University of
South-Eastern Norway

www.usn.no

FMH606 Master's Thesis 2023

Electrical Power Engineering

Grid stabilization through load side mechanisms

Lars Kristian Bekker

Faculty of Technology, Natural Sciences and Maritime Sciences
Campus Porsgrunn

University of
South-Eastern Norway

www.usn.no

Course: FMH606 Master's Thesis, 2023

Title: Grid stabilization through load side mechanisms

Number of pages: 62

Keywords: Ancillary services, Energy balancing, Load side utilization, Market mechanisms, Electrolyser, ENTSO-E, NERC, AEMO.

Student: Lars Kristian Bekker

Supervisor: Kjetil Svendsen

External partner: Nel Hydrogen

Summary:

The composition of the power systems is subject to change, both on the generation and load side. On the generation side there is an increase in renewable energy sources that are connected to the power system with power electronic converters, the same is seen for the load, that the load is connected by means of power electronic converters. Because of this, the kinetic energy is decreasing, and the harmonic and reactive power is increasing. This affects the stability and the voltage control of the power system. But the increase in power electronic converters also leads to that the load is moving from being passive towards active.

This thesis investigates how a large load hydrogen production facility can contribute to stabilize a power system. The objectives are to investigate what market mechanisms exist at different geographical locations, how are the different power markets and how do they compare, and what properties the consumer needs to have to deliver these services. For resolving the objectives, a literature study was performed.

The literature study shows that a hydrogen production facility is applicable for the ancillary services available today and can contribute to stabilizing a power system.

Preface

This thesis is the conclusive work in the course FMH606 Master's Thesis at the two-years Master's program, Electrical Power Engineering at the University of South-Eastern Norway.

I would like to extend my gratitude to my supervisor Kjetil Svendsen for his support, guidance, availability, reflections throughout this thesis.

My colleague Oddmund Vik must not be forgotten, the spring 2021 he said "if you don't start on that Master's program now, it will be way harder to find time for it in future" and now, two busy and enriching years are coming to an end.

Stavanger, 15/05-2023

Lars Kristian Bekker

Contents

Nomenclature

ACE	Area Control Error
ACER	European Union Agency for the Cooperation of Energy Regulators
AEMC	Australian Energy Market Commission
AER	Australian Energy Regulator
aFRR	Automatic Frequency Restoration Reserve
BSP	Balance Service Provider
CIG	Converter Interfaced Generation
DAM	Day Ahead Market
DER	Distributed Energy Sources
DSS	Dispatch Support Service
EBGL	The Electricity Balancing Guidelines
ENTSO-E	European Network of Transmission System Operators for Electricity
FCAS	Frequency Control Ancillary Service
FCR	Frequency Containment Reserve
FCR	Freuency Containment Reserves
FERC	Federal Energy Regulatory Commission
FFR	Fast Frequency Response
IGBT	Insulated-Gate Bipolar Transistor
IGCC	The International Grid Control Cooperation
ISO	Independent System Owner
LFAS	Load Following Ancillary Service
LFC	Load Frequency Control
MWh	Mega Watt Hour
NBM	Nordic Balancing Model
NERC	North American Electric Reliability Corporation
PEM	Polymer Electrolyte Membrane
RESs	Renewable Energy Sources
RTO	Regional Transmission Organization
SWIS	South West Interconnected Systems
TSO	Transmission System Operator

WECC	Western Electricity Coordinating Council
WEIM	Western Energy Imbalance Market
WEIS	Western Energy Imbalance Service Market
WEM	Wholesale Electricity Market

1 Introduction

1.1 Background

Today 20% of the world's energy consumption is electricity, but electricity is also an important energy carrier. In 2021 electricity production was a large consumer of fossil fuels: 59% of all coal, 34% of all natural gas and 4% of all oil globally. With the large consumption of fossil fuels, electricity is also a large producer of CO2 emissions [1].

Towards 2030 the global electricity demand rises with 25-30% [1], production of electricity by fossil fuels will decrease and renewables will increase to 50%, led by solar photo-voltaic (PV) and wind.

With the increase of renewable energy sources (RESs) and consumers connected to the power system with power electronics, introduces a different approach to the stability of the power system.
Traditionally when electricity is produced by hydropower or a thermal power station the rotating mass of the generator provides rotational inertia, which contributes to stabilize the power system. The combination of RESs and intermittent sources of energy makes it difficult to forecast the available power. Most RESs are inverter-based which increases the harmonic distortion and reactive power on the grid. Thus, inverter-based RESs can provide possibilities for frequency and voltage control, fast startup times and control of harmonics and reactive power.

Brief introduction of NEL ASA

NEL is a Norwegian company founded in 1927, the same year they installed their first electrolyser at Norsk Hydro in Norway, for producing hydrogen to fertilizer production. Now their main deliveries are still electrolysers, but also solutions for hydrogen fueling. NELs hydrogen plants are mainly based on polymer electrolyte membrane (PEM) or alkaline electrolysers.

1.2 Objectives

The main purpose of this thesis is to study how a large consumer of electricity e.g., hydrogen production facility, can be utilized to stabilize a power grid. The study will be divided into the following tasks:

1. Investigate what market mechanisms are implemented in the Nordic, European, North American and Australian electricity power markets.
2. How do the different electricity power markets compare and what standards does exist.
3. How can a large electricity consumer contribute to stabilize a weak grid.

4. What properties does the consumer need to be able to be utilized in these settings.

1.3 Limitations

The way the power systems are organized is different depending on where they are geographically. With this the quality and availability of information and standards regarding the power systems varies and this results in that the level of details for the different power systems not being equal.

Economical aspects, neither of electricity or hydrogen is taken into consideration

The process of using electrical energy to produce hydrogen and then producing electrical energy by hydrogen will not be considered in this report.

1.4 Structure

This report has the following structure:

Chapter 2

This chapter covers the basic theory for how hydrogen is produced, basic theory of the power system and stability, and market mechanisms.

Chapter 3

This chapter describes the method used for answering the thesis.

Chapter 4

This chapter covers the market mechanisms for ancillary services in different geographical areas found in the literature study.

Chapter 5

This chapter contains the discussion based on the basic theory and the results from the literature study.

Chapter 6

This chapter contains the conclusion drawn from the literature study and discussion.

2 Theory

2.1 Production of hydrogen

2.1.1 Introduction

Production of hydrogen represents approximately 3% of the global energy consumption [2]. For many chemical processes e.g., production of ammonia, methanol, refining petroleum products, hydrogen is a key component. Hydrogen is also an energy carrier, it can store and deliver energy, but does not exist freely in nature and is produced from other sources of energy. Relatively to its weight hydrogen has a very high energy, but very low for its volume. The four main sources for producing are natural gas, coal, oil, and electrolysis, where natural gas is the largest source and descending to electrolysis which is the smallest.

2.1.2 Production of hydrogen with PEM electrolyser

Producing of hydrogen by electrolysis is the process of splitting a water molecule into hydrogen H_2 and oxygen O_2. This reaction happens inside an electrolyser. A polymer electrolyte membrane (PEM) electrolyser is shown in Figure 2-1. The main parts of a PEM electrolyser consist of a cathode and an anode, in between the cathode and anode is the polymer electrolyte membrane.

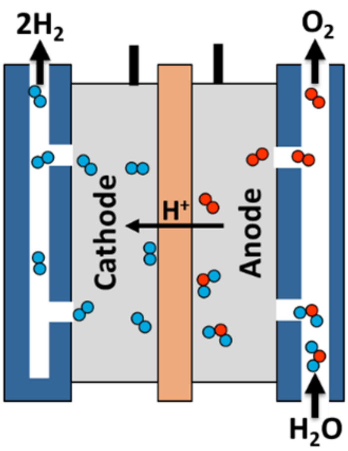

Figure 2-1: Polymer electrolyte membrane electrolyser [3]

By energizing the anode and cathode with direct current, the anode is in contact with water. Positively charged hydrogen ions will move through the polymer electrolyte membrane to the cathode. Equation (2-1) is the anode reaction for the PEM electrolysis, where two water molecules get in touch with the energized anode, the two water molecules are then split in oxygen, four hydrogen ions and four electrons. The four hydrogen ions go through the polymer electrolyte membrane to the cathode. At the cathode the hydrogen ions groups with electrons and hydrogen are formed as shown in Equation (2-2).

Equation (2-1): Anode reaction for PEM electrolysis

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{2-1}$$

Equation (2-2): Cathode reaction for PEM electrolysis

$$4H^+ + 4e^- \rightarrow 2H_2 \tag{2-2}$$

The complete process for producing hydrogen with a PEM electrolyser is shown in Figure 2-2. Hydrogen is produced at the anode in the electrolysis and is then treated through a separator and dryer stage to improve the quality and properties of the hydrogen, so it is suitable for its intended use.

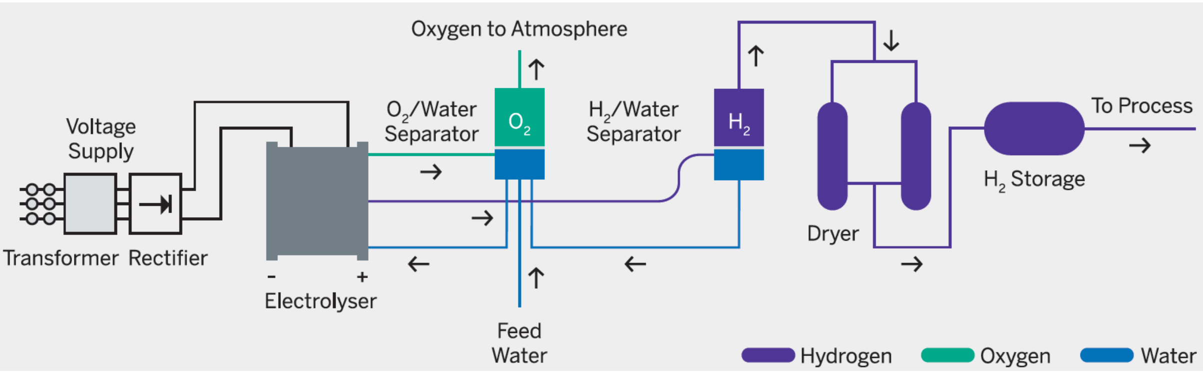

Figure 2-2: Production of hydrogen with PEM electrolyser [4]

Table 1 shows typical characteristics for a PEM and alkaline electrolyser, the alkaline is added for comparison.

Table 1: PEM and Alkaline electrolysers characteristics [5]

Characteristic	PEM	Alkaline
Typical stack size	1 MW	1 MW
Load Range (of nominal load)	0-160 %	10-110 %
Start-up time (warm, cold)	1 s – 5 minutes	1 – 10 Minutes
Shutdown	1 s – 5 minutes	1 – 10 Minutes
Ramp-up / Ramp-down	100 % / Second	0.2-20 % / Second

The electrolyser uses DC-current for producing hydrogen. For large scale electrolyzing, rectifying AC-current from the electricity grid is normally done by a thyristor, diode, or active front end converter. The converters are configured in different setups depending on variables both from the process point of view and the supplying power system. The lifetime of the electrodes in the electrolyser is affected negatively by DC current ripple, on the AC side of the converter harmonic noise and reactive power is produced and injected to the power system.

