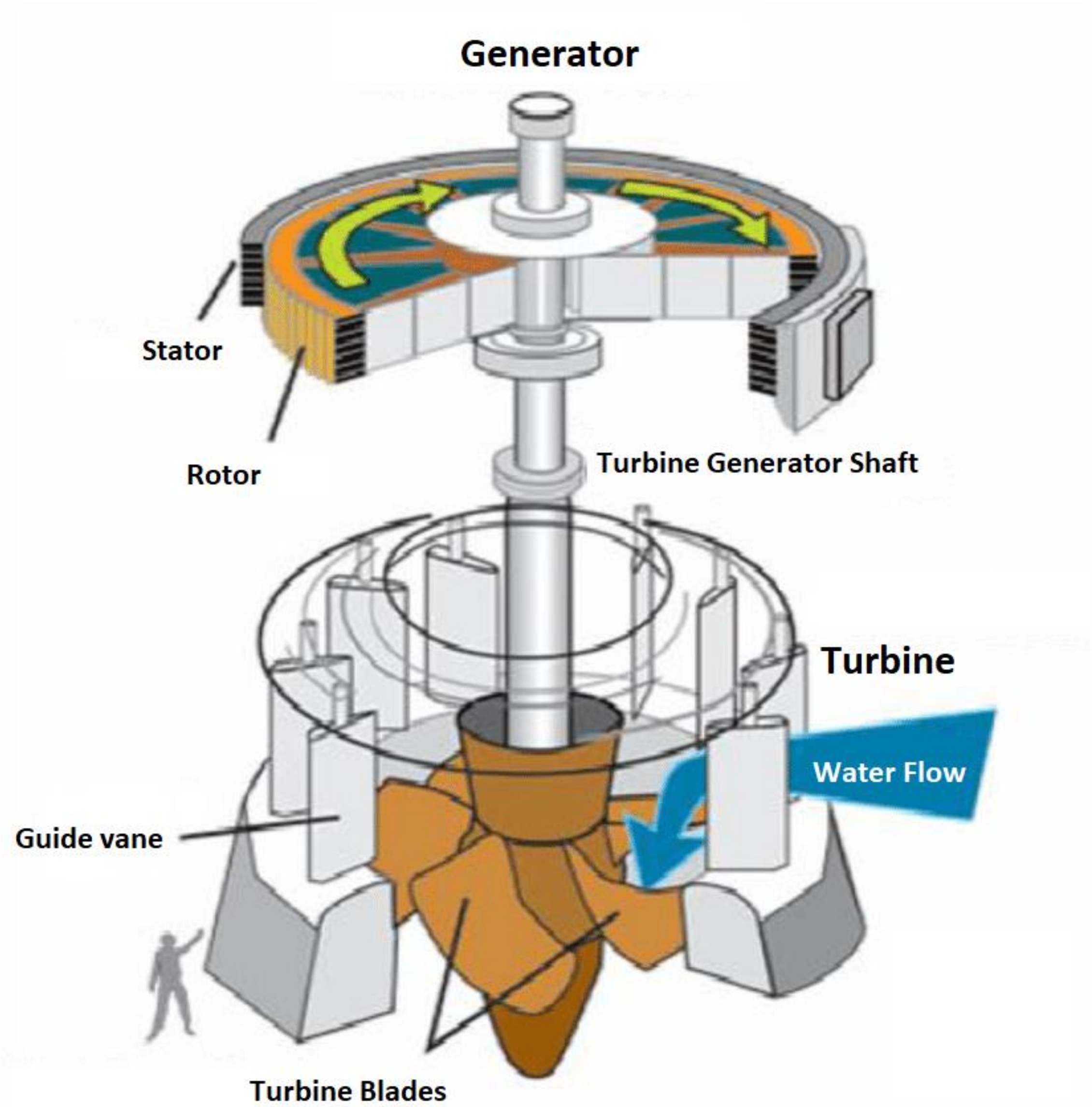


**Figure 8.** Kaplan turbine main components. (Gustafsson 2013.)

The guide vane cascade regulates the water flow to the runner. The guide vanes, also called wicket gates, are seen in figure 8. They are arranged in a circle and they are connected to a regulating ring. Guide vanes are controlled by rotating the regulating ring and this way the machine can meet the varying power demand. (Kjølle 2001: 8.1, 8.4.)

The turbine runner has a few blades that are radially oriented on the hub and there is no outer rim. The runner blades, depicted in figure 6 as Turbine blades, are curved to ensure relatively low flow losses. In addition to this the runner blades can be pitched in order to obtain optimal efficiency under varying flow. (Kjølle 2001: 8.1, 8.4.)

## 4.2 Principles of hydropower control

Run of river hydropower plants operate by using the flow of a river. They do not have a water reservoir, or they can have a small one compared to annual streamflow. Their power production is dependent on the natural and seasonal variations in river discharge and they generate base-load electricity. (Yildiz & Vrugt 2019.) (Gaudard, Avanzi, & De Michele 2018.)

Water levels must often be kept between lower and upper limits in run of river hydropower plants. The nonexistence of an upper reservoir, a low water head and the dependence on the river discharge are the cause of fluctuating water levels in the upper reservoir. This in turns changes the water head and the hydrostatic pressure which leads to changing amounts of energy available for the turbine. This needs to be taken into account in turbine control.

One of the serious problems that faces river intakes in the winter is the accumulation of frazil ice on the intake trash rack which can be partially or fully blocked in a matter of minutes. Frazil ice can also cause damages to other components like turbine runner and guide vanes for example. The problems caused by frazil ice cease to exist once the river reach upstream has developed a stable ice cover. The ice cover insulates the flow and supercooling of water stops. Ice cover formation is affected by high discharges and low flows are needed for a stable ice cover to form. (Gebre, Alfredsen, Lia, Stickler & Tesaker 2013.)

