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# New method for verification of frequency related ancillary services through modeling of power plants

## Verification of FCR-D from hydropower plants

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## Abstract

To participate as an ancillary service, each entity has to pass a prequalification. During the prequalification, several tests are run to ensure that the delivery is preforming well and do not subject the power system of further risk. After a frequency disturbance, Svenska Kraftnät conducts follow-ups on the delivery using a reference power delivery. In 2023, new requirements were established for FCR-D that puts further importance on the dynamic behavior of some FCR providers. The old tool is not well adjusted for the new requirements, especially for FCR-D from hydropower plants. The goal of this project is to construct a new computer tool better suited for verifying FCR-D deliveries from hydropower plants. This is done by modeling a plant in python, and vary regulator parameters and time constants until a model is found that is on the limit of passing the prequalification requirements. By comparing the delivery from the modeled plant with the actual delivery of the FCR-D provider. The computer tool is constructed in three different parts. One that find the multiple models on the limit of passing each requirement, one that identifies the parameters and time constant of the FCR-provider, and one that compares the delivery of the model and provider. In order to compare the two, any potential FCR-N delivery and baseline delivery must be added to the model as well. The computer tool was then tested on disturbance data from three different providers. Requirement 2 and 3 where possible to analyze. Requirement 4, 8 and 9 is analyzed by the computer tool as well but with low probability of an accurate result.



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## *Populärvetenskaplig Sammanfattning*

Svenska kraftnät har som systemansvarig myndighet i uppdrag att hålla det svenska kraftsystemet säkert, pålitligt och kostnadseffektivt. I det nordiska kraftsystemet ska frekvensen alltid vara 50 Hz. Det är balansen mellan produktion och konsumtion som är avgörande för frekvensen, och om konsumtionen vid något tillfälle är större än produktionen kommer frekvensen att sjunka under 50 Hz. Det är Svenska kraftnät som är ansvariga för att hålla frekvensen vid sitt nominella värde, vilket bland annat görs genom frekvensrelaterade stödtjänster. En stödtjänst som Svenska Kraftnät köper är Frequency Containment Reserve, förkortat FCR. Det finns tre olika typer av FCR. FCR-N som verkar under normala förhållanden, FCR-D upp som verkar vid en lågfrekvensstörning och FCR-D ned som verkar under en överfrekvensstörning. En enhet som levererar FCR aktiveras automatiskt om en frekvensavvikelse skulle ske och har i syfte att stoppa frekvensökningen eller sänkningen genom att ändra sitt effektutbyte med nätet. Till exempel kan vattenkraftverk som levererar FCR under en underfrekvensstörning öka vattenpådraget och så även den elektriska produktionen.

Svenska kraftnät utför regelbundet uppföljningar på leveransen för att säkerställa att den uppfyllt de krav som finns på leveransen. År 2023 fastställdes nya krav för FCR leveranser som lägger större vikt i det dynamiska beteende som bland annat finns hos vattenkraftverk. Det dataverktyg som tidigare använts för att verifiera leveransen är inte lika väl anpassat för just detta dynamiska beteende. Syftet med detta projekt är att skapa ett datorverktyg som kan användas under uppföljningsarbetet av FCR-D leveranser från vattenkraftverk. Datorverktyget simulerar effektsvaret från kraftverksmodeller från en bestämd frekvensavvikelse skapad för att kunna analysera de olika kraven för FCR. Genom att variera inställningarna hos modellen kan den modellen som är på gränsen till att klara ett specifikt krav hittas. Efter att gränsmodellen är hittad kan den sedan användas som referens till olika typer av frekvensstyrningar. Genom att simulera effektsvaret från en verklig störning från modellen kan den simulerade leveransen sedan jämföras mot en verklig leverans.

Verktyget består av tre huvuddelar. Den första hittar de modeller som är på gränsen till att klara kraven. Den andra delen identifierar de parametrar hos FCR leverantören som är viktiga för att rätt gränsmodell ska användas i analysen samt utvärderar de krav som är baserade enbart på leverantörens egenskaper. Den tredje delen jämför effektsvaret hos gränsmodellen och från leverantören or presenterar all data, även i form av grafer.

Resultat från analysen ger ett lovande resultat för två av de tekniska kraven, som båda berör hur snabb aktiveringen är. De övriga kraven som analyseras och berör stabilitet, prestanda och avaktivering ger ett resultat som inte är lika tillförlitligt.

# 1 TABLE OF CONTENTS

# 2 GLOSSARY

| | |
|---|---|
| *Droop* | Relationship between frequency deviation and active power activation for an ancillary service |
| *FCR-N* | Frequency containment reserve for normal operation |
| *FCR-D upwards* | Frequency containment reserve for disturbances upward |
| *FCR-D downwards* | Frequency containment reserve for disturbances downward |
| *Frequency zenith* | Max instantaneous frequency peak |
| *Frequency nadir* | Max instantaneous frequency bottom |
| *Penstock* | Waterway before turbine in hydropower plant |
| *Draft tube* | Waterway after turbine in hydropower plant |
| *Backlash* | Non-linear behavior from mechanics |
| *Surge gallery* | Tube in hydropower plants to reduce pressure transients |
| *Hydropower reservoir* | Large collection of water |
| *Per unit (p.u.)* | Value normalized using rated value |
| *Dispatchable* | Controllable power sources |
| *Non-dispatchable* | Non-controllable power sources |
| *TSO* | Transmission system operator |

# 3 INTRODUCTION

## 3.1 BACKGROUND

As our society is becoming more electrified several challenges arise, one of them being maintaining the balance of the power system. An increased population, big industries and the electrification of the transportation sector are all important contributors to the increased use of electricity [1]. At all times, there need to be enough production to match the consumption of electricity for each hour of the day. If the production and consumption at any time instant is different, the frequency on the grid will start to deviate from 50 Hz. The transmission grid in the Nordic countries is interconnected, meaning all of the countries have the same grid frequency. If a disturbance occurs the deviation will propagate through the whole synchronous area, which is all countries in the Nordic power system. A large interconnected system will however improve the stability of the power grid, since local imbalances will have less effect on a big power system. It is up to the transmission system operators (TSOs) in the Nordic power grid to keep the frequency close to 50 Hz, and to be able to stabilize the frequency back to 50 Hz if a deviation occurs. The frequency balance is upheld by power reserves, procured by the TSO from electricity producers and consumers. In Sweden, Svenska kraftnät is the TSO and is responsible for keeping the power system safe, sufficient and cost-effective, as well as keeping the frequency in the Nordic transmission system balanced together with the other TSOs [2]. Svenska kraftnät is an authority and monitors the power grid at all times, making sure the electricity is balanced and well working. The authority is also responsible to ensure trading in the several electricity markets work smoothly, as well as working with dam safety and conduct research to further develop a reliable, sustainable and efficient grid [3].

Keeping the system balanced is not a simple task, and the electrification of society means a more challenging task of keeping the energy, power and transfer capacity sufficient. The yearly production of electrical energy will need to increase to match the increased demand. The Swedish government has declared that Sweden should have 100% fossil free production by 2040 [4]. To reach the renewable energy goal a power expansion is needed, and wind power will be the main energy source of the expansion [5]. However, wind power is non-dispatchable. Wind is an intermittent energy source, meaning we cannot control when the wind is blowing and therefore not control the production of electricity. This increases the risk of production and consumption imbalance, leading to frequency deviation. An increased amount of wind power in the system will further increase the difficulties of keeping the consumption and production balanced, and thus increasing the need for power reserves and ancillary services to stabilize the frequency. To not further destabilize the grid if a deviation occurs, the ancillary services need to meet the requirements for delivery. Follow-ups of the delivery is an important step to ensure that the balancing is working as it should.