Thyristor based converters

The typical topologies for thyristor converters is 6/12/18/24-pulse and different bridge configurations. Figure 2-3 shows thyristor converters with 6 and 12-pulse topology.
A 6-pulse thyristor is simpler and cheaper, but the power factor is a low and the production of harmonics is relatively high, which results in a higher overall system loss and larger filtering equipment. With a 12-pulse thyristor bridge shown to the right in Figure 2-3 with two 6-pulse bridges in parallel, the DC-ripple are reduced, but complexity also increases.

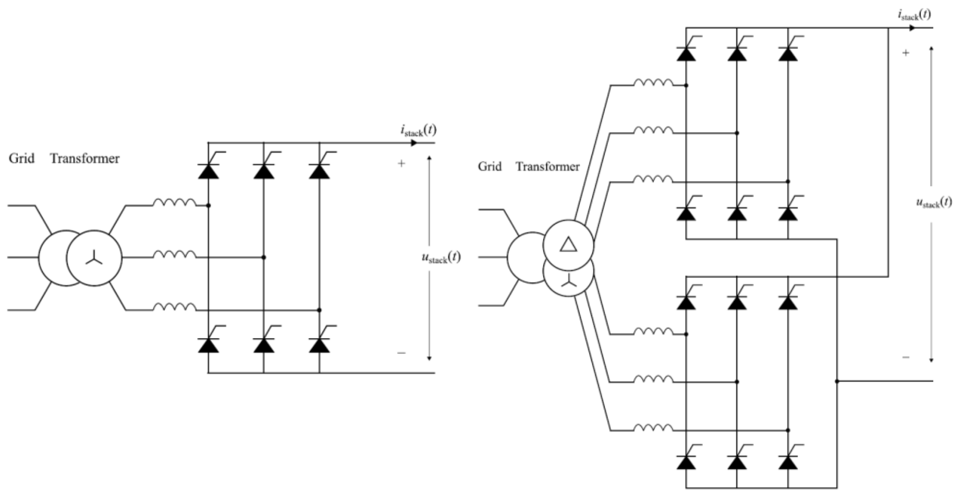

Figure 2-3: Left - 6 pulse thyristor bridge, right 12-pulse thyristor bridge [6].

Diode based converters

6/12/18/24-pulse diode rectifiers with a choppers stage, reduces the DC-ripple and the power factor increases, compared to thyristor-based solutions. But there is still a significant amount of harmonics on the AC and DC sides of the rectifier. The reactive power is reduced but it still needs equipment for compensation of the reactive power exerted on the power system. Figure 2-4 shows a topology for a 12-pulse diode rectifier followed by a chopper stage.

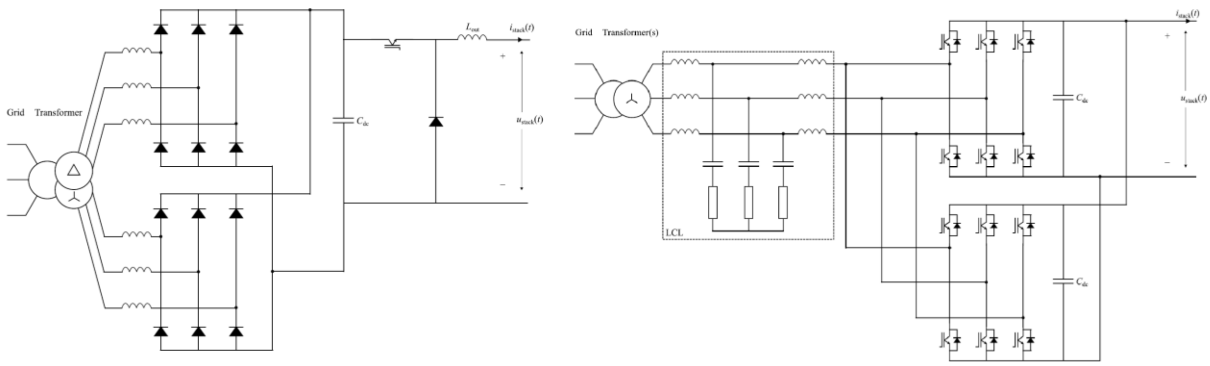

Figure 2-4:Left- diode based converter, right - IGBT based rectifier [6].

Active front end converter
With a rectifier that has a transistor based topology as shown in Figure 2-4 with Insulated-Gate Bipolar Transistors (IGBT), the power factor increases significant and the DC-ripple is reduced to a considerable low level and on the AC-side of the rectifier the reactive power is also considerably lower. Further it can be configured so that it can supply reactive power to the power system. However active front end converters are less mature compared to thyristor and diode converters and price and complexity is higher.

2.2 The Power System

2.2.1 The electric power system

Electricity is to be considered as a secondary energy source, with the term secondary source it means that electricity is generated by a primary source e.g., thermal, wind or hydropower and acts as an energy carrier. The electric power system comprehends generation, transmission, distribution, and utilization of electricity. The terms grid, power system and national grid are commonly used terms for the electric power system. Figure 2-5 shows the transmission network in Northern Europe.

Figure 2-5: The power system in Northern Europe[1]

Figure 2-5 shows the transmission grid for Northern Europe, the power system can normally be divided in to the following three grids:

Transmission grid
The transmission grid is typically where the greatest load flows and the main generation stations are connected. Other power systems are normally interconnected via the transmission grids and the regional grids are connected to the transmission grid. The voltage level for the transmission grid is typically from 220kV and above.

Regional grid
The regional grid or sub-transmission grid connects large industrial consumers and the distribution grid to the transmission grid; the voltage levels is typically between 20-130kV.

Distribution grid
The distribution grid supplies end consumers and is normally from 230V to 20kV. The total length of the distribution grid is larger than the transmission and regional grids. The voltage levels mentioned above is typical in Europe.

2.2.2 Power system stability, balancing and ancillary services.

Power system stability may be defined as the ability of an electric power system, for a given initial operation condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [7]. By generalizing, power system stability is a single problem, but to understand power system instability and do mitigation actions it cannot be treated as a single problem. Figure 2-6 gives an overview of power system stability categorized into different types of stability. The two categories “Resonance stability” and “Converter-driven stability” in Figure 2-6 are recently added to the original classification model [8] in the report “Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies” [9] , as more power generation is interfaced with converter-based technology.

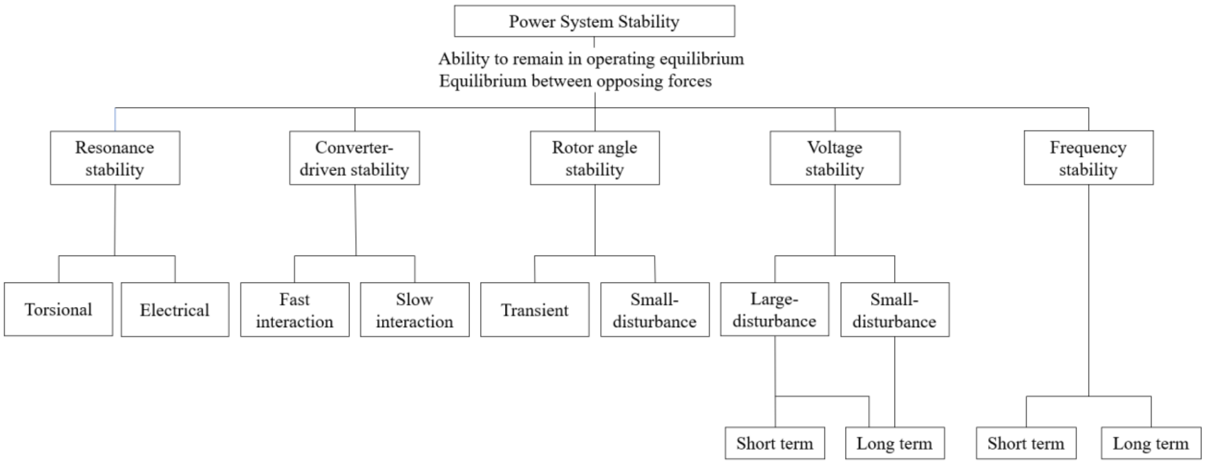

Figure 2-6: Classification of Power System Stability.

Inertia and frequency

In synchronous power systems, the generator and motor load rotate at a speed that is proportional to the frequency of the power system. The sum of all the rotating motors and generators connected to the power system equals the system inertia. The higher the system inertia, the better ability will the power system have to withstand a change in frequency. If a generating source is disconnected or a load connected, the kinetic energy stored in the connected generators is used to maintain the equilibrium between the supply and demand. Figure 2-7 shows the power system frequency response after an incident for two systems with different inertia. The blue curve represents the system with the highest inertia, the high inertia results in a lower rate of change of frequency (RoCoF) and the minimum frequency reached will be higher than the system with the low inertia.

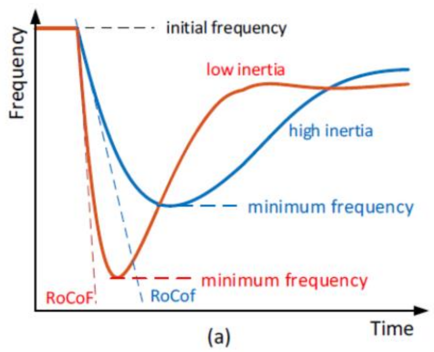

Figure 2-7: Power system frequency response after an incident [10]

The total inertia in a power system is called the synchronous inertia response (SIR), normally given in watt-seconds but for power systems it is normally given in GWs.

Rotor Angle Stability

In a traditional power system, generation of electrical power is done by synchronous machines. During steady state operation of a synchronous machine, there is an equilibrium of the mechanical torque exerted on the machine and the output of electrical torque, then the speed will be kept constant. If this equilibrium is disturbed, then the rotors of the machines will accelerate or deaccelerate, resulting in a rotor angle difference, this “slip” between the rotor field and the stator field (same as the system frequency), which leads to instabilities between the power output, voltage and current.
Rotor angle stability is the ability of synchronous machines to stay synchronized to the power system under a disturbance.

Voltage Stability

Voltage stability is the ability of a power system to maintain steady voltage at all buses in the system during normal operation and after subjected to a disturbance. Voltage instability typically occur when there is a change in the system conditions, increase in load or subjected to a disturbance, hence the main factor is the power systems ability to meet the needs for reactive power.

Frequency Stability

Frequency stability is the ability of a power system to maintain a steady frequency after being subjected to a severe disturbance resulting a discrepancy between the generation and load. Frequency instabilities are typically related to deficient equipment response, not sufficient coordination of protection and control equipment or not enough generation resources.

Resonance Stability

Resonance stability is when energy is exchanged in an oscillatory pattern. If not, sufficient energy is dispatched in the flow path, the oscillations can increase and amplify the voltage/current/torque magnitudes. Resonance instability is categorized in two types, torsional and electrical. Torsional resonance is between the mechanical torsional frequencies of a turbine-generator shaft and the series compensated lines. Electrical resonance is between the electrical characteristics of a generator and the series compensated lines.

Converter-driven Stability
Converter interfaced generation (CIG) differs from the typically synchronous generators, due to mainly voltage-source converters interfacing the grid. CIG is normally based on control loops and algorithms with fast response times, compared to a synchronous machine. This can result in cross couplings with both electromechanical dynamics of machines and the electromagnetic transients of a transmission network, which may lead to an unstable power system with oscillations over a wide frequency range. Converter-driven stability are classified as fast or -slow interactions. Fast interactions instability is typically in the frequency area 10Hz to kHz and are rooted in control systems for power-electronic based systems, CIGs, HVDC and flexible AC transmission system. Slow interactions instability is generated by slow response control systems for power electronics, such as synchronous generators and generator controllers.