### 4.2.1 Turbine control

Guide vanes and turbine blades are both adjustable in Kaplan turbines. These are the key components that enable gaining maximum efficiency in different working conditions and they are regulated in a coordinated fashion. This means that for every guide vane position, there is a corresponding position for the turbine blades to maximize the ratio between output power and water volume. The guide vanes are connected to the guide vane regulating ring and they regulate the water flow into the turbine chamber. An example of the guide vane operating mechanism can be seen in figure 9. (Gustafsson 2013: 7.)

Hydraulic servos are used to control the position of the guide vanes and the turbine blades. Guide vanes are adjusted by turning the guide vane regulating ring that connects to all the guide vanes. The turbine blades position is in turn adjusted with hydraulic servo that sits inside the turbine axis. Turbine axis also holds two pipes that transport the hydraulic oil and sensors that measure the blade angle. For both hydraulic systems there is a separate actuator controlling the oil pressures. From a turbine control point of view an interesting fact is the closing and opening times of the guide vanes and turbine blades. A typical time that it takes to adjust the guide vanes from closed to fully open is between 5 – 15 seconds. For the turbine blades the time is between 30 – 60 seconds from one endpoint to the other. Adjusting the turbine blades is slower because of the limited amount of oil getting through the channels inside the turbine axis. A backlash is sometimes introduced to the turbine blade servo in order to avoid vibrations of the tur-bine blades. This allows the turbine blades to remain at their position when the difference between their actual position and the setpoint position is small. This in turn reduces wear on the hydraulic system. (Gustafsson 2013: 7-8.)

The combination unit is used to achieve the before mentioned coordination between wicket gate position and turbine runner blade position. This allows for the best efficiency over all operating points. The combination unit data is obtained from tests carried out on the turbine. The tests are executed in such a way that the turbine blades are fixed to a certain position and the wicked gates are driven from closed to fully open while the turbine runs at constant speed. This is repeated for several different turbine blade positions and from these tests the turbine efficiency is registered. Empirical data is used to determine the best combination of wicket gate and turbine runner blade positions. A hydropower plant will have several different combination curves because the water head affects the mechanical power of the turbine. So, the combination curve for operating the turbine will be selected depending on the water head. (Gustafsson 2013: 8.)

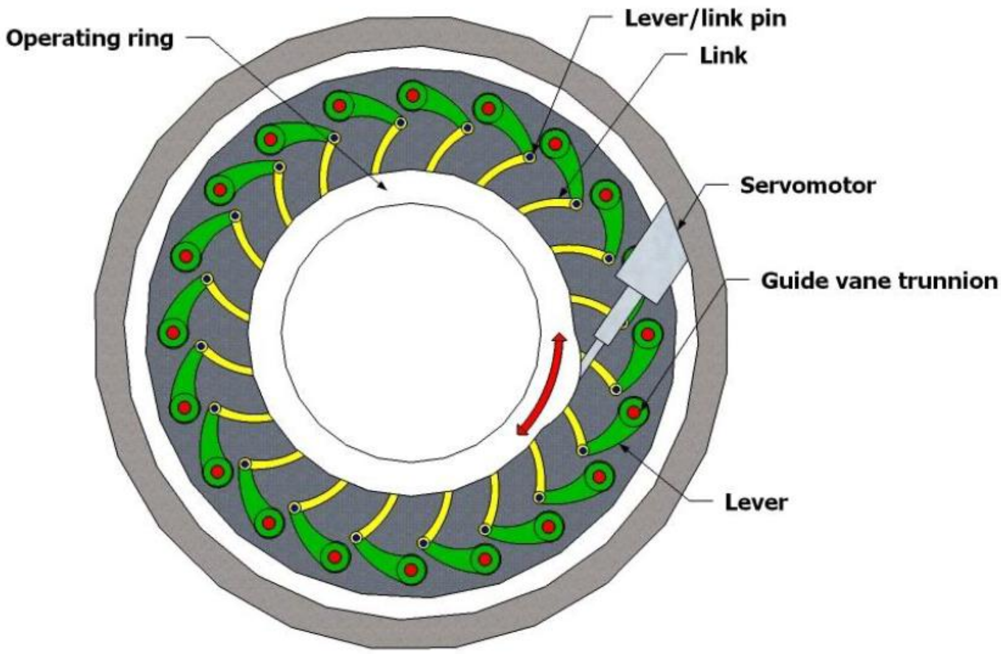


**Figure 9.** Layout of mechanism for guide vane regulation. (Tapper 2016.)

### 4.2.2 Frequency control

Frequency control in Kaplan hydropower plants is managed by a control system that is called a governor. It regulates the electrical frequency by controlling the actuators and servos with two inputs and two outputs. The calculations for the control are usually made with a PID controller. Input signals for the governor are the generator frequency and a power signal feedback. The feedback signal can be the guide vane position, or the electrical power and it is used to control the turbines participation in the frequency control. (Gustafsson 2013: 11.)

The governor has only one output which is the guide vane setpoint position. This signal controls the actuator and the servo for the regulating ring. The same governor output signal is fed to the combination unit that in turn calculates the other output signal for the control of the turbine blade actuator and servo. (Gustafsson 2013: 11.)

If several turbine governors exist in the same electrical grid the change in load will be distributed to more than one turbine. This is called droop and this setting is individual for every governor. (Gustafsson 2013: 13.)

## 4.3 Wear and tear and cavitation

Damages in water turbines are mostly caused by cavitation problems, sand erosion, material defects and fatigue. These damages cause problems primarily in water turbines with high water heads that are over 250 meters, and consequently high pressures. High pressures and variations in pressure as well as high water speeds are the main reasons behind these damages. (Kjølle 2001: 14.1.)