## 3.2 PROJECT DESCRIPTION

Each provider that takes part in the ancillary service needs to log data that can be delivered to Svenska kraftnät upon request. Follow-ups are conducted to ensure that an ancillary service from a reserve procured by Svenska kraftnät has been delivered as agreed upon. The follow-up data is verified by comparing it with the expected power delivery. The expected delivery represents a minimal response, but that do meet the requirements of approval. Frequency containment reserve, FCR for short, is one of the reserves Svenska kraftnät procures and the service can be provided using a large number of different technologies with varying properties. In September of 2023, new technical requirements for FCR came into force. The current method of evaluating an FCR delivery is however not as well adjusted to the new technical requirements. For the new requirements, the dynamic properties of the delivery are of greater importance than before, when activation time was of greater importance. To improve the verification process, the development of a more advanced method of finding the minimum delivery has begun. The new computer tool models a dynamic power plant, including a PI-regulator. By varying the parameters of the regulator, the droop of the power delivery and several time constants, a large number of plants with different properties can be modelled. Each model can then be tested for the new technical requirements by simulating the power response during a pre-defined frequency disturbance. This way, it can be found how well each model preforms according to each requirement, and which models are on the limit of approval. After the models on the limit of approval is found, the power response from the limit models during an actual disturbance can be simulated. By comparing the limit model power response with a FCR power delivery from an actual hydropower plant during the frequency disturbance in question can be compared a conclusion can be drawn about how well the hydropower plant preformed according to the. The goal of the thesis work is to develop the computer tool so it can be used to verify frequency control services.

## 3.3 RESEARCH QUESTIONS

Is it possible to develop a computer-based tool for compliance testing of FCR-D using power plant modeling? How well would such a tool perform when applied to follow-up analysis using real disturbance data? Would the tool provide reliable and accurate results with this method, and which specific compliance requirements would it be able to assess?

## 3.4 LIMITATIONS

The project will focus of FCR-D deliveries from hydropower plants. This both to limit the workload and since this is the area where easy verification is lacking. The steady state activation is assumed to be linear. The same model base is used for all verifications. It is limited to a PI regulator, time constant for the servo controlling the guide vanes and the linear penstock model with time constant for water acceleration with the droop in feedback.

# 4 THEORY

## 4.1 THE SWEDISH GRID

The electric grid in Sweden can be divided into the transmission grid and the distribution grid. The transmission grid is managed by Svenska kraftnät, and consists of 400 kV or 220 kV lines and cables with a total length of 16 000 km [5]. An overview can be seen in Figure 1. The transmission grid transports the power over long distances, and it also connect the Swedish grid to other countries. The distribution grid can further be divided into the regional and local grid, and connects consumers and most producers to the transmission grid [6]. In order for Svenska kraftnät to keep a well working transmission grid, it is important to avoid electricity shortage.

The subject of electricity shortage can be divided into three parts, the need for sufficient transfer capacity, the need for sufficient energy and the need for sufficient power [1]. All of these tree parts are essential for a well working and reliable electricity supply, and the lack of one or several parts will cause problem that can escalate into a blackout. In the future, the amount of dispatchable sources will decrease, whereas the non-dispatchable sources such as wind and solar are becoming more and more prevailed. Non-dispatchable sources further increase the challenge of keeping a sufficient supply of power, since they cannot be controlled in order to match the consumption patterns over a day. This report will focus on the task of maintaining the grid frequency, which is directly connected to power supply. To avoid a grid that becomes unreliable and easily disrupted, balancing services will be of great importance.


*Figure 1: Map of Swedish electricity grid*

## 4.2 FREQUENCY STABILITY

How the frequency fluctuates and its stability mainly depend on three different factors [3]:

- Imbalance between production and consumption of electricity. Imbalance occur naturally throughout the day as the consummation changes. A more noticeable imbalance can also occur due to a fault or another unexpected event.

- Inertia stored in synchronous machines connected to the power system.

- Power reserves that can control their power exchange to balance the frequency, such as ancillary services.

The increased amount of non-dispatchable sources in the power grid will, as mentioned in the previous section, come with stability issues. Non-dispatchable power sources, such as wind and solar power multiple adverse effects on the system stability. Non-dispatchable sources are characterized by their often highly volatile power output that cannot easily be controlled to meet the current demand, which in itself can cause imbalances. Non-dispatchable power may also displace conventional controllable power, which further reduces the ability to balance the system. Furthermore, wind and solar power do not contribute with inertia to the power grid since they are usually connected via power converters. High inertia slows down the change in frequency during a deviation and therefor reduce the impact of a power imbalance. A large amount of renewables connected to the grid therefore not only increase the risk of a power imbalance, but also increase the drop in frequency from 50 Hz. If a bigger deviation happens, for example due to a fault in the transmission grid, a low inertia power system will likely be subjected to larger consequences than a high inertia system with the same fault. Balancing reserves and ancillary services will play a large role in keeping the frequency quality in the grid as the power system continues the ongoing change, and it will be important that the reserves are delivering the correct power without causing further damage to the frequency quality. The reference incident is the single largest event that can cause an imbalance, for example a quick shutdown of a nuclear reactor or loss of a significant power line. Ancillary services, such as FCR-D, are dimensioned after the reference incident [7].

### 4.2.1 Reserves for frequency control

During a power imbalance, transmission system operators utilize reserves to handle the imbalance in the power system. The reserves can adjust their power exchange with the grid, and quickly increase or reduce their consumption or production of electricity, reducing the overall difference in power going in and out of the power system. Svenska kraftnät is responsible for the balancing and procure the different frequency control services from the balancing market. The services are activated during a deviation in frequency, either automatically from the frequency signal or a signal from Svenska kraftnät. If working as intended, the imbalance in power should quickly stabilize and then adjusted to regulate the frequency back to 50 Hz. There are several services in place, but they can be divided into three main categories. Frequency restauration reserve, the remedial action fast frequency reserve and frequency containment reserve. An overview of the different reserves can be seen in Table 1, and the timeline for activation after a disturbance in Figure 2. [2]

| | *Remedial Action* | *Frequency containment reserve* | | | *Frequency restauration reserves* | |
|---|---|---|---|---|---|---|
| *Abbreviation* | FFR | FCR-D upward | FCR-D downward | FCR-N | aFRR | mFRR |
| *Name* | Fast Frequency Reserve | Upward Frequency Containment Reserve - Disturbance | Downward Frequency Containment Reserve - Disturbance | Frequency Containment Reserve - Normal | Automatic Frequency Restauration Reserve | Manual Frequency Restauration Reserve |
| *Regulation* | Upward | Upward | Downward | Symmetrical upward and downward | Upward and/or downward | Upward and/or downward |
| *Activation* | Automatic activation for changes in frequency when there are low levels of rotational energy in the system | Automatic linear activation within the frequency interval 49.9-49.5 Hz | Automatic linear activation within the frequency interval 50.1-50.5 Hz | Automatic linear activation within the frequency interval 49.9-50.1 Hz | Automatic activation for frequencies deviating from 50.0 Hz | Manual activation when requested from Svenska kraftnät |
| *Activation time* | Three alternatives for 100%: -0.7 s (49.5 Hz) -1.0 s (49.6 Hz) -1.3 s (49.7 Hz) | Presented in [8]. See requirement 2 on page 18 | Presented in [8]. See requirement 2 on page 18 | Presented in [8]. See requirement 1 on page 14 and requirement 9 on page 28 | 100% within 5 minutes | 100% within 15 minutes |
| *Endurance* | 30 seconds Reactivation within 15 minutes | At least 20 minutes | At least 20 minutes | 1 hour | 1 hour | 1 hour |