2.2.3 Reactive power and Harmonic distortion

While the balance of active power between load generation has a significant impact on the frequency in a power system, the reactive power has a strong influence on the voltage. Unlike the control of frequency which is dependent on the active power balance within a defined area. Reactive power cannot be transferred over great distances and voltage control must be done by components spread throughout the power system. For a satisfactory operation of a power system, the control of reactive power and voltage should be controlled after the following objects:

- Reduce the reactive power flow so that the iron losses and reactive losses are minimized, so that the transmission system is primarily for active power.
- Keep the voltages on all the terminals in the power system within acceptable levels, as defined in applicable standards.
- System stability is elevated to maximize the utilization of the transmission system.

There is several equipment for generating reactive power and some of the equipment can both generate and absorb reactive power:

- Synchronous generators can produce or absorb reactive power, depending on the excitation of the machine. It produces reactive power when overexcited and absorbs reactive power when underexcited.

- Transformers absorb reactive power, during no load it is the shunt magnetizing that absorbs the reactive power, at full load it is the series leakage inductance that is the primary absorber of reactive power.

- Overhead lines can both absorb and generate reactive power. When the load is below the surge impedance the lines produce reactive power, if the load is above the surge impedance the lines absorb reactive power.

- Underground cables do normally have a higher capacitance and load and are always loaded below their surge impedance and generates reactive power.

- Loads do normally absorb reactive power. But the loads in a power system are dependent on many factors and vary throughout the day and season.

To be able to control the voltage levels in a power system, the generation, consumption, and flow of reactive power must be controlled. For controlling the reactive power, compensating devices are added to the power system to generate or absorb reactive power. These devices can be either passive or active components. Passive components could be shunt capacitors, reactors, and series capacitors, with passive components, they are either permanently connected to the power system, or can be switched in/out as needed. The passive components provide voltage control by changing the power system characteristics when they are inserted in the power system.
Active compensation can be provided by components such as synchronous condensers, static var compensators, regulating transformers, tap-changing transformers, but large loads driven by converters may also provide compensation for reactive power.

2.3 The electricity market and system balancing

2.3.1 Introduction

The electricity market is a wide term, that comprehends the whole value chain from production to consumption of electricity. This chapter will be general introduction as the electricity market may differ geographically and country wise and will focus on market mechanisms that can be utilized for grid stabilizing.
As a product electricity is a commodity and is normally separated from transmission and distribution, as a service. Figure 2-8 shows how the structure of the how electricity market can be organized.

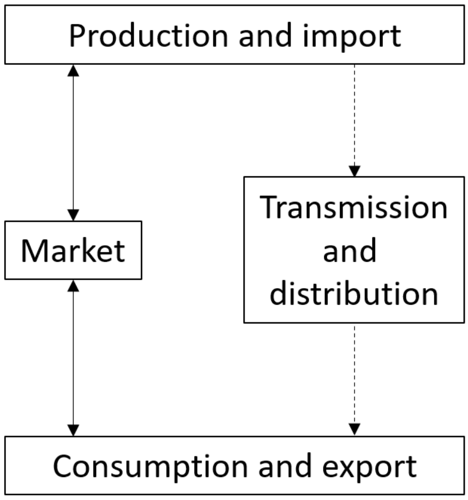

Figure 2-8 Electricity market structure; left, commercial flow; right, power flow.

In comparison with other tradeable commodities electricity have some different characteristics:

- It cannot easily be stored and must therefore be produced and used simultaneously, supply must meet demand exactly.
- Electricity is fully interchangeable, one MWh of electricity produced by wind power is the same as one MWh produced by natural gas.

Market structure

The electricity market can typically be divided into end-user market and wholesale market. With the wholesale market, large volumes are being traded by energy companies, power suppliers, energy traders and large industrial customers. Smaller end-users and industry are being traded for by power suppliers.
The wholesale market can typically be divided into several markets:

- Day-ahead market
- Continuous intraday market
- Balancing markets

The day-ahead and intraday market is normally traded on a power exchange or pool, while balancing markets is primarily run by the TSO. The largest volumes are traded in the day-ahead market (DAM) and in most electricity markets it is the primary market. In the DAM bids and offers are placed within a given timeslot, successively the trading capacities are published and the day-ahead auction closes. The delivery is for the following day and prices for either specific hours or quarter hours are calculated based on the available transmission capacity. When there is a deviation between the production and consumption after the market clearance in the DAM, e.g., when the weather forecast changes with respect to electricity produced by wind or solar power or if there is an unforeseen change in the consumption. Then the deviation in production and consumption is continuously being traded on the intraday market until an hour before physical delivery. The day-ahead and intraday market balances the generation and consumption of electricity, but the combination of those two markets it not sufficient to create an instantaneous balance. The balance market, which is more a mechanism than a market as the TSO is the only buyer and regulates the production and consumption.

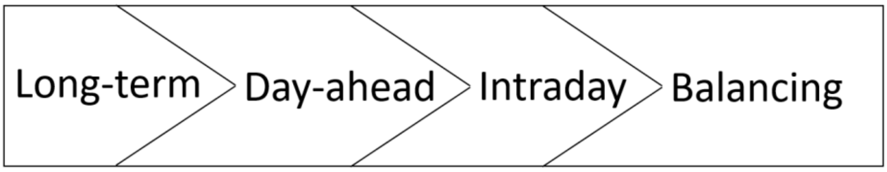

Figure 2-9 Electricity market time frames

The balance market is used to either regulate the production or consumption up or down to keep the system frequency. Typically, the balance market consists of a primary reserves, secondary reserves, and tertiary reserves.
When an imbalance occurs, the primary reserves are automatically activated within a few seconds to stabilize the frequency. The primary reserves involve all TSOs for a synchronous area and utilize the generation plants. Within 30 seconds the generating units can recover the speed and generated power for typically a time period of 15 minutes.
If an imbalance is present for several minutes the secondary reserves are automatically activated to release the primary reserves to that they are available for a new event. The secondary reserves are dedicated reserve power and are typically activated within 200 seconds and may last for 200 minutes. When more reserves are needed the tertiary reserves are manually activated by the TSO, by starting or stopping units to substitute for det secondary reserves.
Normally the primary reserves are traded in an hourly and weekly basis, while the secondary reserves are traded on a weekly basis, by the TSO. For the tertiary reserves the TSO ensures that there is sufficient capacity and participants in the market get paid in advance to make sure that there is regulating power availability, this market is often called regulating power market.

2.3.2 Market mechanisms for balancing power

For maintaining the integrity of the power system there are several market mechanisms for assuring the operational security of the power system. Depending on how the power system is organized, these mechanisms are normally under the responsibility of the TSOs, system operator, balance authority or a cooperation between these. Based on the different markets and system operators the terminology used for these services may vary, which will be categorized in this chapter.

The market mechanisms can be divided into three main categories: Operating Reserve, Planning Reserve and Voltage/reactive power control/reserve as shown in Figure 2-10.

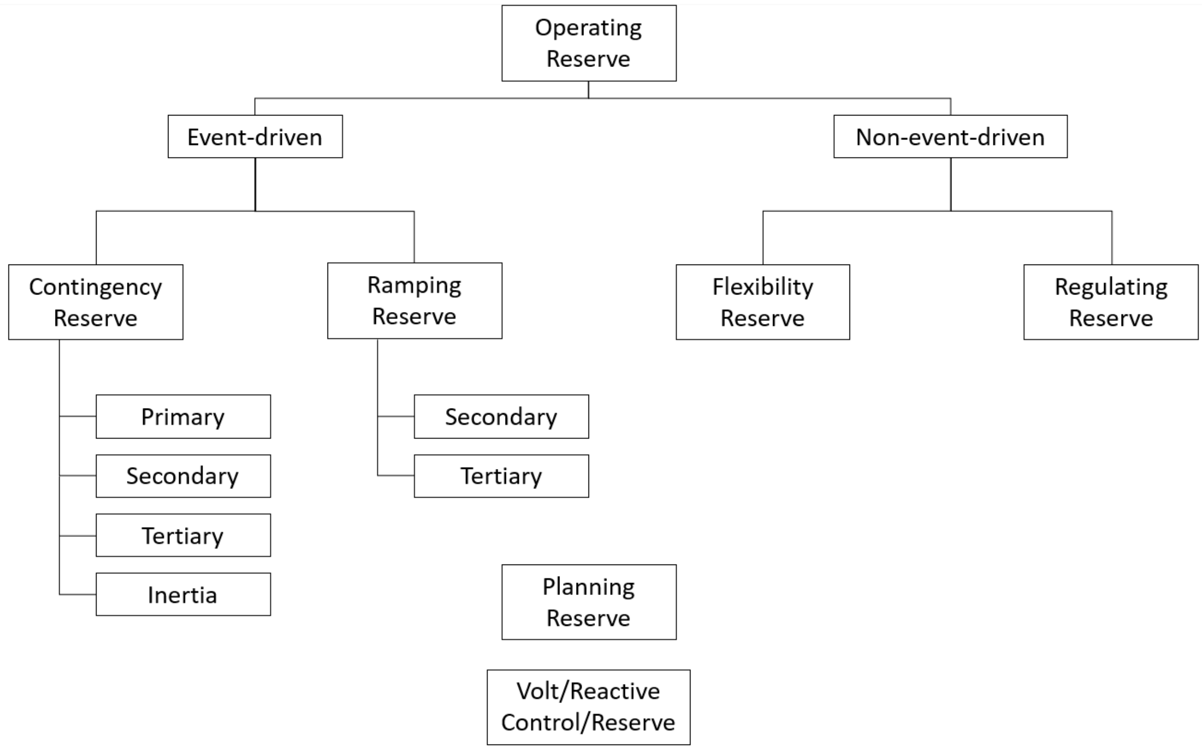

Figure 2-10: Main categories for ancillary services.

Operating Reserve

The operating reserve is the active power capacity available in a power system that is available within a relatively short time. The operating reserves are typically within a balancing area, but some are shared across multiple areas. Operating reserves can again be divided into categories if they are activated due to an event or planned.

Primary Contingency Reserves

Primary contingency reserve is typically called primary frequency response. It is an automatic response to deviations in the system frequency, by changing either the active power output or load. Figure 2-11 shows when the Primary frequency response is being activated in response to a contingency.

Other used names for Primary Contingency Reserves: Primary Control Reserve, Primary Frequency Response, Frequency Containment Reserve, Governor Response, FFR.

Primary Reserves
The primary reserves are used for constant control of the frequency. The response time is fast typically a few seconds, and the duration is normally below a minute. A standard name for these resources is Frequency Containment Reserves for Normal Operation (FCR-N) and Frequency Containment Reserves for Disturbance (FCR-D). FCR-N keeps the frequency within the standard range, while FCR-D activates when the frequency is out of the normal range.