Kaplan turbines are closed turbines and they operate under varying pressure. When the pressure drops below the evaporation pressure of the liquid, in any part of the turbine, the water boils and bubbles of vapor are formed. These vapor bubbles then travel to areas with higher pressure and they condense to liquid form again. When these bubbles collapse, the water around rushes in to fill the void which creates very high local pressures. This procedure is repeated many thousand times per second. This phenomenon causes pitting on the metallic surfaces and it is called cavitation. Cavitation causes fatigue on the materials which may fail and can even be torn away by this process. (Kumar & Saini 2010: 375.)

In Kaplan turbines, the areas that are exposed to cavitation are runners and draft tube cones. Measures to combat cavitation include improving the hydraulic design of components, searching and testing materials that are more erosion resistant, component manufacturing, and operating the turbines withing a good range of cavitation conditions. (Kjølle 2001: 14.1.)

Guide vane movements and their distance are important factors when considering wear and tear of the turbines. Wear and tear of materials are considered more serious for small movements than large movements. When simulating the guide vane movements based on real frequency record over one-week period, and for a turbine that is participating in primary frequency control, the following was found. Between 75 and 90% of all opening movements are very small, less than 0.2% of full stroke. The amount of movements is also a large number: over 20 000, and each movement corresponds to a change in di-rection. (Yang et al. 2016.)

Yang et al. (2016) concluded that on doubly regulated units, such as Kaplan turbines, the study of runner blade movements for wear and tear is of importance. There is not enough research in this area currently available. They also raise the following question: How to reduce small movements of the guide vanes, which they claim are more harmful for the turbine parts, especially considering that their regulation value to for the grid is not that obvious?

# 5 Reserve electricity market in Finland

Fingrid Oyj is a public limited company that is in charge of electricity transmission in the high-voltage transmission system in Finland. Fingrid owns about 14 300 km of 110-, 200- and 400-kV transmission lines, over 100 substations and 10 reserve power plants. Finland is part of the Nordic power system which is connected to the Central European system and Finland also has HVDC transmission links with Estonia and Russia. One of Fingrids statutory tasks is developing the electricity market. (Fingrid 2018: 6.)

Electricity production should be in balance with consumption at all times. The nominal grid frequency in Finland is 50 Hz when consumption and production are equal. Fingrid balances deviations between production and consumption through reserves that can be automatically activated or ordered by the operator. These reserves are procured from market parties. (Fingrid 2020.)

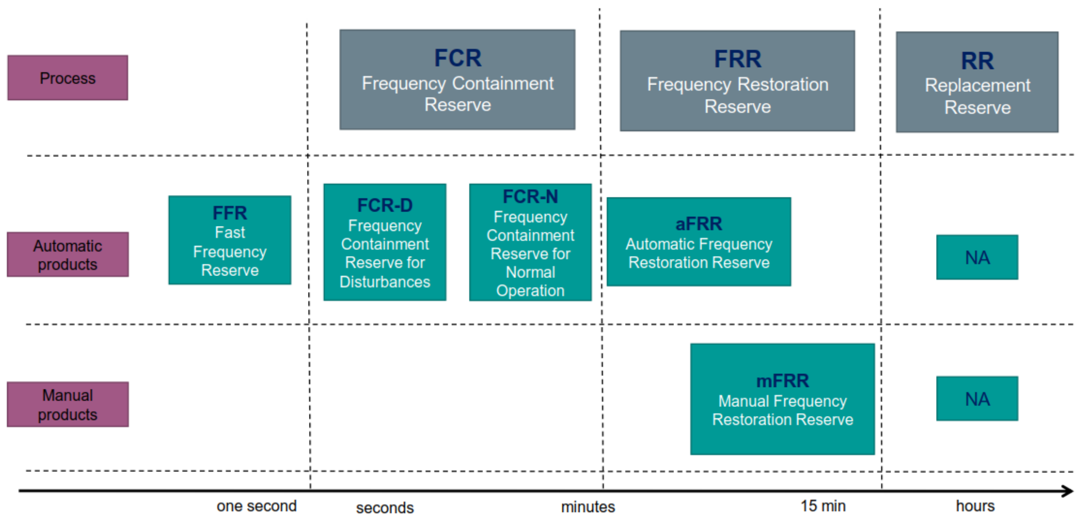


**Figure 10.** Reserves used in the Nordic countries. (Fingrid 2020.)

Figure 10 illustrates the reserves used in the Nordic countries. From the figure you can see how fast different reserves need to be activated and if they are automatic or manual products. In Table 2 you can see different marketplaces, their type of contract, minimum bid sizes, activation times, price levels and more.

**Table 2.** Electricity marketplaces in Finland (Fingrid 2019)

| **Market place** | **Type of contract** | **Min. bid size** | **Market gate closure (EET)** | **Activation time** | **How often activated** | **Price level 2018 *)** |
|---|---|---|---|---|---|---|
| Frequency controlled normal operation reserve | Yearly and hourly markets | 0.1 MW | Yearly market previous autumn, hourly market day before at 18.30 | 3 minutes | Several times a day | 14 € / MWh (yearly market) |
| Frequency controlled disturbance reserve (FCR-D) | Yearly and hourly markets | 1 MW | Yearly market previous autumn, hourly market day before at 18.30 | Linearly or partly linearly within 5 s / 50 % and 30 s / 100 %, when f < 49.9 Hz, OR single step activation 5 s when f<49.7 Hz 3 s when f<49.6 Hz 1 s when f<49.5 Hz | Several times per day - per year | 2.8 € / MWh (yearly market) |
| aFRR | Hourly markets | 5 MW | Day before at 17.00 | Must begin within 30 s of the signal's reception, must be fully activated in 2 minutes | Several times a day | Hourly market price + balancing energy price |
| Balancing power market (mFRR) | Hourly markets | 5 MW | 45 min before each hour | 15 minutes | According to the bids, several times per day - per year | Market price |
| Balancing capacity market (mFRR) | Weekly auctions | 5 MW | Week before on Tuesday at 12.00 | 15 minutes | According to the bids, several times per day - per year | ~ 3 € / MWh |