*Table 1: Overview of reserves for frequency regulation and their requirements*

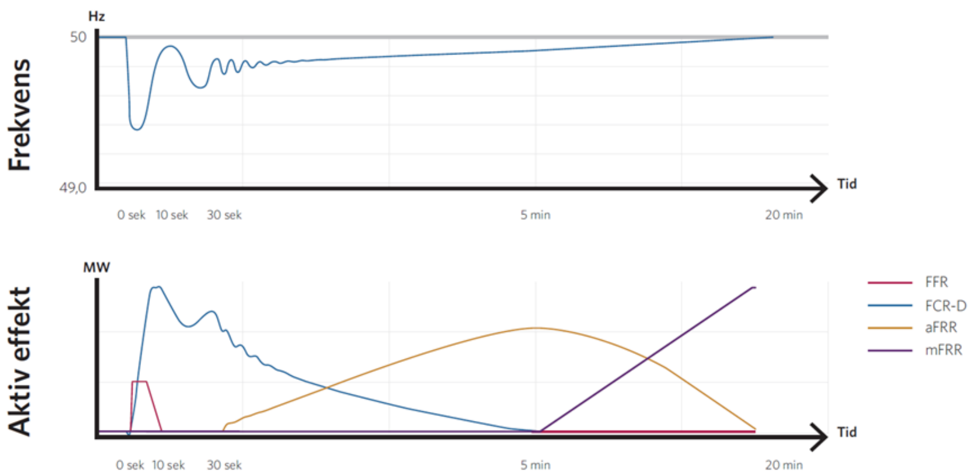


*Figure 2: Timeline of frequency related power reserve activation*

#### 4.2.1.1 Frequency Restauration Reserve, aFRR and mFRR

FRR is designed to restore the frequency back to 50 Hz after the power balance is stabilized by the FCR. It therefore has a much slower activation, and can be activated either due to an existing or predicted imbalance. It is activated on a signal from Svenska kraftnät, and the signal can be generated both automatically and manually. The FRR is divided into two different services, aFRR which is automatic and mFRR which is manual. aFRR is activated first, and mFRR is activated later on if there still exists an imbalance in the frequency. Both of the products can be used both to regulate up or down the frequency.

#### 4.2.1.2 Fast Frequency Reserve, FFR

FFR is a relatively new product, implemented in May 2020. It was implemented provide a fast power activation in case of low inertia in the grid and to quickly stop the frequency to deviate too much from the nominal 50 Hz. Low inertia causes fast changes in frequency during a power imbalance and FFR is activated when the inertia in the grid is too low for FCR-D to guarantee frequency stability. FFR is activated automatically, and is used to regulate up the frequency.

#### 4.2.1.3 Frequency containment reserve, FCR-N and FCR-D

The frequency containment reserves are automatically activated reserves that prevent the frequency from deviating to far from the nominal frequency of 50 Hz. There are three different kinds of FCR. FCR-N is continuously active and stabilize smaller deviations that usually occur due to ordinary changes in consumption and production FCR-D is activated outside the span of normal operation, usually after a disturbance in the grid. The purpose of FCR-D is to quickly stabilize the power imbalance after a larger disturbance and is therefore activated faster than the FRC-N. The FCR-D reserve is not supposed to bring back the frequency to the nominal frequency, only to stop the deviation from increasing. There are two separate products for regulating up or down the frequency, FCR-D upwards and FCR-D downwards. This project has mainly concerned verifying provision of FCR, especially during disturbances. The linear activation of FCR makes it relatively easy to determine how big the activation should be during a disturbance.

There are three FCR products, and each one is active in a specific frequency range. The activation is linear, or can be approximated as linear, for all products. The span for FCR-N is 49.9-50.1 Hz. This is the span of normal operation. Outside of this span the FCR-N power capacity is fully activated. FCR-D upwards regulate the frequency up and is activated linearly in the span 49.5-49.9 Hz, whereas FRC-D down regulates the frequency down and is activated linearly in the span 50.1-50.5 Hz. The different products and their activation can be seen in Table 2. Over the activation range for each product, the amount of activation should increase linearly with the frequency deviation. [8]

*Table 2: Activation region for FCR products*

| *Product* | *100% negative activation* | *0% activation* | *100% positive activation* |
|---|---|---|---|
| *FCR-N* | $f \geq 50.1\ Hz$ | $f = 50\ Hz$ | $f \leq 49.9\ Hz$ |
| *FCR-D upwards* | N.A | $f \geq 49.9\ Hz$ | $f \leq 49.5\ Hz$ |
| *FCR-D downwards* | $f \geq 50.5\ Hz$ | $f \leq 50.1\ Hz$ | N.A |

For FCR-D products, as the frequency goes below 49.5 Hz or above 50.5 Hz for up or down regulation respectively, the provider is allowed to both keep the activation at ±100% or to keep linearly increase the activation. In the computer tool, this will be realized by cutting the frequency signal at 49.5 Hz for FCR-D upwards and 50.5 Hz for FCR-D downwards. The activation should continue for as long as the deviation remains.

Droop is a method of automatically controlling the output power based on the grid frequency. In the context of FCR, droop is used to denote a unit´s change in power for a given frequency input relative to its nominal power. Droop can have many different units, but in this report a unitless droop in p.u. will be used. The parameter is often symbolized as $e_p$, and is calculated using the FCR capacity $\Delta P_{FCR}$ and the one-sided frequency band for activation $\Delta f_{FCR}$. For FCR-N activation $\Delta f_{FCR}$ is 0.1 Hz and for FCR-D $\Delta f_{FCR}$ is 0.4 Hz. The entity rated power $S_n$ and grid nominal frequency $f_0$ is used as a scaling factor to go from droop in Hz/MW to p.u. [8]

$$e_p = \frac{\Delta f_{FCR}}{\Delta P_{FCR}} \cdot \frac{S_n}{f_0} \tag{1}$$

The theoretical steady state power during a FCR activation if then calculated using the deviation in frequency and droop. [8]

$$\Delta P_{SS} = -\frac{1}{e_p} \Delta f \frac{S_n}{f_0} \tag{2}$$

### 4.2.2 Technical requirements for FCR

To participate in the balancing market and provide FCR services, it is important that the technical requirements for FCR is fulfilled. The requirements are based on European guidelines, but adjusted to suit the Nordic transmission system and Nordic conditions. Each requirement is tested on each participating entity during a prequalification process that establishes both that the entity can fulfill the requirement and that all necessary documentation is provided. The entity should then be re-assessed every 5 years, or when changes are made that can affect the result of the prequalification to make sure that the quality of delivery is upheld [8]. In Table 3 the different prequalification tests and which FCR product the test is applied to. If an entity cannot fulfill the dynamic requirements listed in Table 3, the entity can provide an alternative static FCR-D. The main difference between dynamic and static FCR-D is a 15 minute grace period after a disturbance, where the entity is not required to immediately deactivate nor to activate again in case a second disturbance occurs.

*Table 3: Requirements and tests for FCR activation [8]*

| Test | Requirement | | FCR-N | Dynamic FCR-D | Static FCR-D |
|---|---|---|---|---|---|
| *Ramp/step sequence* | 1 | Steady state response | X | X | X |
| | 2 | Power after 7.5 s | | X | X |
| | 3 | Energy after 7.5 s | | X | X |
| | 4 | Deactivation | | X | |
| *Static ramp sequence* | 5 | Activation | | | X |
| | 6 | Re-activation | | | X |
| | 7 | Deactivation rate | | | X |
| *Sinusoidal sequence* | 8 | Frequency domain stability | X | X | |
| | 9 | Frequency domain performance | X | X | |
| | 10 | Dynamic linearity | X | X | |
| *Linearity step sequence* | 11 | Linearity (non-continuous) | X | X | |
| *Ramp/step sequence* | 12 | Endurance | X | X | X |
| *Ramp sequence* | 13 | Mode shifting | | X | |

There are 13 different tests that can be divided into five categories depending on the frequency sequence used in the test as input signal. Ramp sequence, step sequence, sinusoidal sequence, linearity step sequence and static ramp sequence. Three of the categories are relevant in this report and the discussed further. The ramp sequence is a predefined frequency signal containing 8 ramps of sudden changes from the nominal value of 50 Hz and is used to test FCR-D. The step sequence is used to test FCR-N and contain 5 steps, also deviation from 50 Hz similarly to the ramp sequence. The ramp/step sequences are mainly used to test the speed of FCR activation. The sinusoidal sequence tests contain several predefined sinusoidal frequency deviations used to test the stability and performance of the entity. Each of these tests and the requirements related to them is discussed in the following sections.