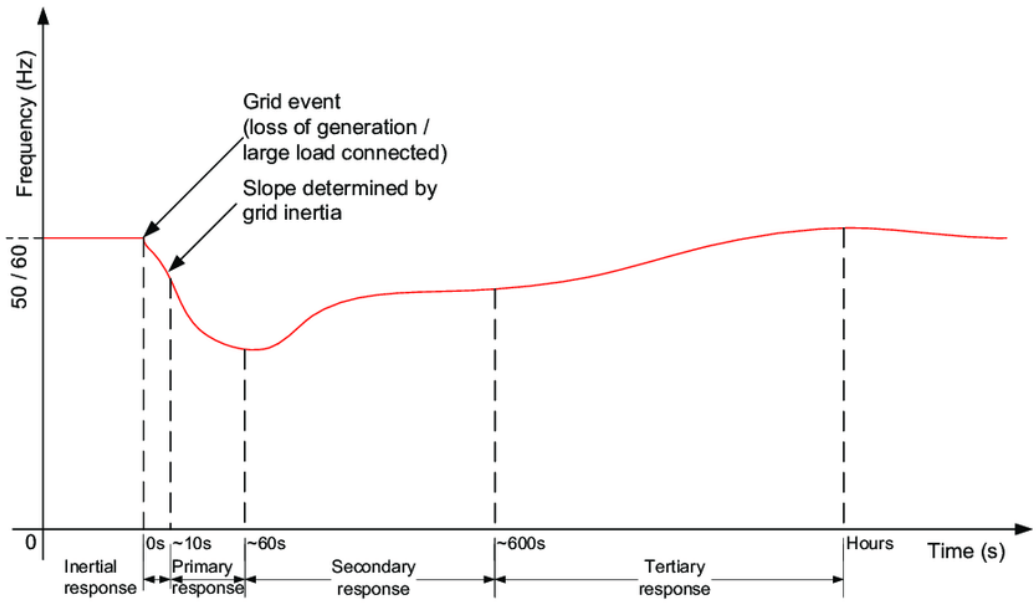

Figure 2-11: Different type of contigency reseserves in repsponse to an event [11].

Secondary Contingency Reserves

The purpose of the secondary contingency reserves is to return the frequency to the standard range and release the primary contingency reserves. Figure 2-11 shows a response time of 10 minutes for det secondary reserve, although it may differ from that. The secondary reserves is made by both online and offline reserves. The online reserves are typically named spinning or synchronized reserves and can immediately respond to a contingency. While the offline reserves non-spinning/synchronized must be available with full response within a time limit.

Other used names for Secondary Contingency Reserves: Synchronized reserves, spinning reserves, non-spinning reserve, frequency restoration reserves.

Tertiary Contingency Reserves

The tertiary contingency reserves release the activated primary and secondary reserves, so that the required amount of contingency reserve is available again after a contingency. It is a slower product and typically has a response time from 15-60 minutes. Tertiary reserves could e.g. be starting up a power plant that is not being used for electricity production during normal production or disconnecting a large load connected to the power system.

Other used names for Tertiary Contingency Reserves: Replacement reserves, thirty-minute operating reserves.

Inertia Reserves

Inertia is typically provided by the rotating mass from synchronous generators. The more inertia there is in a power system the slower the rate of change of frequency will be. In Figure 2-11 the frequency for a power system is shown before and after a contingency, before the primary contingency reserves responds the behavior of the frequency of the system depends on the available inertia in the system. Inertia reserves are normally not an ancillary service, but some system operators have a minimum requirement for inertia in their system. This is typical in regions where large loads have a longer respond time to avoid that under-frequency load-shedding.

Ramping Reserves

Ramping reserves are not an ancillary product, but there are some large and sparse events that require the power system to be in balance, e.g., be a large GW-sized forecast error or a planned outage of a transmission line.

Other used names for Ramping Reserves: Ramping margin.

Regulating Reserves

The regulating reserves are used to reduce the system operator's area control error (ACE). Regulating reserves are procured capacity, the regulation is controlled by automatic generation control (AGC). The AGC is activated between the dispatched energy in the real time market. The regulating reserves are dispatched continuously to keep the equilibrium between the load and the generated power. Regulating reserves are both upwards and downwards in case of over/under-generation. Normally the regulation reserves are traded in the day-ahead market, the time length of the traded regulating reserves moves from 60-minute intervals towards 15 minutes intervals, depending of how the connected power market is organized.

Other used names for Regulating Reserves: Load frequency control, AGC reserve, regulation, regulation up/down.

Fast Frequency Reserves

Fast Frequency Reserves (FFR) is a newer product for ancillary services. Normally primary contingency reserves handle frequency instabilities, but the response time of these reserves may be slow in cases where the inertia in the power system is low. This is typically for power systems which have a seasonal increased power production from renewable energy sources. When the frequency drops below a certain limit FFR are dispatched either as increased active power production or a reduction of a load. The FFR are dispatched within a second, before the primary contingency reserves are activated, to minimize the difference between generation and consumption until the primary reserves have returned the frequency to a stable state.

Other used names for Fast Frequency Reserves: Fast Frequency Response.

3 Method

The methodology for this thesis is split into two parts, a literature study, and a feasibility evaluation. The literature study covers a brief look of the process for producing hydrogen with a PEM-electrolyser. What market mechanisms and standards exist in different regions for balancing electricity.

With the information found in the literature study a feasibility evaluation will be conducted. The feasibility evaluation will investigate how a PEM-based hydrogen production facility can be used for stabilizing an electrical power system.

4 Market mechanisms

This chapter will give an overview of the market mechanisms for balancing energy in Northern Europe, Europe, North America, and Australia.

4.1 Europe

The Continental Europe Synchronous Area is the largest synchronous power system in the world, measured by connected power. Most of the countries in Europe are members of the European Union (EU) or the European Economic Area (EEA). The European Union Agency for the Cooperation of Energy Regulators (ACER) was established by the European Union, as an independent body for the integration and completion of the European market for electricity. ACER makes and issues regulatory framework on the behalf of the EU. The other key player for developing and implementing standards, network codes, platforms, and tools to ensure the power system and market operation is ENTSO-E. ENTSO-E is the European Network of Transmission System Operators for Electricity, representing 42 member TSOs in 35 countries.

The Commission Regulation (EU) 2021/280 [12] is the framework for a guideline for energy balancing within the EU. Based on guideline for energy balancing Commission Regulation (EU) 2021/280, four mandatory market platforms for trading electricity for energy balancing are implemented in the following projects:

- Manually Activated Reserves Initiatives (MARI), for design and implementation of the European platform for exchange of balancing energy from Frequency Restoration Reserves with manual activation (mFRR), in response to Article 20 Commission Regulation (EU) 2021/280.
- Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO), for design and implementation of the European platform for exchange of balancing energy from Frequency Restoration Reserves with automatic activation (aFRR), in response to Article 21 Commission Regulation (EU) 2021/280.
- International Grid Control Cooperation (IGCC), for design and implementation of the European platform for exchange of balancing energy from Imbalance Netting (IN), in response to Article 22 Commission Regulation (EU) 2021/280.
- Trans-European Replacement Reserves (TERRE), for design and implementation of the European platform for exchange of balancing energy from Replacement Reserves, in response to Article 19 Commission Regulation (EU) 2021/280.

The voluntarily platform for the exchange of Frequency Containment Reserves is the FCR Cooperation.

4.1.1 Manually Activated Reserves Initiatives (MARI)

The objective of the MARI platform is a market platform for Manual Frequency Restoration Reserves (mFRR). The mFRR is a balancing reserve for restoring the frequency to within its standard range. The mFRR is provided as a service by a balancing service provider (BSP) but is activated by a TSO. The TSO receives the bids from the BSP, and the TSO communicates their balancing needs and the available cross border transmission capacity. So that if a connecting TSO has cheaper or available reserves, the reserves within another TSO can be utilized. There are two products for the MARI platform, mFRR Scheduled Product/Scheduled Activation (SA) and Direct Activation (DA) of mFRR. The scheduled activation is used to balance forecasted imbalances or to level out already active aFRR bids. Primarily the Scheduled Activations are used, but if an unexpected imbalance occurs between two SAs, DA can activate mFRR bids at any time. Figure 4-1 shows the member countries of the MARI platform.

Figure 4-1: European countries that have implemented the MARI platform [13]

Table 2: Characteristics for mFRR MARI [14]

	Scheduled Activation	Direct Activation
Bid size	MW	MW
Full activation time	12.5 min	12.5 min
Minimum duration	5 min at full activation capacity	5 min at full activation capacity
Direction	Positive demand, negative demand	Positive demand, negative demand

4.1.2 FCR Cooperation

The Frequency Containment Reserves (FCR) Cooperation is a regional project for 11 TSOs in the countries in Figure 4-2. The FCR Cooperation is a TSO-TSO model, the FCR is procured through a pool where the TSO lists the offers, they've received, and the offers are sorted by the price per MW. The interaction between the TSO and balance service providers is handled on a national level.

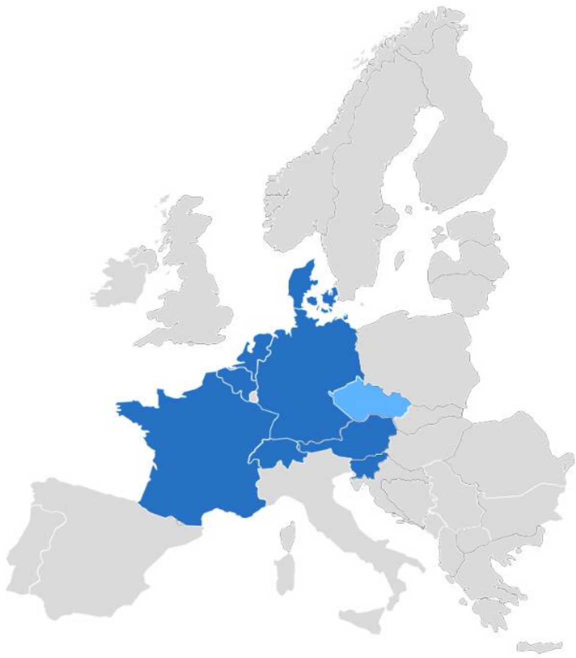

Figure 4-2: Members of FCR Cooperation [15]

Table 3 shows the specifications for the product traded in the FCR Cooperation. The product can be split into two types of bids, indivisible and divisible bids. The indivisible bids can only be fully awarded or not awarded, but for the divisible bids a quantity between 0 and the full offered quantity of the bid can be awarded.

Table 3: Characteristics for FCR Cooperation [16]

	Indivisible bids	Divisible bids
Bid size	1-25 MW	Min 1 MW
Bid resolution	1 MW	1 MW
Delivery duration	4 Hour	4 Hour
Direction	Symmetrical	Symmetrical

4.1.3 Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO)

The PICASSO platform is a European project for making a common market platform for Automated Frequency Restoration Reserves (aFRR). Figure 4-3. Shows the member countries of the PICASSO platform, however the platform is implemented by Austria, Czech Republic, Germany per Q2 2023, the remaining countries will follow in 2023-2024.

Figure 4-3: European countries that have implemented the PICASSO platform [17]

Table 4 shows the requirements for the aFRR bids for the PICASSO platform. Throughout the ongoing implementation process of the specifications for the aFRR bids are subject to change, and it is likely that it will be local specifications.

Table 4: Characteristics for aFRR bids on the PICASSO platform [18]

Bid size	Depending on what the provider is qualified for, resolution 1 MW.
Full activation time	5 minutes
Duration	15 minutes
Direction	Up/Down

4.1.4 International Grid Control Cooperation (IGCC)

The International Grid Control Cooperation is the European platform for imbalance netting of automatic Frequency Restoration Reserves (aFRR). The purpose of the IGCC platform is to reduce the total volume of activated balancing reserves. Example, if Load Frequency Control (LFC) Area-A needs 150 MW and LFC Area-B have a surplus of 80 MW, after netting the imbalance LFC Area-A needs 70 MW. The activation of the remaining 70MW will be in the LFC area with the original demand. The netting is only possible if there is cross border capacity between the two LFC-Areas.