| | | | | | | |
|---|---|---|---|---|---|---|
| Day ahead market **) | Hourly markets | 0.1 MW | Day before at 13.00 | - | - | Market price |
| Intraday market **) | Hourly markets | 0.1 MW | 30 min before each hour | - | - | Market price |
| Strategic reserves ***) | Long term contract | 10 MW | ***) | 15 minutes for DSR, 12 h for power plants | Rarely | - |
| *) the price levels are suggestive<br>**) Nord Pool markets<br>***) The Energy authority makes the procurement every 2-3 years | | | | | | |

## 5.1 Frequency containment reserve (FCR)

Frequency containment reserve for normal operation (FCR-N) is continually activated based on frequency deviation, activation happens with a delay of a few minutes. The FCR-N is a symmetrical product which means it needs to be able to increase or decrease power when needed. The FCR-N is automatically controlled by locally measuring the frequency and adapting according to changes in frequency. Hourly market has payment respective to available capacity and activation payment according to activated net energy. Yearly market price is 13 €/MW/h and hourly market price is dozens of €/MW/h. The smallest amount for bidding is 0.1 MW. FCR-N is activated several times per day. (Fingrid 2020.)

Frequency containment reserve for disturbances (FCR-D) is only activated in larger deviations of frequency. When the participating generation is activated it needs to be at 50 % power output within 5 seconds and at 100 % power output within 30 seconds (power output according to the bid, linearly increasing). This product contains only up-regulation which means that power plants increase their power production and loads decrease their power consumption. Loads can also participate in FCR-D marketplace with one step activation in case of larger disturbances in frequency. These steps and their corresponding activation times are: 49.7 Hz 5 s, 49.6 Hz 3 s and 49.5 Hz 1 s. FCR-D is also automatically controlled in respective to locally measured frequency but it has an activation time in the order of seconds compared to FCR-N which has an activation time of couple of minutes. The smallest amount for bidding is 1 MW. Yearly market price is around 2 €/MW/h and hourly market price is dozens of €/MW/h. Payments for available capacity in the hourly market. (Fingrid 2020.)

## 5.2 Frequency restoration reserve (FRR)

Automatic frequency restoration reserve (aFRR) is frequently activated based on the activation signal sent by Fingrid and the activation delay can be a couple of minutes. Bids for up or down regulation are separate. Minimum bid size is 5 MW and payments according to capacity (dozens of €/MW/h) and activation (price from balancing energy market). (Fingrid 2020.)

Balancing energy markets (mFRR) are part of the Nordic balancing energy markets. Here bids are activated in price order, but technical conditions are taken into account. Also, this market place has separate bids for up and down regulation. The minimum bid amount is 5 MW or 10 MW depending on the activation orders delivery manner (10 MW by telephone and 5 MW electrically by message). Manual activation happens in 15 minutes. (Fingrid 2020.)

## 5.3 Fast frequency reserve (FFR)

This product is for handling disturbances in low inertia situations. It has a very fast response in the case of large underfrequency deviation. Activation times are proportional to the underfrequency in steps: 1.3 seconds when frequency is under 49.7 Hz, 1.0 seconds when frequency below 49.6 Hz or 0.7 seconds when frequency is under 49.5 Hz. The need for FFR is highly dependent on the hydrological situation. (Fingrid 2020.)

## 5.4 Chosen electricity market participation

The FCR-N market place was chosen as the main target for the combined turbine and BESS operation. This conclusion came from the fact that the turbine was already accredited for the participation on the FCR-N market. The FCR-N market suits a BESS well because of its symmetrical properties, which means that both down and up regulation are included in the product.

The operation of a hydropower plant requires finding a balance between the operational constraints and the maximizing of profits. The FCR-N market participation causes more strain to the components of the turbine, but also gives better proceeds. The BESS would alleviate the wear and tear of the turbine by reducing the control movements that are constant during FCR-N market participation.

Other market places were not the main consideration for this pilot project. However, they are considered for future upgrades on other hydropower plants. The idea is that a BESS would enable other hydropower plants to participate in reserve markets that have previously been out of reach due to operational restrictions these hydropower plants face. This would facilitate new revenues for the hydropower plant owner.

# 6 Case: Hydropower Plant 1

This is a real working hydropower plant located in Finland. To protect the power plant owner's intellectual property, no names or technical specifications that could lead to identification of the customer or the power plant shall be revealed. Unfortunately, this means that no specific figures will be given, rather ranges and if possible relative numbers and percentages.

Hydropower plant 1 is a medium sized power plant with a power output in the region of 25 – 35 MW and a water head in the region of 7-12 meters. The power is produced by several Kaplan turbines. The turbines in this case, are prequalified to participate on the FCR-N market with a bid size in the range of 0.1 – 0.9 MW.

Point of interest from the operators' side is a possibility to participate on the FCR-N market consistently with larger bids without straining the turbines more. As mentioned in chapter 3.4, primary frequency control causes a lot of small movements of the guide vanes, which in turn can cause wear and tear of the components, thus shortening the time between repairs and maintenance.

## 6.1 Measurements carried out at Hydropower plant 1

To achieve a better understanding on the scale of the power and energy needed for the primary frequency control of the Kaplan turbine, measurements were made with operational Kaplan turbines. The objective was to find out several different aspects. Firstly, a key point of interest was the grid frequency over a period and how much power and energy is used for primary frequency control normally. Secondly, a more comprehensive picture on the guide vane and runner blade movements was established during primary frequency control. Thirdly, new governor models for turbine control were tested.