There are two categories that will not be discussed further in the report. The Static ramp sequence is used to test static FCR-D, which will not be discussed in this report. Lastly, the linearity step sequence is used to test the linearity of the entity. In this report, linearity is assumed to be true for all entities and the test will therefore not be executed.

#### 4.2.2.1 Step sequence

To test requirement 1-3, as well as 12-13, the entity is subjected to a test sequence with raps or steps of frequency deviations from 50 Hz. The sequence used as input to the system is a pre-defined frequency disturbance, and the power output of the provider is the test result data. In response to the changes in input frequency during the test, the power should be in accordance with the requirements. The sequence used in the tests are different depending on which FCR product are being tested.

To test requirement 1 and 12 for FCR-N a step sequence with deviations up to 0.1 Hz is used. In

Figure 3, the test sequence together with an activation response with droop = 0.05 can be seen. The test contains five different frequency steps. As the frequency drops below 50 Hz, the power can be seen going up. The requirements for FCR-N are described in equations below. Requirement 1 exist to make sure the power exchange delivered by the provider is at the correct magnitude. Requirement 1 uses the power after ramp 3 and after ramp 4 to calculate the steady state power of the delivery. According to the requirement, a 20% over delivery and a 5% under delivery from the theoretical steady state value is allowed.

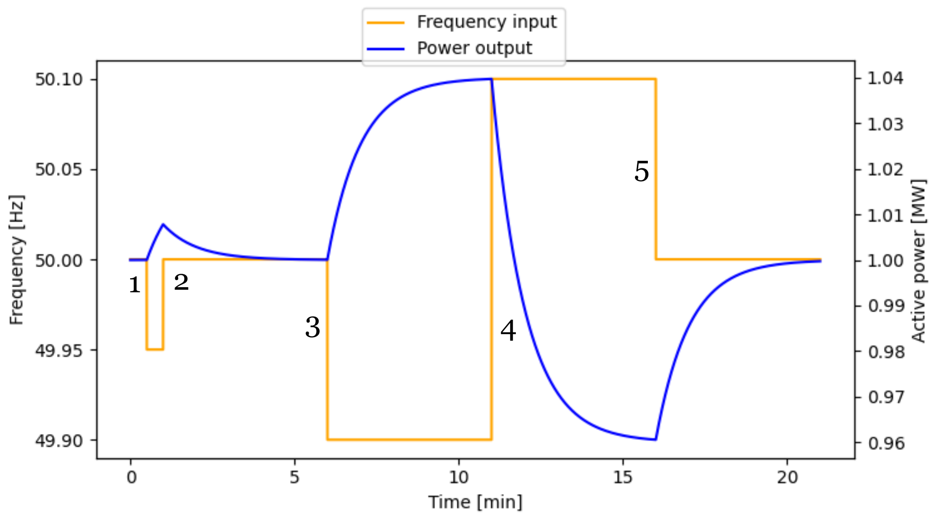


*Figure 3: FCR-N test sequence and response with droop = 0.05*

**Requirement 1 FCR-N upwards:**

$$-0.05 \leq \frac{\Delta P_{ss,3} - K_{red} \cdot |\Delta P_{ss,theoretical}|}{|\Delta P_{ss,theoretical}|} \leq 0.2$$

**Requirement 1 FCR-N downwards:**

$$-0.2 \leq \frac{\Delta P_{ss,4} + K_{red} \cdot |\Delta P_{ss,theoretical}|}{|\Delta P_{ss,theoretical}|} \leq 0.05$$

$\Delta P_{ss,3}$ and $\Delta P_{ss,4}$ is the difference between the steady state power after ramp 3 and ramp 4, where the frequency is 49.9 and 50.1 Hz respectively. $K_{red}$ is a capacity reduction factor that can be introduced if the provider has a difficulty to fulfill the requirement. Reduction factors can be introduced both if there is a difficulty to fulfill the steady state response and the dynamic performance, and should not be smaller than 0.95 or 0.9 respectively. The equations can be derived to an alternative requirement, that 60 seconds after a ±0.1 Hz frequency step, 63% of the procured power should be activated. [9]

#### *4.2.2.2 Ramp sequence*

Testing FCR-D delivery, a sequence with ramped frequency deviations is used instead. The ramp sequence is used as input when testing requirement 1-3 and requirement 12-13 and contains 8 different ramps. The sequence ranges from 49.0 to 50.0 Hz for FCR-D upwards testing and 50.0 to 51.0 for FCR-D downwards testing. The ramp sequence and power response for a delivery with droop = 0.05 can be seen in Figure 4 and Figure 5. Note that given the same droop, the magnitude of the response for FCR-D operates is four times larger than that of FCR-N. This is because the frequency control error in with FCR-D operated is 0.4 Hz compared to 0.1 Hz for FCR-N.

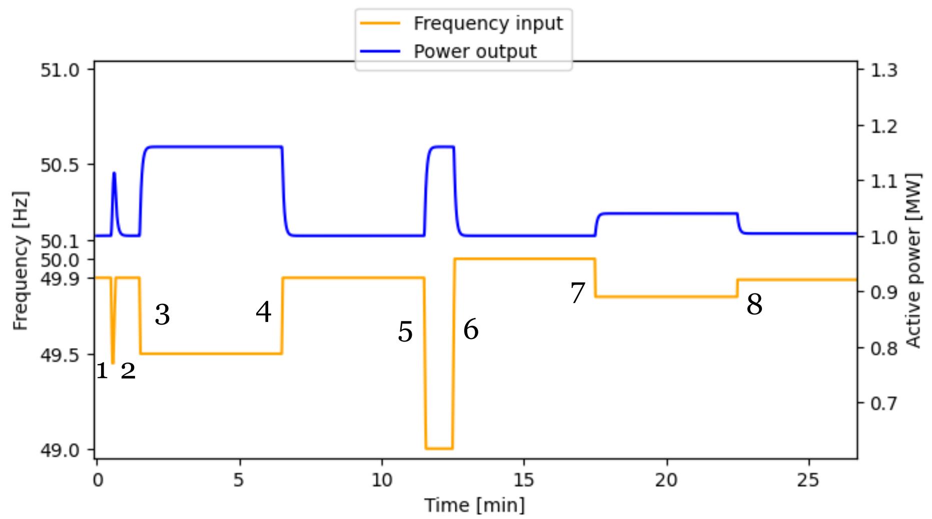


*Figure 4: FCR-D upwards test sequence and response with droop = 0.05*

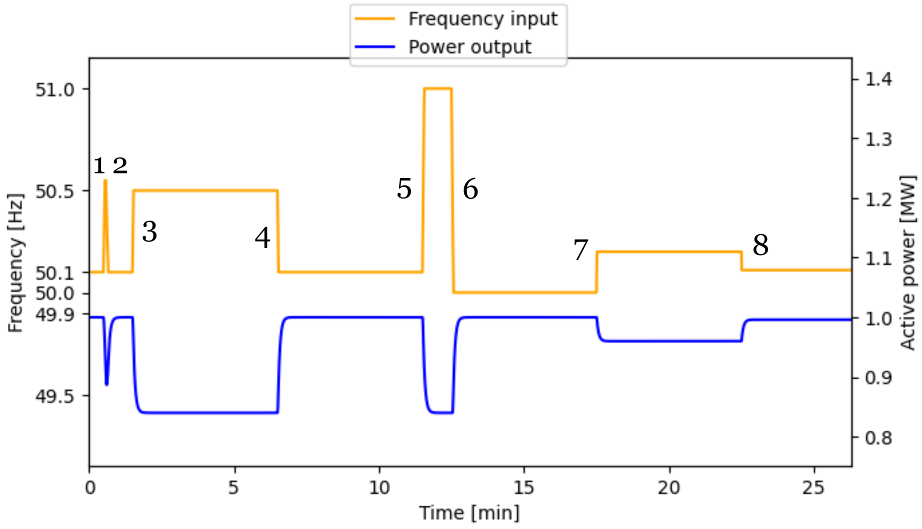


*Figure 5: FCR-D downwards test sequence and response with droop = 0.05*

Requirement 1 for FCR-D is similar to requirement 1 for FCR-N, stating that the steady state power delivery must be between -5% or +20% of the stated power delivery to be approved. This is described in the equations below. $\Delta P_{ss,3}$ is the steady state power after ramp 3, occurring 1.5 minutes after the start of the test. $\Delta P_{ss,4}$ is the steady state power after ramp 4, occurring 6.5 minutes after the start of the test. The capacity reduction factor $K_{red}$ should not be bigger then 0.75 for requirement 1, 2 and 3.