There are no defined specifications for the imbalance netting, but it follows the aFRR for the TSOs, the limiting factor is however the cross-border capacity.

Figure 4-4 European countries that have implemented the IGCC platform [19]

Trans-European Replacement Reserves Exchange (TERRE)

The Trans-European Replacement Reserves Exchange is a platform for the exchange of replacement reserves, Figure 4-5 shows the TERRE members. Table 5 presents the characteristics for the Terre Platform.

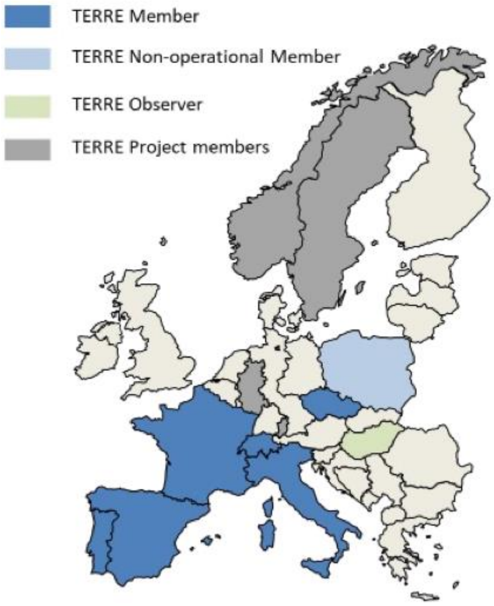

Figure 4-5 European countries that have implemented the TERRE platform [20]

Table 5: Characteristics for TERRE energy balancing [21]

Minimum volume	0 MW
Maximum volume	Decided by the TSO, depends on LFC area.
Minimum delivery time	15 Minutes
Maximum delivery time	60 Minutes
Direction	Positive (System short)/ Negative (System long)

4.2 Norway

The ancillary markets in Norway are split into a capacity market and activation market. The capacity market ensures that there is enough available reserve capacity when needed. Providers of reserve capacity that are accepted in the capacity market, must either respond automatically or commit to participate in the activation market. The activation market is used for buying bid that regulates that either regulates up or down the production or consumption. Figure 4-6 shows the load frequency areas in Norway, which is also the balancing areas, as referred to in the upper right corner in Table 6. Table 6 shows the characteristics for the ancillary services in Norway.

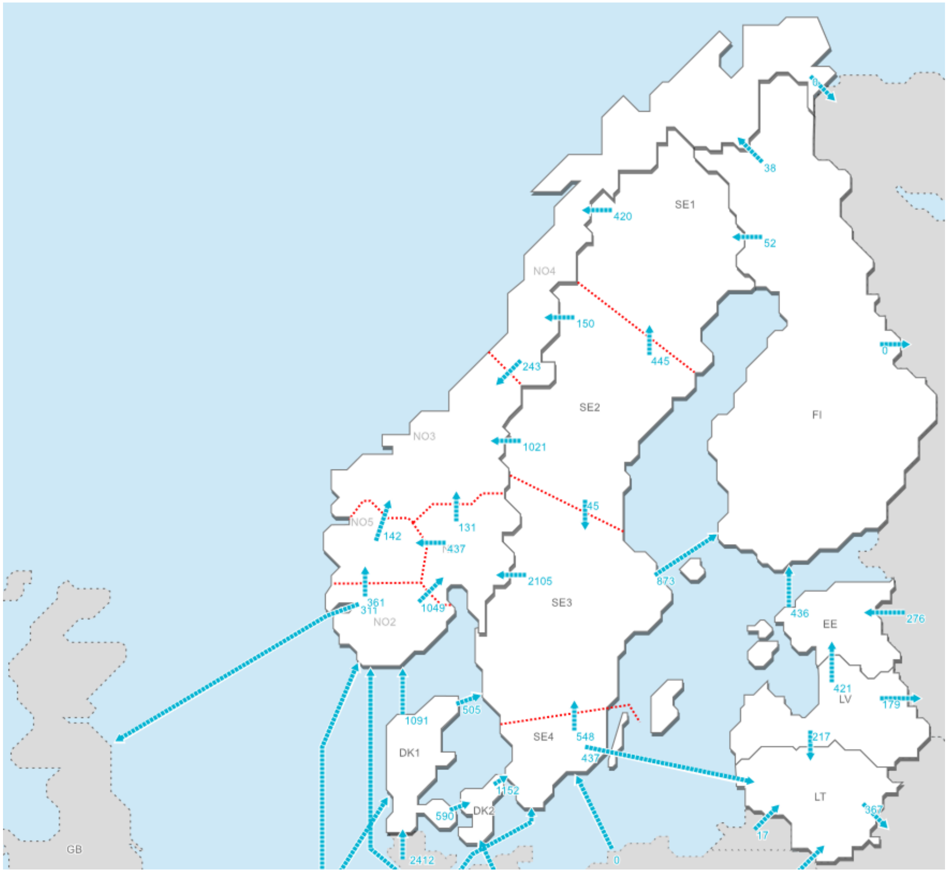

Figure 4-6:Map of the Nordic electricity price areas with interconnections [23]

Table 6: Characteristics for the products in the Norwegian ancillary market [22]

Product	FFR	FCR	aFRR	mFRR
Minimum volume	1/5 MW	1 MW	1 MW	10 MW in NO2, NO5 and NO4. 5 MW in NO1 and NO3.
Maximum volume	50 MW			
Response time	0,7-1-1,3 Seconds Depends on frequency	30 Seconds	Full response within 2 minutes	Full response within 12,5 minutes
Duration	5 or 30 Seconds	15 Minutes	As long as the bid lasts	As long as the bid lasts
Market	Capacity	Capacity	Capacity and Activation	Capacity and Activation
Miscellaneous	There are seasonal contracts for FFR, Flex and Profil, with different terms & conditions.	Two products, FCR-N, FCR-D. N-Normal reserves, D-Disturbance reserves,		

Norway is a part of the Nordic synchronous area, which covers Norway, Sweden, Finland, and Zealand in Denmark. The Nordic TSOs have established the Nordic Balancing Model for better utilizing balancing reserves. A Nordic aFRR capacity market was established in Q4 in 2022, further a Nordic capacity and activation market for mFRR is planned in 2023-2024. After a successful implementation of a common Nordic market for aFRR and mFRR, an integration of the Nordic activation market for aFRR and mFRR in respectively PICASSO and MARI are planned.

4.3 North America

The North American Electrical Reliability Corporation (NERC) is a non-profit international regulatory authority with the purpose to assure effective and efficient reductions of risks to the reliability of security of the grid. NERC is the Electrical Reliability Organization for North America and develops & enforces reliability standards. NERC's area of responsibility is shown in Figure 4-7 and covers the United States of America, Canada, and northern parts of Mexico. The responsibility areas can be divided into the following regions: Western Electricity Coordinating Council (WECC), Midwest Reliability Organization (MRO), Texas Reliability Entity (TRE), SERC Reliability Corporation (SERC), Reliability First (RF) and Northeast Power Coordinating Council (NPCC).

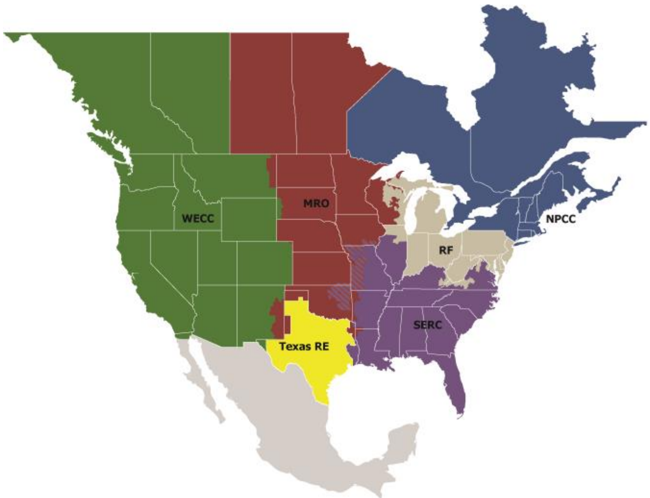

Figure 4-7: NERC regions [24]

The North American power system can be divided in five main power systems, or interconnections, Western, Eastern, Québec, Texas, and the Alaska Interconnection. The two main interconnections are Eastern and Western. The Alaska Interconnection is a two separate power system and is not connected and does not have any power exchanges with any other interconnections. While the Québec and Texas Interconnection are connected to the Eastern Interconnection. The interconnections cover several NERC regions as shown in Figure 4-7. Each interconnection works as a separate synchronous area, with the purpose to maintain the frequency as close as possible to the system frequency. Figure 4-8 shows which areas are being covered by the five interconnections. Within these interconnections Reliability Coordinators, Transmission Operators, Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) work as balancing authorities. The US, Canada and the majority of America have a power system frequency of 60 Hz.

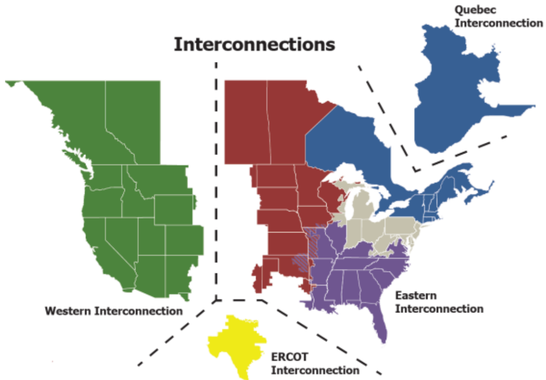

Figure 4-8: NERC Interconnections [25]

Market-based mechanisms for ancillary services within the NERC Interconnections

For grid balancing within the NERC Interconnections, balance authorities ensure in real time that the demand and supply for electricity is in balance. Balancing authorities (BAs) are responsible for maintaining operating conditions by the standards from NERC. The BAs have the responsibility for a balance authority area that may cover different NERC interconnections and entity regions. Figure 4-9 shows BAs in the US interconnections, not all BAs have their ancillary services in a market, Figure 4-10 shows the electricity markets for ancillary services.

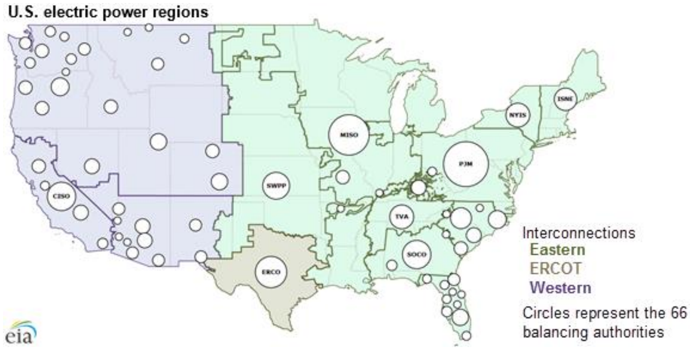

Figure 4-9: Circles representing balance authorities within US Interconnections [26]

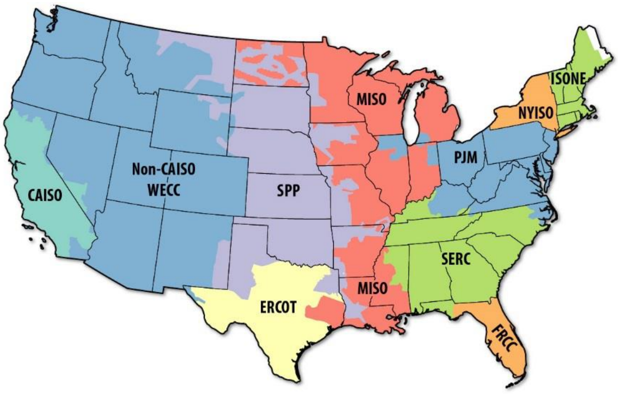

Figure 4-10: US markets for ancillary services [27]

4.3.1 Western Interconnection

The main market for ancillary services within the Western Interconnection is the Western Energy Imbalance Market (WEIM). The WEIM is governed by California ISO (CAISO) and covers the area shown in Figure 4-11.