During the first measurements, turbine number one was participating in the FCR-N market normally with a governor model that had been approved by Fingrid for the FCR-N market. The turbine number two had a new governor model that was applied. This new governor model was designed for the purpose of load sharing between the turbine and the BESS.

The first measurements were carried out over a 48-hour period with constant monitoring of the two Kaplan turbines mentioned before. The positions of the guide vanes and runner blades are collected by their position sensors. This position data was read directly from the PLC processor memory and it was logged by using an interval of 100ms for both turbines. This position data for the guide vanes and runner blades was then used to calculate the total distance covered by these components during this first test and measurement period.

The second tests were carried out in similar fashion to the first measurements, this time with the new governor models for the turbine number two. The difference in active power output for turbine number one (which was participating normally in FCR-N market) and turbine number two (which had a new governor model to enable the desired load sharing with a BESS) was calculated. This difference in active power output tells us directly the active power output that is needed from the BESS.

A third test instance was carried out to test different turbine governor models. The turbine governor model was optimized in these later measurements and the selection for the best turbine control method while operating together with a BESS was established.

## 6.2 Results and considerations

The preliminary results were validated with new tests, and they gave promising insights. It was found that a battery energy storage could diminish the control movements of the turbine by six-fold compared to a stand-alone turbine participating in the FCR-N market. This estimate stems from a battery storage, that would have a power output that is 20 percent of the full power capacity sold to the FCR-N market. It is important to note, that the scale of the energy storage power output is inversely proportional to the reduced control movements of the turbine. From a financial point of view, it is important to find a balance between the size of the energy storage and its investment costs compared to the desired savings coming from reduced mechanical wear and tear.

### 6.2.1 Guide vane and runner blade movements

The guide vane regulating ring movements were taken from the plant automation system. All movements were recorded as a percentage figure from a full stroke of the guide vane regulating ring. From this data, it was easy to calculate the movements in meters, when the distance of a full stroke is known. The calculations revealed that while a turbine was operating in primary frequency control mode, the control movements of the regulating ring increased by a factor of 6 compared to a kilowatt mode, where the turbine was driven at a constant power output. The turbine control movements in kilowatt mode were a good reference point for the consideration of this new, hybrid solution. If the control movements can be reduced to the same level as in kilowatt mode, then the participation on the FCR-N market would be an obvious choice for the owner of the hydropower plant since the prices for energy are higher.

From the measurements executed at Hydropower plant 1, the movement of the guide vane regulating ring was found to be 0.4 meters per hour on the average. These first measurements were made during a fairly quiet season in terms of frequency deviations. When comparing to Fingrids historical data of the grid frequency, these movements were estimated to be approximately 0.7 meters per hour on the average over the course of one year. This would add up to over 6 km of travelled distance for the regulating ring if the turbine was operated in primary frequency control mode for a full year.

From later tests, the wicket gate and runner blade positions were plotted for the two turbines in the same graph and this graph is shown in appendix 1. This graph gives a clear visual explanation on the reduced control movements for a turbine that would share the load of primary frequency control with a BESS. On top of this graph you can see the wicket gate positions and on the lower end the runner blade positions. You can see that the turbine that is participating on its own in primary frequency control is constantly changing the positions of the wicket gates and the runner blades. The smooth straight lines are on the other hand are from the turbine that is sharing the load with the BESS. The difference is noticeable. This graph sums up greatly the purpose behind this idea.

### 6.2.2 Battery energy storage size

When calculating the battery energy storage size in terms of energy capacity, the main objective is to find how much power is needed and for how long time. In the case of FCR-N product, where the bids are symmetrical, there is a need for both discharging and charging capacity. This means that the battery storage should operate on a predefined charge level area and work together with the turbine.