**Requirement 1 FCR-D upwards:**

$$-0.05 \leq \frac{\Delta P_{ss,3} - \Delta P_{ss,4} - K_{red} \cdot |\Delta P_{ss,theoretical}|}{|\Delta P_{ss,theoretical}|} \leq 0.2$$

**Requirement 1 FCR-D downwards:**

$$-0.2 \leq \frac{\Delta P_{ss,3} - \Delta P_{ss,4} + K_{red} \cdot |\Delta P_{ss,theoretical}|}{|\Delta P_{ss,theoretical}|} \leq 0.05$$

When it comes to speed of activation however, the requirements for FCR-D differ from FCR-N. Requirement 2 and 3 describe the activation criteria for dynamic FCR-D and can be seen below.

**Requirement 2:**

$$|\Delta \boldsymbol{P}_{7,5s}| \geq \mathbf{0.86}\ \cdot \boldsymbol{K}_{red}\ |\Delta \boldsymbol{P}_{ss}|$$

**Requirement 3:**

$$|\Delta \boldsymbol{E}_{7,5s}| \geq \mathbf{3.2}\boldsymbol{s}\ \cdot\ \boldsymbol{K}_{red}\ |\Delta \boldsymbol{P}_{ss}|$$

$\Delta \boldsymbol{E}_{7,5s}$ and $\Delta \boldsymbol{P}_{7,5s}$ is the delivered energy and instantaneous power 7.5 seconds after the 5:th ramp begins, which occurs 11.5 minutes into the test. The ramp has a derivative of $\pm$0.24 Hz/s, and reach 49.0 Hz for FCR-D upwards or 51.0 Hz for FCR-D downwards. The provider should have activated at least 86% of the theoretical power capacity at 7.5 seconds. In addition to power activation, the total energy delivered up until 7.5 seconds after the start of the deviation need to meet the expectations stated in requirement 3. During activation for FCR in a hydropower plant, there is a possibility of a small delivery in the negative direction. As the waterflow is increased, some of the power will temporarily go towards accelerating the water instead. The pressure in the plant will temporarily decrease, causing a small dip in the production of electricity. This activation energy should be counted as negative energy delivery when doing calculations to test requirement 3. The energy delivered during an activation can be seen as green, and the negative delivery as red, in Figure 6.

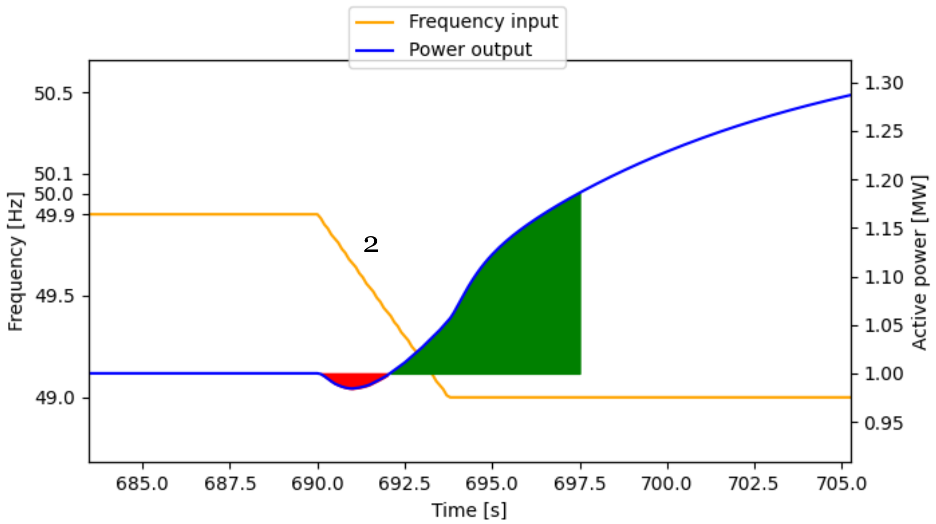


*Figure 6: Energy delivered 7.5 seconds after FCR-D activation*

As the frequency return to its nominal value after a disturbance, the FCR-D response should begin to deactivate. The activation and deactivation from the provider should behave similarly. The deactivation is tested during ramp 1 and 2, and evaluated at the nadir or zenith between the two ramps, which is the point in time when between increasing and decreasing frequency deviation. The test evaluates the energy overshoot after the frequency nadir or zenith. Once the frequency has reached its zenith/nadir, the power system is balanced and the derivative of the frequency error is zero. Energy delivered after this point will push the frequency disturbance in the opposite direction. Thus, it is critical that FCR-D deactivates its response swiftly enough. The activation and deactivation from the provider should ideally behave similarly, meaning FCR-D deactivates linearly with decreasing frequency error. However, controllers are often tuned so that activation is faster than deactivation. During the prequalification tests, the energy overshoot is calculated by integrating the instantaneous power subtracted by eighter the measured power at the time of the frequency zenith/nadir or half the theoretical steady state power, whichever is the smallest. The integral is evaluated from the time of the zenith/nadir and 40 seconds forward. The requirement is expressed as an equation below. At no point in time should the integral be larger than 2.5 times the theoretical steady state power. In Figure 7, the energy that surpasses the power at the frequency nadir can be seen in red. In the figure, the frequency ramps 1 and 2, as well as the frequency nadir is marked as well.

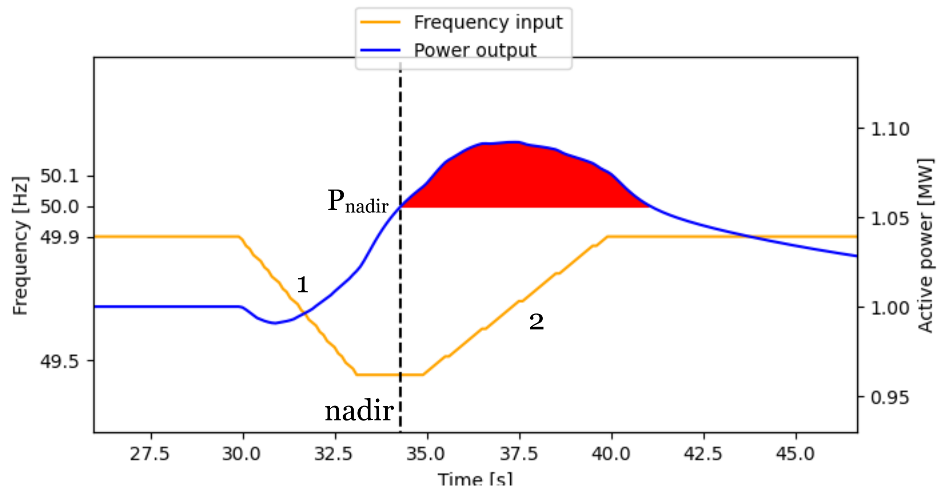


*Figure 7: Energy overshoot for power that surpasses the power during the frequency nadir*

## Requirement 4 FCR-D upwards:

$$\max_{k=t_{nadir}\to t_{nadir+40}} \int_{t_{nadir}}^{t=k} \left(\Delta P(t) - \min\left(|\Delta P_{nadir}|, 0.5 \cdot |P_{ss,teo}|\right)\right)dt \le 2.5 \cdot |P_{ss,teo}|$$

**Requirement 4 FCR-D downwards:**

$$\max_{k=t_{zenith}\to t_{zenith+40}} \int_{t_{zenith}}^{t=k} \left(-\Delta P(t) - \min\left(|\Delta P_{zenith}|, 0.5 \cdot |P_{ss,teo}|\right)\right)dt \le 2.5 \cdot |P_{ss,teo}|$$

#### *4.2.2.3 Sinusoidal sequence*

Frequency domain stability and frequency domain performance of the provider is tested by applying an input signal with a sinusoidal frequency deviation.