Figure 4-11: Western Energy Imbalance Market [27]

The Western Energy Imbalance Market have four products for ancillary services that are shown in Table 7.

Table 7: Characteristics for ancillary services in the WEIM [28]

WEIM	Regulation Up/Down	Spinning Reserves	Non-Spinning Reserves
Volume	Specified for each sub-region and trading hour in MW.	MW	MW
Activation	Continuously, each 5 second. Automatic Governor Control	Must respond within 10 Minutes	Must respond within 10 Minutes
Minimum duration	15 minutes	60 minutes	60 minutes
Miscellaneous			

Southwest Power Pool (SPP) has a market named Western Energy Imbalance Service Market (WEIS) that is a competitive market to WEIM and covers the eastern part of the WEIM and eastbound.

Table 8: Characteristics for ancillary services in the WEIS [29]

WEIS	Regulation Up/Down	Spinning Reserves	Non-Spinning Reserves
Specifications agreed between each provider			

4.3.2 Eastern Interconnection

The Eastern Interconnection is the interconnection where there are the most markets for ancillary services. The largest markets are the Southwest Power Pool, PJM Interconnection, Midcontinent Independent System Operator (MISO), ISO-NE and NYISO. Shown in Figure 4-10.

SPP

Southwest Power Pool have members in the following areas: Arkansas, Colorado, Iowa, Kansas, Louisiana, Minnesota, Missouri, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas and Wyoming. The ancillary services provided in SPP are shown in Table 9.

Table 9: Characteristics for ancillary services in SPP

SPP	Regulation Up Regulation Down	Spinning Reserves	Non-Spinning Reserves
Amount	MW	MW	MW
Activation	Continuously, each 5 second. Automatic Governor Control	Must respond within 10 Minutes	Must respond within 10 Minutes
Minimum duration	60 minutes	60 minutes	60 minutes
Direction	NA	Symmetrical	
Applicable standards	Market Protocols 6.1.11		

MISO

MISO covers 15 states in US and Manitoba in Canada, there is five products for ancillary services as shown in Table 10.

Table 10: Characteristics for MISO ancillary services [30]

MISO	Regulation Up/Down	Spinning Reserves	Non-Spinning Reserves	Ramp Capability	Short-term reserve
Amount	MW	MW	MW	MW	MW
Activation	Continuously, each 5 second. Must respond within 5 minutes	Must respond within 10 Minutes	Must respond within 10 Minutes	Must respond within 10 Minutes	
Minimum duration	15 minutes	60 minutes	60 minutes	10 minutes	30 minutes

PJM Interconnection

The PJM Interconnection covers 14 states in the US, there is three products on the ancillary market as shown in Table 11.

Table 11: Specifications for PJM Ancillary services [28]

PJM	Regulation Service	Synchronized Reserves	Non-synchronized Reserves
Minimum Volume	0.1 MW	-	-
Maximum ramp time	10 Minutes	10 Minutes	30 minutes
Minimum duration	15 minutes	30 minutes	30 minutes
Miscellaneous	Two types of regulation exist, slow and fast		

ISO-NE

The ISO-NE has four regions for ancillary services, Southwest Connecticut, Connecticut, Northeast Massachusetts and Boston, and the rest of New England. There are four products in the ancillary market shown in Table 12.

Table 12: Characteristics for ISO-NE Ancillary services [28]

ISO-NE	Regulation UP/	Ten-minute Synchronized Reserves	Ten-minute Non-Synchronized Reserves	Thirty-minute operating reserves
Amount Activation	-	-	-	
Maximum ramp time	10 Minutes	10 Minutes	10 minutes	30 minutes
Minimum duration	15 minutes	60 minutes	60 minutes	
Miscellaneous	1MW/min and 5MW	-		

NYISO

The New York-ISO have three ancillary markets that covers west of Central-East, East of Central-East (excluding Long Island) and Long Island, shown in Table 13.

Table 13: Characteristics for NYISO ancillary services [28]

NYISO	Regulation Service	Ten-minute Spinning Reserves	Ten-minute Non-Spinning Reserves	Thirty-minute Spinning Reserves	Thirty-minute Non-Spinning Reserves
Amount	Regulation capacity response rate times 5 minutes or max capacity	MW	MW		
Activation					
Maximum ramp time	10 Minutes	10 Minutes	30 minutes		
Minimum duration	15 minutes	30 minutes	30 minutes	60 minutes	60 minutes

4.3.3 Texas Interconnection

The Electric Reliability Council of Texas (ERCOT) is a non-profit member organization that operates the electrical grid in the Texas Interconnection. ERCOT covers the whole Texas Interconnection as shown in Figure 4-8. ERCOT have four ancillary service products:

- Regulation service – Up/Down

Regulation service up & down can be supplied from two sources, either as a resource capacity from a specific generator source or energy storage resource (ESR), or supplied from a load specific capacity. With the term regulation down service, it means that resource specific capacity is deployed to increase or decrease generation below the generation resource base point in response to a change in system frequency. For a load specific capacity the load resource is changed to that it is below the maximum power consumption limit of the load resource. For regulation-up it follows as above but the generation is changed to a higher level than the generation resource base point for a resource capacity, and for a load resource the load is changed higher than the load resource low point consumption limit. The characteristics for the regulation service is shown in Table 14.

Table 14: Characteristics for Regulation Service [32] [33]

	Regulation service
Amount	Determined by ERCOT in MW
Activation	LFC signal sent by ERCOT each 5 second for compensate for changes to load and generation.
Direction	Symmetrical

- Response Reserve Service

Response Reserves Services (RRS) is ERCOTs product for Fast Frequency Response. RRS can be provided as operating reserves from generation resources, energy storing resources, load resources and other resources available for providing FFR maintained by ERCOT. RRS on generation resources energy storing resources and controllable loads can also be activated as energy when the power system is in an energy emergency alert.
RSS can be activated by Automatic governor or under frequency relay, by an electronic signal from ERCOT based on the need or ordered by an ERCOT operating during an energy emergency alert.Table 15

Table 15: Characteristics Response Reserve Service [32] [33]

Response Reserve Service	Generation Source	Load Source
Amount	Determined by ERCOT in MW	
Activation	-Automatic governor action or under frequency relay - Electronic control signal from ERCOT, defined by the need. -Ordered by an ERCOT operator during an emergency	

- ERCOT Contingency Reserve Services

The ERCOT Contingency Reserve Services ECRS is ERCOTs secondary resources and is categorized into the following three groups:

i. Offline generation resource, ESR capacity or reserved capacity from online generation resources or ESR, available for being ramped to a specific setpoint within 10 minutes and maintain it for minimum 60 minutes.
ii. Controllable load SCED, available for being ramped to a specific setpoint within 10 minutes and maintain it for minimum 60 minutes.
iii. Load resources that are not controllable and not controlled by an under frequency relay and can interrupt within 10 minutes by demand form ERCOT can continue for minimum 60 minutes.

Table 16: Characteristics for ERCOT Contingency Reserve Services [32] [33]

ECRS	Generation Source	Load Source
Amount	MW	MW
Maximum ramp time	10 Minutes	10 Minutes
Minimum duration	1 Hour	1 Hour
Direction	Symmetrical	Symmetrical

- Non-spinning Reserve Service

The non-spinning resources are categorized within three main groups:

i. Offline generation resource, energy storage capacity or reserved capacity from online generation or energy storage resources, able to ramp up to a specific output within 30 minutes and operating at a specific output at minimum one hour.
ii. Controllable load resources that can ramp within 30 minutes to a specific load that is instructed by ERCOT and maintain that load for minimum 1 hour.
iii. Load resources that are not controllable and not controlled by an under-frequency relay and load resources that are not controllable spin must be able to reduce load in response to a pre-defined dispatch scheme within 30 minutes and until recalled by ERCOT.

Table 17: Characteristics for Non-spinning Reserve Services [32] [33]

Non-spinning reserves	Generation source	Load source
Amount	MW	MW
Maximum ramp time	30 minutes	30 minutes
Minimum duration	1 Hour	1 Hour

Direction	Symmetrical	Symmetrical

Quebec Interconnection

Northeast Power Coordinating Council (NPCC) is the regulating entity covering the Quebec Interconnection. The NPCC covers both the US and Canada, 70% [34] of the Canadian net energy load is within the NPCC. Within the NPCC entity, NPCC defines a minimum standards and requirements for operating reserves for the entity which the ISO/BA must full fill, shown in Table 18.

Table 18: Minimum Ancillary services within NPCC [35]

NPCC	Ten-Minute Reserve	Ten-Minute Synchronized Reserve	Thirty-Minute Reserve
Requirements	The BA shall have reserve equal to the largest contingency within 10 minutes.	The BAs minimum requirement for synchronized reserves is 25% of the ten-minute reserve.	The BA must have capacity equal to 50% of its second largest contingency loss. Can consist of synchronized and non-synchronized reserves.

4.4 Australia

The Australian electricity market and infrastructure is governed by several instances. On a top level the Energy Council that is organized within the Council of Australian Governments, sets the policy and regulatory framework. The Australian Energy Market Commission (AEMC) are responsible for making rules and market development. The Australian Energy Regulator (AER) enforces the rules made by AEMC. The Australian Energy Market Operator (AEMO) is responsible for the power system and market operation, maintaining a required amount of electric reserve and coordinating how the electricity is dispatched. These three institutions oversee the power system and market.

Australia is covered by three main power systems:

- National Electricity Market (NEM)
- South West Interconnected Systems (SWIS)
- North West Interconnected Systems (NWIS)

The Northern Territory consists of three smaller power systems, and it is not covered.

4.4.1 National Electricity Market

NEM is the largest power system and market in Australia and covers eastern and southern Australia as shown by the grey area in Figure 4-12.

Figure 4-12: The grey area shows the regions that is a part of the National Electricity Market. [36]

The ancillary services in NEM can be divided into three categories:

- Frequency Control Ancillary Services (FCAS)
- Network Support & Control Ancillary Services (NSCAS)
- System Restart Ancillary Services (SRAS)

Frequency Control Ancillary Services

The FCAS is to keep the power system frequency by maintaining the generation/demand balance and can be divided in to two types of frequency control, regulation, and contingency. Regulation is a correction of generation/demand balance when there is a smaller change in generation or load. Contingency frequency control is a correction of generation/demand balance after a severe contingency e.g., loss of a generation unit or a large industrial load. There are eight FCAS markets in NEM. Table 1Table 19 presents an overview of the ancillary services in NEM.

Regulation
- Regulation Raise – Continuous regulation service to correct a minor drop in frequency
- Regulation Lower – Continuous regulation service to correct a minor rise in frequency.

Contingency
- Fast Raise – 6 second response to correct a large drop in frequency following a contingency.
- Fast Lower – 6 second response to correct a large rise in frequency following a contingency.
- Slow Raise – 60 second response to stabilize frequency following a large drop in frequency.
- Slow Lower – 60 second response to stabilize frequency following a large rise in frequency.
- Delayed Raise – 5 minute response to recover frequency within the normal operating limits following a large drop in frequency.
- Delayed Lower – 5 5 minute response to recover frequency within the normal operating limits following a large rise in frequency.