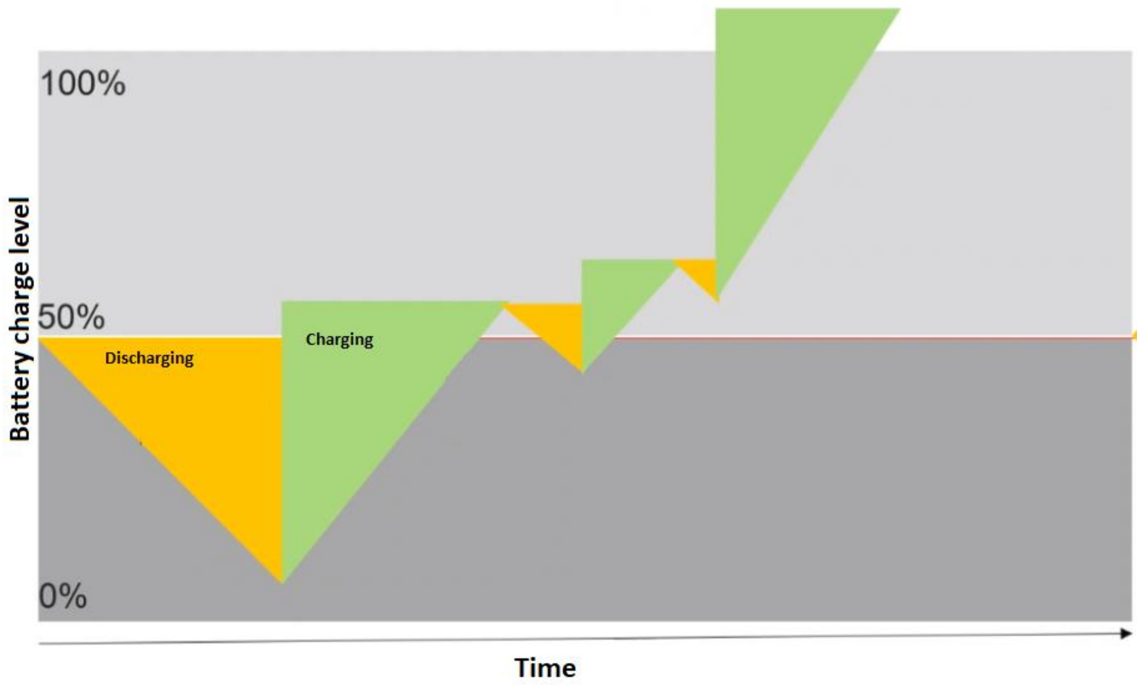


**Figure 11.** Battery energy storage charge levels in primary frequency control.

In figure 11 you can see how the battery charge cycles could look while assisting the turbine in primary frequency control. This figure illustrates the possibility that the battery energy storage would over time reach a full charge and would not be able to assist the turbine in down regulation. This case needs to be considered when dimensioning the battery energy storage. It should normally operate on a predefined charge level, say for example between 40 % an 80 % charge. It is not wise to dimension the battery pack so that it would do full charge/discharge cycles as it would mean a shorter battery life and faster changes in the turbine control in edge cases, when the battery would be fully charged or low on charge.

The amount of needed energy storage capacity was calculated from the Fingrids historical frequency data and the size of the FCR-N bid. The deviations of grid frequency from 50.00 Hz were looked at paying special attention to two aspects: what is the duration of frequency deviations on the average in the scope of FCR-N market, and how symmetrical are the frequency deviations for up and down regulation for longer periods of time. The first aspect gives an estimate on how much energy the battery energy storage should be capable of storing or releasing at any given time. The second aspect is interesting, because it shows if the battery energy storage has a tendency of going empty or getting fully charged.

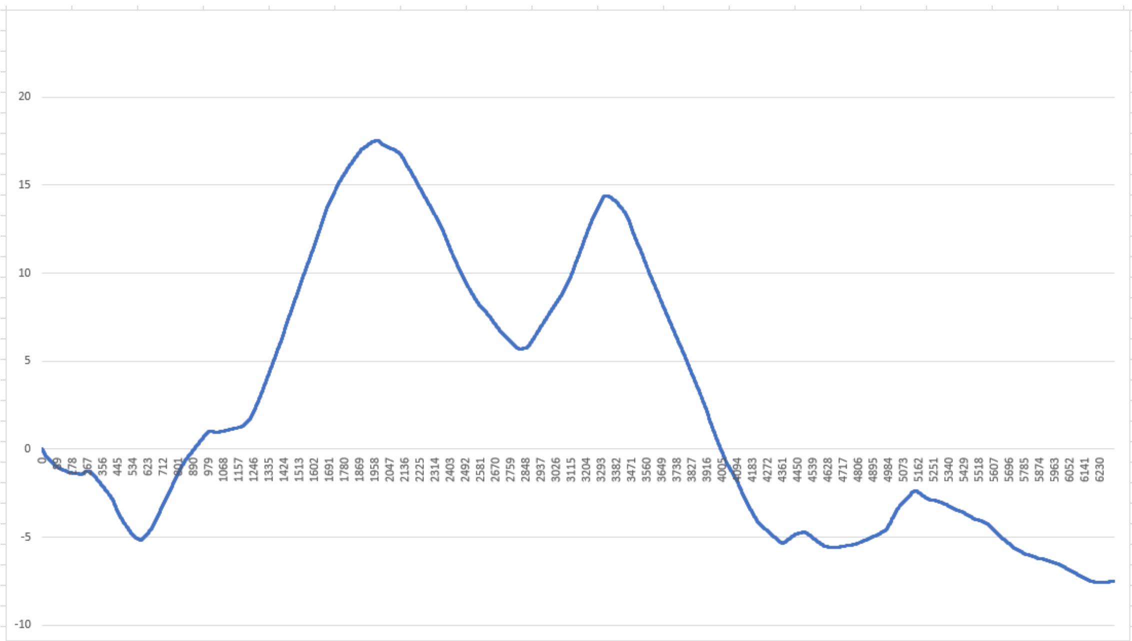


**Figure 12.** Energy absorbed and injected by the proposed BESS from measurement data.

Figure 12 describes the amount of energy that would be absorbed or injected by the battery during one measurement. Y-axis represents energy in kWh and the x-axis time in seconds. These figures are derived from a measurement from later tests which took a bit under two hours. In this instance, the battery would have stored 17 kWh of energy at the highest peak. From the peak value to the local minimum the difference was 24 kWh. This figure is just to show how the size of the BESS was determined.

The power output of the energy storage was another key figure. The power output has more to do with the combined control of the Kaplan turbine and the battery energy storage. The meaning of this application is not to stop control movements of the turbine fully but rather to make the turbine control less sensitive. Therefore, the power output of the battery energy storage should be dimensioned from the turbine control point of view. The meaning is to reduce the small control movements of the turbine, so the change in turbine output power in accordance to these control movements gives an estimate on the desired power output of the battery energy storage.