The sinusoidal frequency signal has an amplitude of 0.1 Hz and a period that ranges from T = 10 s to T = 300 s, and the resulting power output should have a sinusoidal shape.

$$Central\ frequency: \quad \begin{array}{ll} FCR-N: & 50\ Hz \\ FCR-D\ up: & 49.7\ Hz \\ FCR-D\ down: & 50.3\ Hz \end{array}$$

$$Sinosoidal\ period: \quad T = [10, 15, 25, 40, 50, 60, 70, 90, 150, 300]\ s$$

During a frequency event, there is many providers that deliver FCR, however, it is important that every providing entity has a stabilizing effect on the whole system. A simple illustration of the connection can be seen in Figure 8. In the figure, F(s) is the transfer function of the FCR providing entity and G(s) is the transfer function on the power system, given in equation (3).

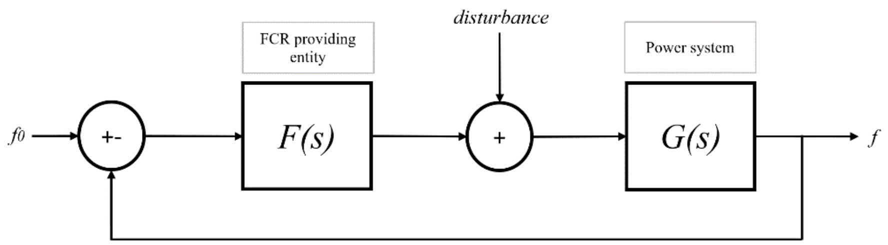


*Figure 8: Block diagram of FCR providing entity and power system connection*

$$G(s) = \frac{\Delta P_{FCR}}{\Delta f_{FCR}} \cdot \frac{f_0}{S_n} \cdot \frac{1}{2H\, j\omega + K_f \cdot f_0}\ [p.u] \tag{3}$$

The power system model G(s) is given by the parameters in Table 4. When testing the dynamic stability of a provider, the parameters for stability is used. These represent a power system with low inertia to make sure the system is stable in the case of model uncertainties. When testing the performance of the provider, performance parameters are used instead. The parameters make up a power system model with average inertia [10].

*Table 4: Power system parameters*

| *Parameter* | *Description* | *FCR-N performance* | *FCR-N stability* | *FCR-D performance* | *FCR-D stability* |
|---|---|---|---|---|---|
| $\Delta P_{FCR}$ | FCR volume | 600 MW | 600 MW | 1450 MW | 1450MW |
| $\Delta f_{FCR}$ | One-sided frequency band | 0.1 Hz | 0.1 Hz | 0.4 Hz | 0.4 Hz |
| $f_0$ | Nominal frequency | 50 Hz | 50 Hz | 50 Hz | 50 Hz |
| $S_n$ | Nominal Power | 40 000 MW | 23 000 MW | 42 000 MW | 23 000 MW |
| $H$ | Inertia constant | 4.5238 s | 5.2174 s | 4.5238 s | 5.2174 s |
| $K_f$ | Load frequency dependence | 0.01 p.u/Hz | 0.01 p.u/Hz | 0.01 p.u/Hz | 0.01 p.u/Hz |

F(s) is the normalized transfer function of the provider. The transfer function is found by subjecting the provider to the frequency test signal and study the power output delivered, which is illustrated in

Figure 9. The test signal is a sinusoidal frequency error, which corresponds to a situation where the grid frequency itself varies between two values in a sinus like matter.

During prequalification of an entity, the transfer function F(s) is not known. The transfer function can be found from the frequency input signal and the power output signal using equation (4) and (5) below. The magnitude of the transfer function is found by dividing the amplitude of the sinusoidal output signal $A_p(\omega)$, with the amplitude of the sinusoidal input signal $A_f(\omega)$ . When expresses as a frequency error, the input signal amplitude is 0.1 Hz for all tests. To normalize the transfer function, the result is scaled by multiplying with the one sided frequency band $|\Delta f_{FCR}|$, which is 0.4 Hx for FCR-D and 0.1 Hz for FCR-N. The result is divided with $|\Delta P_{FCR,theoretical}|$ which is the procured FCR capacity in MW and the theoretical steady state activation during a frequency event of the same size as the one sided frequency band $|\Delta f_{FCR}|$. To calculate the phase shift φ from the transfer function, the time difference $\Delta t$ between input signal and output power is used, and then recalculated to degrees.

$$|F(j\omega)| = \frac{A_p(\omega)}{A_f(\omega)} \frac{|\Delta f_{FCR}|}{|P_{FCR,theoretical}|} \tag{4}$$

$$\varphi = Arg(F(j\omega)) = \frac{\Delta t(\omega)}{T} 2\pi \tag{5}$$

From the magnitude and the phase shift, the final normalized transfer function for the FCR providing entity can be conducted. The transfer function can then be used to study stability and performance of the entity, evaluated according to requirement 8 and 9. See equation (6).

$$F(j\omega) = |F(j\omega)| \cos\big(\varphi(\omega)\big) + |F(j\omega)|\, j \sin(\varphi(\omega)) \tag{6}$$

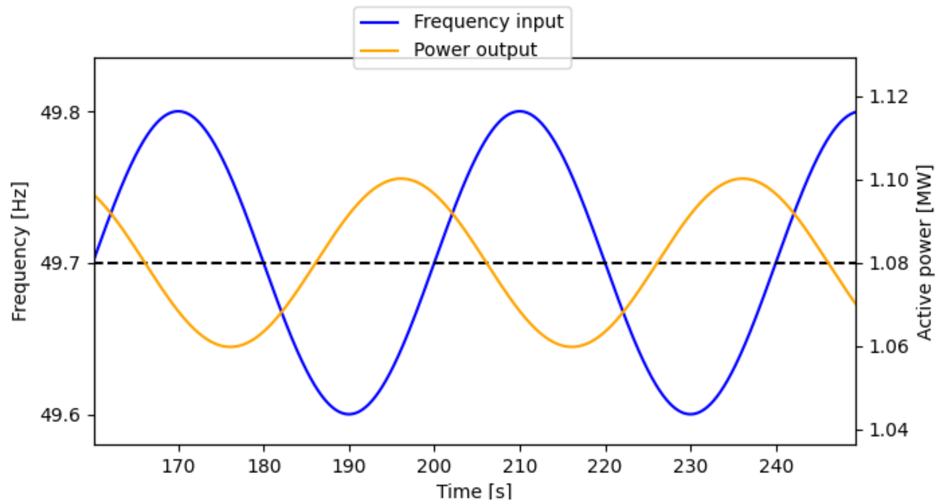


*Figure 9: Frequency input and active power response of plant with FCR-D upwards activation and droop 0.05*

When evaluating the frequency domain stability, the open loop system $G_o(s) = F(s)G(s)$ is used. By plotting $G_o(j\omega)$ in the complex plane for each $\omega = \frac{2\pi}{T}$ given by the test description, the Nyquist curve of the open loop system can be examined which is illustrated in Figure 10: Nyquist plot of plant that pass requirement 8.