Network Support & Control Ancillary Services

The NSCAS can be divided into three categories:

- Voltage Control Ancillary Service (VCAS)

VCAS is ancillary services for regulating the voltage in the power system within specified tolerances. With these ancillary services, generators absorb or generates reactive power to or from the power system to control the voltage.
There are two products for VCAS:

- Synchronous Condenser: A DC-excited synchronous machine that provides improved voltage regulation and stability by continuously generating/absorbing reactive power.
- Static Reactive Plant: Reactors or capacitors that can supply reactive power.

- Network Loading Control Ancillary Services (NLCAS)

The NLCAS controls the power flow in interconnection within short-term limits. If the power flow from region A to region B exceeds the short-term limits, the power flow can be reduced by increasing the generation in region B, or by load shedding in region B.

- Transient and Oscillatory Stability Ancillary Service (TOSAS)

If a short circuit or equipment stops working, a spike in the power flow may occur. TOSAS controls and fast-regulate the power system voltage, increase the inertia of rotating mass connected to the grid or with very fast response increase/reduce load connected to the power system. It could be services such as: Power system stabilizers, synchronous condensers, SVCs & generators.

System Restart Ancillary Services (SRAS)

These services are required to enable the power system to be restarted after a partial or full black-out. SRAS are provided with two different technologies:

- General Restart Source: A generator that can start and supply energy to the power system without any external source of supply.
- Trip to House Load: A generator that can sense a system failure, disconnect from the power system, and run in idle, until AEMO is ready to use it for restarting the system.

Table 19: Ancillary services in the New Electrical Market [36]

NEM	Regulation	Contingency	NLCAS	SRAS
Type	Raise Lower	6 Second Raise 6 Second Lower 60 Second Raise 60 Second Lower 5 Minute Raise 5 Minute lower		
Miscellaneous		1 Second Raise/Lower will effective from 09/10/2023 [37]		

4.4.2 South West Interconnected Systems

The SWIS covers the southern part of west Australia, the main electricity supplier in SWIS is the Wholesale Electricity Market (WEM). AEMO is responsible for operating the ancillary services within SWIS. There are four ancillary services, but only one is procured through a market. Table 20 shows the summarized ancillary services in the SWIS.
The following ancillary services in the SWIS:

Load Following Ancillary Services (LFAS)
LFAS is equal to the Frequency Control Ancillary Services- Regulation in NEM.
Load Following Ancillary Service is only ancillary that is procured through a market, LFAS market.

Spinning Reserve Ancillary Services (SRAS)
SRAS is the same as Frequency Control Ancillary Services- Contingency in NEM, the difference is in the respond time for delayed Raise/Lower is called Class C, and is 6 minutes instead of 5 minutes as in the FCAS.
Potential providers may be qualified and contracted by AEMO to supply the service.

Load Rejection Reserve Ancillary Services (LRRAS)
LRRAS requires that a generating source is in a state where it can fast reduce the output in case of a system fault results in loss of a load. This service is normal during the night when most generating sources are operating at a minimum load. Potential providers can be qualified and contracted by AEMO to supply the service.

Dispatch Support Service (DSS)
DSS is the same as NSCAS in the NEM. Potential providers can be qualified and contracted by AEMO to supply the service.

Table 20: Ancillary services in SWIS [38] [39]

SWIS	LFAS	SRAS	LRRAS	DSS
Type	Normal Range 49,8-50,2 Hz Single Contingency 48,75-51Hz	6 Second Raise 6 Second Lower 60 Second Raise 60 Second Lower 6 Minute Raise 6 Minute Lower	6 Seconds 60 Seconds	
Response time	Normal range, 15 Minutes Below 50.5 Hz, within 2 minutes	60 Seconds 6 Minutes 15 Minutes	Sustain or exceed the required load for min 6 minutes Sustain or exceed the required load for min 60 minutes	

4.4.3 North West Interconnected Systems

The northern part of west Australia is less populated than the southern part of west Australia, and the NWIS is the smallest of the three major power systems in Australia. NWIS is overseen by state owned Horizon Power, which owns approx. ¼ of the system. Within the NWIS there are five companies – Horizon Power, Alinta, BHPBilliton, Pilbara Iron and ATCO Australia responsible for generating, distributing, and trading electricity. The organization of NWIS differs from other traditional power systems, as some of the consumers also supply generation and owns part of the transmission lines. These are large consumers as e.g., resource facilities like Pilbara Iron and BHPBillition that is categorized as integrated mining network. Further NWIS also covers standalone generating units and several micro grids and isolated power systems. The different power systems in the NWIS results in different rules and standards that are applicable in the NWIS regions.
For the North West Interconnected Systems there is an ongoing process of standardize the system operations arrangements [40], per now the individual Network Service Providers within the NWIS have handled the ancillary services informal by themselves, with no overall plan [40].

5 Discussion

The purpose of this project is to assess how the flexibility of a large consumer of electricity such as a hydrogen production facility can be implemented, and to analyze the corresponding market mechanisms. The assessment compromises four main sections based on a literature study; investigate what market mechanisms exist in different areas, how do the different compare and what standards do exist, how can a large consumer contribute to stabilize a weak grid, and what properties does the consumer need to be able utilized in this setting.

5.1 Market mechanisms & different electricity power markets compare and what standards does exist.

On a higher level there is requirements and standards for ancillary services for areas as Europe, North America and Australia.

In Europe the Electricity Balancing Regulation [41] is a European framework for the technical, operational, procuring and exchanging of balancing services. The Electricity Balancing Regulation is a comprehensive framework, and the main settlements can be divided into five categories:

i. Rules for settlement between TSOs to assure that exchanges between TSOs are done with common rules.
ii. Compliance of imbalance settlement. The imbalance settlement is done on a national level, by having a compliance at a European level of the rules applicable for the member states, all market participants will have the same terms and conditions for supplying energy with the effect of an improved utilization of the balancing market.
iii. Rules for the exchange of balancing capacity and cross-zonal distribution. This set of rules allows the TSOs to procure and use balancing capacity as unity, the TSOs can then take benefit of reserves outside their region.
iv. Rules for BSPs and Balancing Responsible Parties are terms and conditions on a national level for balancing services, to ensure transparent and fair rules for all the participants in the balancing markets.
v. Establishment of common European platforms for its members for the exchange of balancing energy as described in 4.1.

In the USA the Federal Energy Regulatory Commission (FERC) have defined six ancillary services in order 888 [42]:

i. Operating reserve – Synchronized reserves.
ii. Operating reserve – Non synchronized reserves.
iii. Scheduling, system control and dispatch.
iv. Reactive supply and voltage control from generation service.
v. Regulation and frequency response service.
vi. Energy imbalance service.

However, iii, Scheduling, system control and dispatch is done by the system operator and is not a direct ancillary service.
The orders issued by FERC are applicable in the continental US on a high level, beside from ERCOT region of Texas. On the level below, the North American Electric Reliability Corporation (NERC) and/or a regional coordinating council, issues and enforces reliability standards that are applicable in the US and other North American jurisdictions. The regional standards are based on the NERC standards as a minimum, but they may also issue additional.
Although regulations from FERC and NERC are the primary governing regulations, specific state policies e.g., requirements for RES may affect the regional requirements for ancillary services.

The following NERC regulations are applicable for ancillary services:

- BAL-001 – Real Power Balancing Control Performance, purpose is to keep the steady state frequency within defined limits for an interconnection, by balancing real power supply and demand in real-time.
- BAL-002 – Disturbance Control Performance, purpose of returning the frequency within the defined limits post a contingency event by utilizing the contingency reserves.
- BAL-003 – Frequency Response and Frequency Bias Setting, purpose of this regulation is to define the minimum for primary contingency reserves in a balancing area.
- EOP-005 – System Restoration from Blackstart Resources, the purpose of this regulation is for the TSO/balancing area to have a plan for resources to be used for blackstart for a defined region.
- VAR-001 – Voltage and Reactive Control, this standard settles that voltage levels are to be held within defined limits with a point from the TSO as a reference, and that the TSO plans enough reactive power to be able to regulate the voltage levels.

The Australian power system have on a higher level the National Electricity Rules 179, rule 3.11 [43] issued by The Australian Energy Market Commission (AEMC), the Australian Energy Market Operator procures the listed market ancillary services as a part of the spot marked:

i. Fast raise service
ii. Fast lower service
iii. Slow raise service
iv. Slow lower service
v. Regulating raise service
vi. Regulating lower service
vii. Delayed raise service
viii. Delayed lower service

AEMO may instruct a facility to provide a non-market ancillary service through and service agreement. Nonmarket ancillary services are categorized as:

i. NSCAS – Network support and control ancillary service, with the purpose of controlling the active or reactive power flow in a transmission network.
ii. SRAS – System restart ancillary service .

AEMO have the responsibility of determine, procure, and schedule ancillary services in accordance with the National Electric Rules, with this there is also regional difference as the progress of the implementation….

Regardless of the geographical location of the power systems they are subject to the same physical laws. From a top perspective, the regulations that are on a European, Australia and North American level are relatively similar. The European regulations differ as they encourage the exchange of ancillary services through common markets. The increase of intermittent renewable energy sources leads to the development of ancillary services. This is seen in the cross-border exchange of ancillary reserves and the need for solutions to maintain the inertia in the system. FFR is an ancillary service that is being implemented in most markets as a mitigating action. Further with the increase of consumers that are connected by means of power electronic converters, this means that the consumers move from being a passive consumer towards an active consumer. Which gives the possibility that the consumer can be a more active part of the ancillary services. Regulations & standards for these ancillary services are made on a regional level, as the composition of the power systems may vary significantly.

5.2 How can a large electricity consumer contribute to stabilize a weak grid.

With a large electricity consumer such as hydrogen production facility with the possibility of flexible operation may bring additional value to the operation of the connected power system. An electrolyser of the PEM-type is favorable in comparison with an alkaline, as the PEM electrolyser have a faster start up time and a ramping response that is greater than the alkaline.

The potential services a hydrogen production facility with a PEM- electrolyser could be, Frequency Containment Reserves, both automatic and manual Frequency Restoration Reserves, Fast Frequency Reserves and Reserve Restoration. If the power electronics supplying the electrolyser is based on active front end technology, it can also supply reactive power and provide voltage control. If the hydrogen production facility is one of the larger loads in a part of a power system, it can be used to limit the dimensioning incident by reducing the power consumed.

There are two projects in Europe where PEM electrolysers have been certified as participant in all the electricity markets in their respective countries. The projects are HyBalance [44] in Denmark and H2Future [45] in Austria.

5.3 What properties does the consumer need to be able to be utilized in these settings.

To be able to provide ancillary service a prequalification of the facility provided the service must be performed, succeeded by a test of the provided service. This is standard within all power systems. Depending on the ancillary service to provide there are some key properties that they need to have to be able to contribute.
The minimum amount of active power to deliver for most ancillary services is 1 MW, with a granularity of whole MW. The response time is from a few seconds to tens of minutes, depending on the service provided.

Furthermore direct technical requirements are more diffuse, but there is typically requirement for a measuring unit with for active power and frequency with a specific resolution, data logging, and real-time telemetry typically determined by the local TSO.