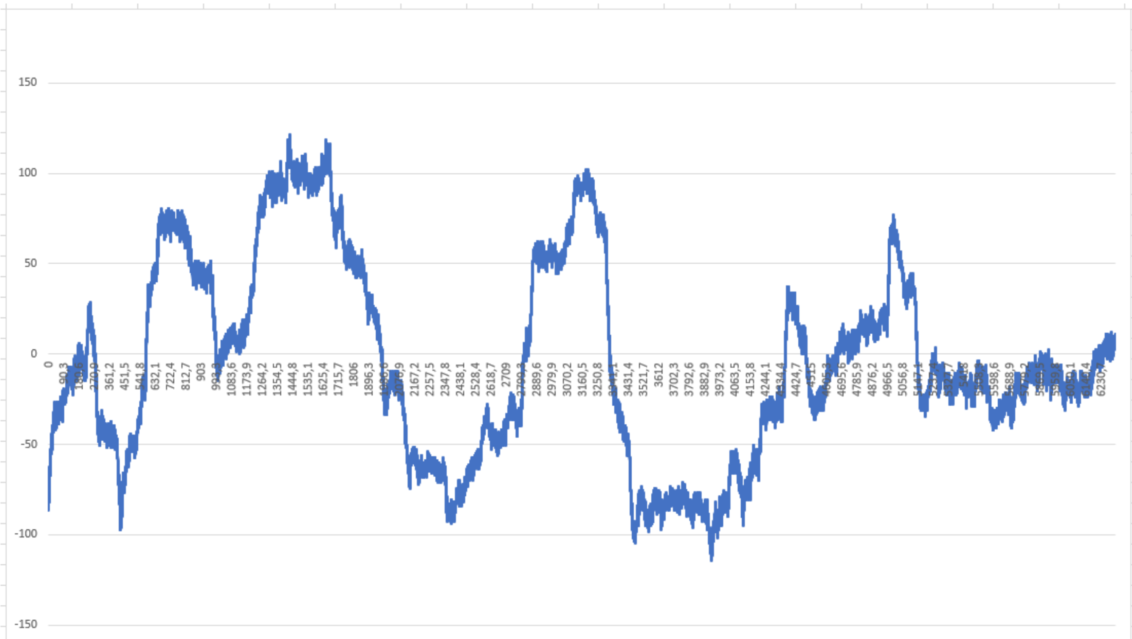


**Figure 13.** Output active power of the proposed BESS from measurement data.

Figure 13 describes the BESS output power for the same timeline as figure 12. Y-axis represents active power in kW and the x-axis time in seconds. Here we can see that the maximum values for the BESS output at the time of the measurement would have been approximately 110 kw for power generation to the grid as well as for loading the grid.

# 7 Proposed system

Unfortunately, specifics of the system designed for the Hydropower plant 1 are confidential for the time being. This system would be a first of its kind, as far as we know, which explains the secrecy. I will still try to give a picture of the proposed system while guarding the intellectual property of the plant owner as well as VEO Oy.

The battery energy storage system will have batteries with a 1C rating. The total energy capacity will be in around 80 – 200 kWh. This scale of battery energy storage is quite small in terms of physical volume so it will fit inside the existing electrical rooms of the Hydropower plant 1. The connection point of the battery is designed to be an existing low voltage cubicle which eliminates the need of a new transformer or a more expensive power converter for higher voltages. The BESS will be connected to a 400 V busbar via an existing outgoing feeder breaker.

The turbine governor will need a new control scheme. For the battery energy storage system and the turbine to operate together, the turbine governor needs to know what the state of charge of the battery is at any given moment. The meaning is to build a new controller that would be higher in hierarchy and would control the turbine governor and the BESS together.

A new control logic needs to be designed bearing the before mentioned aspects in mind. One of the required features will be limits for the state of charge of the battery, so that it will always be available for up and down regulation. If the battery energy storage is nearing the low or high limit for the state of charge, then the turbine needs to increase or decrease its power output. A new control cabinet will be designed at VEO which will integrate the new controller and the needed IO.

## 7.1 Estimate of prospective profit

The exact amounts of costs used for estimating the profitability of the investment are protected by a non-disclosure agreement. Initial investment cost of the system will be used as a reference and other sums will be proportional to it and reported as a percentage figure. It is important to note, that these figures are just approximations of the costs and they are given by the Hydropower plant 1 owner.

**Table 3.** Investment and other costs.

| Expense | Cost (as % of initial investment) |
|---|---|
| BESS, Configuration, Software, Integrations, installation | 100 |
| Licenses | 0.57 yearly |
| Maintenance (fixed) | 0.57 yearly |
| Maintenance (Changing) | 1.71 yearly |
| Energy losses BESS (cost calculated with production cost of kWh) | 0.25 yearly |
| Yearly costs 3.1 % of the initial investment | |

**Table 4.** Returns on investment.

| Profit origin | Income (as % of initial investment) |
|---|---|
| BESS part of FCR-N earnings | 12.3 yearly |
| Savings from maintenance of turbine | 1.14 yearly |
| Avoiding a large fault | 11.3 yearly |
| Yearly incomes and savings 24.74 % of the initial investment | |

Table 3 contains the costs for the proposed system. Yearly costs are 3.1 percent of the initial investment cost. The yearly costs include expenses from licences, maintenance, and energy losses of the BESS.

On the other hand, the expected returns are 24.74 percent of the initial investment cost. The returns are a mix of savings and revenues allocated to the new system. The prolonging of maintenance intervals and the avoidance of large faults can only be confirmed once the new system is running. According to these calculations the payback time for the investment would be a little under 5 years.

A factor that will affect the payback time for the investment is the energy market participation. When a BESS is installed at a hydropower plant it could change the plant operator's strategy for power generation and revenue calculation. The energy storage could facilitate the participation on new electricity market places that have previously been unavailable for the hydropower plant.

# 8 Conclusions

The power grid and the electricity markets are changing. Wind power and other renewables, that are intermittent by their nature, are causing problems for the power balance in the grid. As mentioned in this thesis, this makes the primary frequency control a vital part of grid stability, but at the same time it strains the power generation units taking part in it.

One of the main purposes of the thesis was to get experience and knowledge on the dimensioning of the energy storage system for the application suggested in this thesis. The theoretical research on electrical energy storages in chapter 2 revealed that currently the best technology for the case study would be a battery energy storage. The conclusion while analysing the measurement data was that the size of the energy storage could be relatively small in terms of energy storage size and power output capacity. The main contributing factor to this conclusion were the measurement data which reflected the oscillating behaviour of the grid frequency and the fact that the FCR-N product is symmetrical. Symmetrical in this case means that it consists of both down and up regulation.