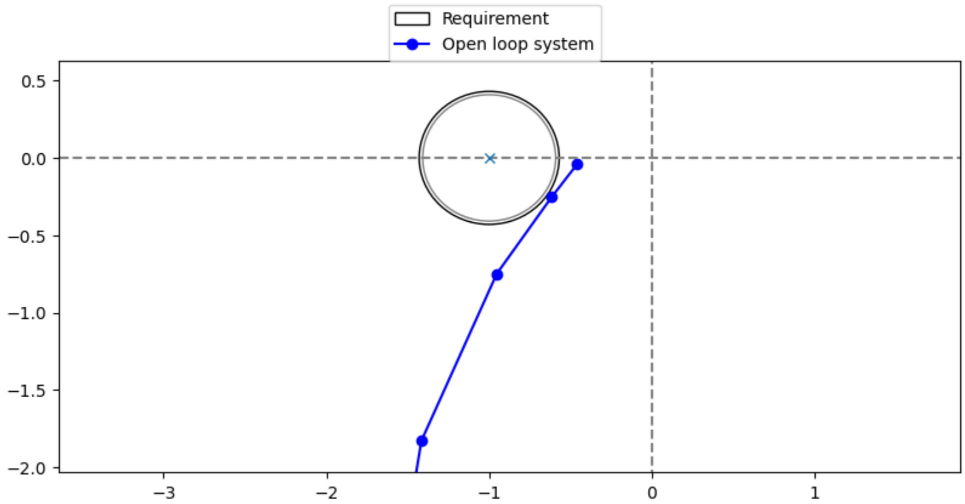


*Figure 10: Nyquist plot of plant that pass requirement 8*

A system is mathematically stable if the line in the plot do not encircle or pass on the left side of the point (-1, 0j) [11]. In practice the system needs to have a margin to the point (-1, 0j), so a stability margin of 2.31 is added to the requirement. The circle with radius $r$ that is visible in the plot around the point (-1, 0j) is derived from the margin, $r = 1/M_s$. If the plot at any of the points or the interpolated curve in-between enter the circle with more than 5% of the radius, the dynamic stability requirement is not fulfilled. In Figure 10 the Nyquist curve of a model plant with droop 0.05 is plotted. Since the line does not enter the circle or pass on the left side, the plant is considered stable.

**Requirement 8:**

*The Nyquist curve of the normalized open loop system $G_0(S) = F(j\omega)G(j\omega)$, shall pass on the right side of a circle with radius 0.43 around the point (-1, 0j) in the complex plane. A 95% margin on this requirement will be accepted as long as it stays out of a circle with radius $0.43 \cdot 0.95$. $F(j\omega)$ and $G(j\omega)$ shall be calculated separately for FCR-N, FCR-D downwards and FCR-D upwards*

When exanimating requirement 9, it is the closed loop system $G_C(s)$ from the disturbance $d$ in the system visible in Figure 8 that is used. The system is compared to the typical disturbance profile $D(s)$. For all frequencies in the test, the system needs to have an effective disturbance attenuation, meaning a lower magnitude than the typical disturbance profile. This can be seen in Figure 11, where the magnitude of the closed loop system $G_C(s)$ in below the inverted typical disturbance profile for all input frequencies.

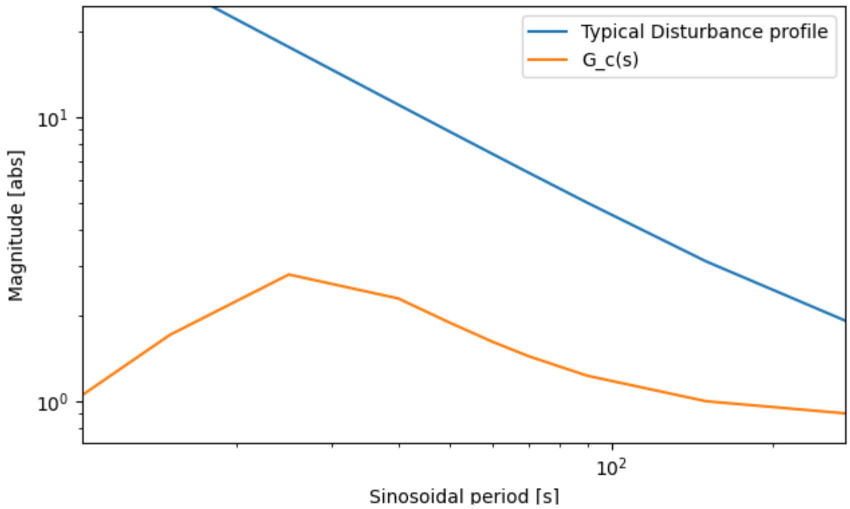


*Figure 11: Magnitude for different sinusoidal input signals for plant that pass requirement 9*

$$\text{Typical disturbance profile:} \qquad D(s) = \frac{1}{70s + 1}$$

**Requirement 9:**

$$\boldsymbol{G_C(s) = \frac{\left|G_{FCR,pref}(s)\right|}{\left|1 + \frac{F(s)}{K_{red}} \cdot G_{FCR,pref}(s)\right|} < \frac{1}{|D(s)|}}$$

$K_{red}$ is a reduction factor, and can be introduced if the provider do not pass the requirement without a reduction factor. The reduction factor must be 0.75 or bigger for FCR-D, and 0.9 of bigger for FCR-N. [8]

### 4.2.3 Mode shifting

Some entities cannot fulfill both the stability requirement and performance requirement with the same controller. If an entity cannot fulfill both at the same time, it is allowed to introduce a mode shifting in the controller to achieve both requirements but at different times. The two modes are the *high stability mode* and the *high performance mode*, and is tested during the ramp sequence. The high performance parameters can be activated if there is a frequency deviation bigger than 0.2 Hz, being 49.8 Hz for FCR-D upwards and 50.2 Hz for FCR-D downwards. The entity can keep the high performance parameters for a maximum of 10 seconds before the high stability parameters need to be activated again. After a performance parameter switch, the entity is not allowed to use the high performance parameters again for 5-15 minutes.

**Requirement 13:**

*For entities that utilizes **mode shifting** from high stability mode to high performance mode, the ramp test sequence should verify the following:*

1) *The high performance mode is activated during ramp 1 and then deactivated within 10 seconds and blocked*
2) *The high stability mode is active during ramp 3 and ramp 4*
3) *The high performance mode is active during ramp 5 and then blocked*
4) *The high stability mode is active during ramp 5 and then blocked*
5) *The high stability mode is active during ramp 6*
6) *The deactivation of the high performance mode must be smooth and bump-less*

## 4.3 THE HYDROPOWER PLANT

The technical requirements for FCR described above apply for all FCR delivering entities. However, in this report we will focus on the dynamical behaviors in hydropower plants, since the method for evaluating FCR deliveries against the requirements is not well adjusted for these behaviors today. In the computer tool, the power delivery from an entity will be compared to a modeled power delivery form a hydropower model plant. The modeled plant consists of a PI-regulator, a transfer function of the waterways and the guide vanes in the hydropower plant, together with a feedback loop. The construction of the hydropower model is described in further detail below. The typical hydropower plant is shown Figure 12 and described in Table 5. Plants can have more complicated structures as well, with more tunnels, shafts and other solutions.

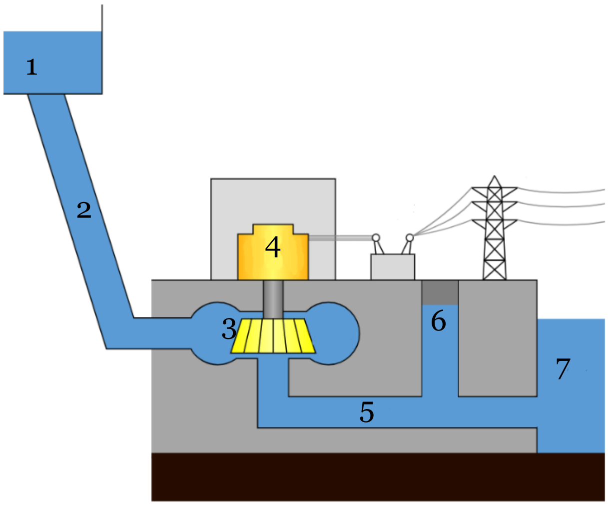


*Figure 12: Parts of a hydropower plant*

*Table 5: Description of hydropower plant parts*

| *Number* | *Part* | *Description* |
|---|---|---|
| *1* | Reservoir | Often a dam or river upstream of the hydropower plant where the water intake is |
| *2* | Penstock | Tube from reservoir to turbine where water is accelerated |
| *3* | Guide vanes and turbine | Guide vane adjust the water flow to the turbine that transfers the energy in the water to rotational energy |
| *4* | Generator | Transforms the rotational energy to electrical energy |
| *5* | Tail race tunnel | Leads water away from turbine |
| *6* | Surge gallery | Extra pipe to relive pressure during fast changes in waterflow |
| *7* | Lower reservoir | Water body at outlet, often a river |