6 Conclusion

The conclusion of this thesis is that a large electrical load can provide services to stabilize a power system. By taking a hydrogen production facility with an electrolyser as a load, the electrical characteristics of the production facility have been investigated.

A survey based on a literature study have been conducted to establish an overview of what market mechanisms and standards that exist for ancillary services in Europe, North America, and Australia. Besides giving an overview of the applicable standards & regulations. The literature study indicated a large trend and focused on the development and updating of the regulation and standards. During the literature study it occurred that regulations were updated. The availability and the way standards & regulations were organized on a regional level was of great variance, resulting in that the focus for the study was on a higher level above the regional level.

The literature study showed that in both Europe, North America, and Australia the markets are becoming more coupled, including the exchange of ancillary services.

The survey showed that a hydrogen production facility with an electrolyser can provide ancillary services in all the investigated power systems, beside from services that includes blackstart facilities.
However, a production facility with a PEM electrolyser is favorable due to a faster response time and the ability to ramp a larger volume of active power. If the rectifiers that are used for the electrolyser are power electronic converters based on active front end, they can also provide ancillary services for voltage control by supplying reactive power to the power system.
The ability to use facilities with electrolysers to provide ancillary services is confirmed by HyBalance [44] and H2Future [45].

6.1 Further work

As this thesis is more generalized and the rules and standards for ancillary services are continuously being developed and implemented, it could be of interest to focus the work in too the following topics:

i. Some areas have available historical market data as price per MWh and volume GWh procured for the specific ancillary services. With the historical market data and economic model could be developed for three different areas, to see where the largest economic potential for a hydrogen production facility to provide these services.

ii. With the characteristics of the power electronics supplying the power for the electrolyser and the data from a specific power system, a study comprehending how a hydrogen production facility can reduce harmonics and use or supply reactive power in that specific power system could be performed.

iii. The assessment of market mechanisms can be made more detailed for limited areas and regions.

References

[1] IEA, " World Energy Outlook 2022," 2022. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2022.

[2] I. R. E. Agency, "Hydrogen overview," [Online]. Available: https://www.irena.org/Energy-Transition/Technology/Hydrogen. [Accessed 20 01 2023].

[3] O. o. E. &. R. Energy, "Hydrogen Production: Electrolysis," [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis#:~:text=In%20a%20polymer%20electrolyte%20membrane,the%20PEM%20to%20the%20cathode..

[4] N. HYDROGEN. [Online]. Available: https://nelhydrogen.com/wp-content/uploads/2020/03/Electrolysers-Brochure-Rev-D.pdf.

[5] ENTSO-E, " Potential of P2H2 technologies to provide system services," 2022.

[6] A. P. V. R. A. K. M. N. Joonas Koponen, "Comparison of thyristor and insulated-gate bipolar transistor -based power," *Journal of Power Sources,* vol. 491, 2021.

[7] J. P. V. A. G. A. B. C. C. N. H. D. H. A. S. C. T. T. V. C. a. V. V. Prabha Kundur, "Definition and Classification of Power System Stability," *IEEE TRANSACTIONS ON POWER SYSTEMS,* vol. 19, no. 1387, p. 15, 2004.

[8] P. S. Kundur and M. Om, Power System Stability and Control, Second Edition, McGraw Hill, 2022.

[9] N. Hatziargyriou, J. V. Milanovi, C. Rahmann, V. Ajjarapu, C. Caizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, P. Pourbeik, J. J. S.-. Gasca, A. Stankovi, T. V. Cutsem, V. Vittal and C. Vournas, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," IEE, 2022.

[10] ENTSO-E, "Fast Frequency Reserve - Solution to the Nordic inertia challenge," ENTSO-E, 2019.

[11] E. Rebello, D. Watson and M. P. Rodgers, "Developing, implementing and testing up and down regulation to provide AGC from a 10 MW wind farm during varying wind conditions," *Journal of Physics Conference Series,* 2018.

[12] EUR-Lex, "COMMISSION IMPLEMENTING REGULATION (EU) 2021/280," [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32021R0280.

[13] ENTSO-E, "Manually Activated Reserves Initiative," [Online]. Available: https://www.entsoe.eu/network_codes/eb/mari/.

[14] ENTSO-E, "MARI Activation Optimization Function Public Description," 28/10-2022.

[15] ENTSO-E, "FCR," [Online]. Available: https://www.entsoe.eu/network_codes/eb/fcr/.

[16] ENTSO-E, "Network Codes - Electricity Balancing - Frequency Containment Reserve," [Online]. Available: https://www.entsoe.eu/network_codes/eb/fcr/.

[17] ENTSO-E, "PICASSO," [Online]. Available: https://www.entsoe.eu/network_codes/eb/picasso/.

[18] RTE, "PICASSO (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation)," [Online]. Available: https://www.services-rte.com/en/learn-more-about-our-services/picasso.html.

[19] ENTSO-E, "Imbalance netting," [Online]. Available: https://www.entsoe.eu/network_codes/eb/imbalance-netting/.

[20] ENTSO-E, "TERRE," [Online]. Available: https://www.entsoe.eu/network_codes/eb/terre/.

[21] ENTSO-E, "The proposal of all Transmission System Operators performing the reserve replacement process for the implementation framework for the exchange of balancing energy from Replacement Reserves in accordance with Article 19 of Commission Regulation (EU) 2017/2," 2018.

[22] Statnett, "Nordic power flow," [Online]. Available: https://driftsdata.statnett.no/Web/Map/?language=en.

[23] Statnett, "Introduksjons til Statnett Sine reservemarkeder," [Online]. Available: https://www.statnett.no/globalassets/for-aktorer-i-kraftsystemet/systemansvaret/reservemarkeder/slik-fungerer-reservemarkedene.pdf.

[24] Ne, "NERC Regions Map," [Online]. Available: https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/Regions%20Map.jpg.

[25] NERC, "NERC Interconnections," [Online]. Available: https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/NERC%20Interconnections.pdf.

[26] U. E. I. Administration, "U.S. electric system is made up of interconnections and balancing authorities," [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=27152.

[27] Y. S. T. M. Paul Denholm, "An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind," National Renewable Energy Laboratory .

[28] " Western Energy Imbalance Market," WEIM, [Online]. Available: https://www.westerneim.com/Pages/About/default.aspx.

[29] E. P. R. Institute, "Ancillary Services in the United States Technical Requirements, Market Designs and Price Trends," 2019.

[30] "WESTERN ENERGY IMBALANCE SERVICES MARKET PROTOCOLS," Southwest Power Pool, 2023.

[31] MISO, "Redefining Energy and Ancillary Service Markets," MISO.

[32] ERCOT, "ERCOT Current Protocols - Nodal," 1 February 2023. [Online]. Available: https://www.ercot.com/files/docs/2022/11/01/02-020123.doc.

[33] ERCOT, "ERCOT NODAL PROTOCOLS - April 1, 2023," 1 April 2023. [Online]. Available: https://www.ercot.com/files/docs/2023/03/31/03-040123_Nodal.docx.

[34] NPCC, "About NPCC," [Online]. Available: https://www.npcc.org/about.

[35] ISO-NE, *Reliability Standards Supporting Day-Ahead Ancillary Services Requirements – Revised Edition,* ISO-NE, 2023.

[36] ElectraNet, "National Electricity Market and Rules," [Online]. Available: https://www.electranet.com.au/what-we-do/network/national-electricity-market-and-rules/.

[37] A. E. M. Operator, "GUIDE TO ANCILLARY SERVICES IN THE NATIONAL ELECTRICITY MARKET," November 2021. [Online]. Available: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/-/media/2C771C82C8054929B16E4545216ACE03.ashx.

[38] A. S. Performance, "Market ancillary service specification," [Online]. Available: https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/amendment-of-the-mass/final-determination/market-ancillary-services-specification---v80-effective-9-oct-2023.pdf?la=en.

[39] AEMO, "Wholesale Electricty Market-System Operations-Ancillary Services," [Online]. Available: https://aemo.com.au/en/energy-systems/electricity/wholesale-electricity-market-wem/system-operations/ancillary-services.

[40] W. E. Market, "WHOLESALE ELECTRICITY MARKET RULES," 29 04 2023. [Online]. Available: https://www.wa.gov.au/system/files/2023-04/Wholesale%20Electricity%20Market%20Rules%20-%2029%20April%202023.pdf.

[41] G. o. W. A. D. o. Treasury, "Regulatory framework for the Pilbara electricity networks: System operations arrangements," [Online]. Available: https://www.wa.gov.au/system/files/2019-08/Detailed-Design-Consultation-Paper-ISO-Arrangements_3.pdf.

[42] T. E. Union, "Establishing a guideline on electricity balancing," [Online]. Available: http://data.europa.eu/eli/reg/2017/2195/2022-06-19.

[43] FERC, "Order No. 888," [Online]. Available: https://www.ferc.gov/industries-data/electric/industry-activities/open-access-transmission-tariff-oatt-reform/history-oatt-reform/order-no-888.

[44] AEMC, "National Electricity Rules 179," [Online]. Available: https://energy-rules.aemc.gov.au/ner/379/94947.

[45] Hybalance, "HyBalance - Grid Balance," [Online]. Available: https://hybalance.eu/hybalance/short-presentation/grid-balance/.

[46] H2Future, "H2Future - Technology," [Online]. Available: https://www.h2future-project.eu/technology.

[47] ENTSO-E, "ENTSO-E Balancing Report 2022," ENTSO-E, 2022.

[48] ENTSO-E, "ENTSO-E Market Report 2022," ENTSO-E, 2022.

Appendices

Appendix A Task description

Appendix A: Task description for the master thesis

Title: Grid Stabilization through Load Side Mechanisms

USN supervisor: Kjetil Svendsen

External partner: Nel Hydrogen

Task background:
We are currently in a transitional period where an increasing fraction of the world energy consumption is conveyed through electricity. This is done to decrease CO2 and greenhouse gas emissions. At the same time energy from renewable sources like wind and solar are making a up a substantial fraction of the produced power. This is especially the case in light grid load situations when the renewable energy production is high.

The stability of the grid to load variations, is rooted in the rotating mass of the generators in the power stations. This mass is present in hydroelectric, nuclear, and coal-based power stations. In solar power plants and in wind power, where the generators are not connected directly to the mains (modern wind turbines), however, there is no inertia to stabilize the grid. To make matters worse, the fraction of the loads providing stability (directly connected motors) or neutral loads (like resistive heating) are decreasing and is replaced by power electronic converters controlling a lot of the same sources. This decreases the inertia and increases the harmonic and reactive power exerted on the grid.

Traditionally, the stability of the grid has been purely a task for the grid operators (TSO). In the current situation where the stability of the grid and the distortion of the voltage on the grid are increasingly difficult to control from the grid side itself, the consumers are increasingly included in the solution.

Task description:
Nel Hydrogen is a major producer of Hydrogen production equipment based on electrolysis of water. The Hydrogen production sites are large consumers of electric energy.
The assignment is to investigate how load side flexibility can be implemented and what market mechanisms are already implemented in the Norwegian, European, and American electric power markets. How do they compare? Is this different in other parts of the world? Which standards exist? How can a large consumer contribute to stabilize a weak grid or a grid in island mode?
What properties does the consumer equipment need to be able to be utilized in such arrangements?

Student category: EPE

Is the task suitable for online students (not present at the campus)? Yes

Practical arrangements: -

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature):
?2 23

Student (write clearly in all capitalized letters):
LARS KRISTIAN BEKKER
Student (date and signature):
02/02-23 Lars Kristian Bekker