Sizing the battery energy storage is a kind of optimisation problem that should be considered as hydropower plant specific solution. Although the same principles can be used for other plants, there is always a need to investigate the possibilities and requirements for the hydropower plant in question. Determining factors are, of course, the power output and energy capacity, but also the physical placement and available options for connectivity. Investment costs need to be weighed against the future savings and possible new revenues. For any new system, if not crucial for operation, the payback time for the investment is the main factor for decision making.

The battery energy storage was found to have a great impact in reducing the control movements of the turbine. For a battery energy storage that has an energy and power output capacity of 20 percent of the turbine's capacity sold to the FCR-N market, it was concluded that the regulating ring movements for the guide vanes could be reduced by approximately 97 %. The small size of the BESS would also mean smaller investment costs.

The future work will consist of optimizing the new control method for the combined use of the turbine and BESS. A pilot for this application is being planned for Hydropower plant 1, and this will most likely give great experience in the development of a new, turn-key product for a totally new market.

An interesting aspect is the formation of ice cover on the river. Turbulence hinders the formation of ice cover in a river. When the turbine control is smoothened, it in turn reduces the changes in water discharge and turbulence as well. How big of an effect could the system proposed in this thesis have on ice related problems could be a future study topic.

## Bibliography

Adewuyi, O. B., Shigenobu, R., Ooya, K., Senjyu, T., & Howlader, A. M. (2019). Static voltage stability improvement with battery energy storage considering optimal control of active and reactive power injection. *Electric Power Systems Research, 172*, 303-312.

Agbossou, K., Kolhe, M., Hamelin, J., & Bose, T. K. (2004). Performance of a stand-alone renewable energy system based on energy storage as hydrogen. *IEEE Transactions on energy Conversion*, 19(3), 633-640.

Aneke, M., & Wang, M. (2016). Energy storage technologies and real life applications–A state of the art review. *Applied Energy*, 179, 350-377.

Boicea, V. A. (2014). Energy storage technologies: The past and the present. *Proceedings of the IEEE*, 102(11), 1777-1794.

Budt, M., Wolf, D., Span, R., & Yan, J. (2016). A review on compressed air energy storage: Basic principles, past milestones and recent developments. *Applied energy*, 170, 250-268.

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in natural science*, 19(3), 291-312.

Datta, U., Kalam, A., & Shi, J. (2019). The relevance of large-scale battery energy storage (BES) application in providing primary frequency control with increased wind energy penetration. *Journal of Energy Storage, 23*, 9-18.

Díaz-González, F., Sumper, A., & Gomis-Bellmunt, O. (2016). *Energy storage in power systems*. John Wiley & Sons.

Fingrid. (2019). *Annual report 2018.* Retrieved from [2019-06-05] https://www.fingrid.fi/en/pages/investors/financial-reports-and-presentations/

Fingrid. (2020). *Reserve products and reserve market places.* Retrieved from [2020-01-27]https://www.fingrid.fi/haku/?query=reserve%20products%20and%20reserve%20market%20places&pageSize=10&page=1&language=fi

Gaudard, L., Avanzi, F., & De Michele, C. (2018). Seasonal aspects of the energy-water nexus: The case of a run-of-the-river hydropower plant. *Applied Energy, 210*, 604-612.

Gebre, S., Alfredsen, K., Lia, L., Stickler, M., & Tesaker, E. (2013). Review of ice effects on hydropower systems. *Journal of Cold Regions Engineering, 27*(4), 196-222.

Gustafsson, M. (2013). Improved governing of Kaplan turbine hydropower plants operating island grids.

Hall, P. J., & Bain, E. J. (2008). Energy-storage technologies and electricity generation. *Energy policy*, 36(12), 4352-4355.

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and sustainable energy reviews*, 12(5), 1221-1250.

IEA. (2014). *Technology Roadmap Energy Storage*. Retrieved from [2019-02-28] https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf.

IEA. (2020). *Evolution of Li-ion battery price, 1995-2019.* Retrieved from [2020-10-12] https://www.iea.org/data-and-statistics/charts/evolution-of-li-ion-battery-price-1995-2019

Kjølle, A. (2001). Mechanical equipment. *Waterpower laboratory, NTNU.*

Kumar, P., & Saini, R. P. (2010). Study of cavitation in hydro turbines—A review. *Renewable and Sustainable Energy Reviews*, 14(1), 374-383.

Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied energy*, 137, 511-536.

Maheshwari, A., Paterakis, N. G., Santarelli, M., & Gibescu, M. (2020). Optimizing the operation of energy storage using a non-linear lithium-ion battery degradation model. *Applied Energy, 261*, 114360.

MIT Electric Vehicle Team. (2008). *A guide to understanding battery specifications.* Retrieved from [2021-01-29] http://web.mit.edu/evt/summary_battery_specifications.pdf

Olsson, H. (2017). Future frequency control services in the Nordic power system.

Ovaskainen, M., Öörni, J., & Leinonen, A. (2019, June). Superposed control strategies of a BESS for power exchange and microgrid power quality improvement. In *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-6). IEEE.

Tapper, A. (2016). A fatigue investigation in a Kaplan hydropower station operated in frequency regulating mode.

Yang, W., Norrlund, P., Saarinen, L., Yang, J., Guo, W., & Zeng, W. (2016). Wear and tear on hydro power turbines–Influence from primary frequency control. *Renewable energy*, 87, 88-95.

Yildiz, V., & Vrugt, J. A. (2019). A toolbox for the optimal design of run-of-river hydropower plants. *Environmental modelling & software, 111*, 134-152.

# Appendices

## Appendix 1, Contol movements of wicket gates and runner blades with different governor parameters