### 4.3.1 PI-regulator

Most hydropower plants control the water flow using a PI-regulator with a feedback loop. A PI-regulator consists of two parts, one proportional and one integrating. The regulator uses the output signal to determine the input signal to the system. How much each part contributes to the input signal is determined by the proportional gain $K_P$, and the integral gain $K_I$. The input signal $u(t)$ is shown in equation (7), with the regulation error $e(t)$ described by equation (8). [11]

$$u(t) = K_P e(t) + K_I \int_{t_0}^{t} e(\tau) d\tau \tag{7}$$

$$e(t) = r(t) - y(t) \tag{8}$$

The integrating part of the controller is necessary in order to completely eliminate the static error in the output signal, but introducing an integrating part in the controller can also come with stability issues if $K_I$ is chosen too big. A larger $K_I$ will also lead to larger oscillations in the response. [11]

In a typical hydropower plant, the PI-regulator controls the opening of the guide vanes. The controller is connected to the guide vanes via a servo, which can introduce a time delay in the control system. The transfer function of the servo, $G_s(s)$, is described by equation (9).

$$G_s(s) = \frac{1}{T_g s + 1} \tag{9}$$

The mechanical apparent power from water delivered to the turbine in a hydropower plant is given by the following equation. [12]

$$P_m = K_{prop} \cdot H \cdot U \tag{10}$$

$H$ is the head of the head of the power plant, which is the height difference in meter between the water surfaces of the upper and lower reservoir. If the plant has a surge gallery, it is the water level in the surge gallery that determines the head instead of the lower reservoir. $U$ is the speed in m/s of the water in the penstock, and $K_{prop}$ a proportionality constant. The speed $U$ in the penstock of a power plant depends in return both on head $H$, a proportionality constant $K_u$ and on guide vane opening $Y$ given in percent.

$$U = K_u \cdot Y \sqrt{H} \tag{11}$$

Newtons second law of motion can then give the acceleration of the water in the penstock. In the equation below, L and A describes length and area of the water conduct, and $\rho$ is the density of water.

$$\rho L A \frac{d\Delta U}{dt} = -A\rho\Delta H \tag{12}$$

From these three equations, a transfer function of how change in guide vane opening relates to change in mechanical power delivered to the turbine, assuming only small deviations from the initial values $U_0$ and $H_0$.

$$G_t(s) = \frac{\Delta \bar{P}_m}{\Delta \bar{Y}} = \frac{1 - T_w s}{1 + \frac{1}{2} T_w s} \tag{13}$$

$$T_w = \frac{L U_0}{g H_0} \tag{14}$$

Where s is a complex frequency-domain parameter and $T_w$ is the water time constant of the plant and for the current operation of the plant. Both the time water constant and the transfer function $G_t(s)$ will be of importance in the hydropower model used in the computer tool. [12]

This transfer function however does not take into account for imperfections in the plant. Friction, turbulence from and hydraulic transients will play a part in the outcoming power. The losses are proportional to the velocity of the water squared. However, it is very hard to determine the exact losses due to the multitude of parameters that effect the power loss. It is also the power output of the provider that is used in this report. Estimation of power loss will therefore not be a part of the report.

The guide vane opening of the hydropower plant is usually controlled with a PI controller, with negative feedback from the guide vane opening setting scaled with the droop setting. Droop, $e_p$, is given in %, and limits the static gain of the controller. Droop ensures that the steady state power during a frequency disturbance is correct.

$$FCR - D\ droop: \qquad e_p = \frac{0.4}{50} / \frac{FCR - D}{P_{max}}$$

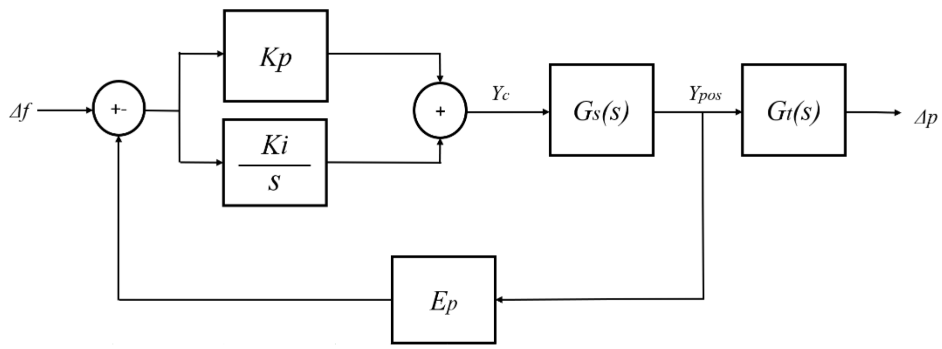


*Figure 13: Modeled control system F(s) of hydropower entity*

### 4.3.2 Hydraulics in a hydropower plant

Dynamic behaviors that occur in a hydropower plant usually comes from the acceleration of water in the waterways. Acceleration of water cause hydraulic transients that can have an oscillating effect on the power output that can cause complications when evaluating the delivery for each requirement. It is therefore important to know the hydraulic transients that can occur and the effect they will have on the power output. There are three main types of hydraulic transients occurring in a hydro power plant, and all three can have an effect on the output power. The hydraulic transients occur when there is a change in the velocity of water, for example when the power is increased or decreased. The three types, listed from slowest oscillation to fastest, is channel waves, mass oscillation and pressure transients. [13]

#### *4.3.2.1 Channel waves*

Channel waves are visible as a change in water depth in the water reservoir or river surrounding the power plant. It can be visible both up and downstream of the power plant. The oscillations however are very slow traveling with a relative speed of around 10 m/s for a typical power plant. The speed compared to the large size of reservoirs and rivers will result in a neglectable power oscillation. Channel waves will therefore not be taken into consideration in the report. [13]

#### *4.3.2.2 Mass oscillations*

Mass oscillation is visible in the surge gallery of a power plant. Due to the inertia of water in the tail race tunnel, a surge gallery is needed to relive large pressure transients in the turbine and draft tube. However, if a fast change in power output is done water will begin to oscillate between the surge gallery and the downstream reservoir, causing a fluctuating active head over the turbine. The period time of the fluctuations can be computed with the following equation.

$$T_{MO} = 2\pi \sqrt{\frac{L_{tunnel} A_{surge}}{g\ A_{tunnel}}} \tag{15}$$

Tunnel indicated the tail race tunnel between the surge gallery and water reservoir, whereas surge indicates the surge gallery. g is the gravitational constant. Using this formula, one can see that for a typical hydropower plant. [13]

#### 4.3.2.3 Pressure transients

Pressure transients occur in the penstock and draft tube after a change in power output. The flow of water in the penstock and draft tube cannot be changed instantly due to inertia of the water. For example, during a sudden stop the water flowing in the penstock will continue to flow for a short time due to inertia. The pressure that builds up as more water flows toward the turbine is large enough to cause the water to compress, building a very high pressure. The pressure wave will travel up the penstock until it reaches the upstream reservoir. A larger pressure in the penstock than in the reservoir will cause the water to flow backwards, and restore the pressure in the penstock. The pressure wave will continue to flow back and forward in the penstock until friction losses has damped the process completely. During a fast, complete stop these pressure waves can damage the pipes or turbine, and during smaller changes the pressure will cause an oscillation in the output power. The period time of the pressure transients can be calculated with the following formula.

$$T_{PT} = \frac{4L}{a} \tag{16}$$

In the formula, L is the length of the penstock. a is the velocity of sound in the water, which typically is 1400 m/s in free water, or 1000 m/s in a typical tunnel. [13]

## 4.4 FFT FILTERING

The disturbance data used in the computer tool is often noisy and in need of filtering. When choosing filter, the dynamic behaviors from water listed in the section above should be taken into consideration. An oscillation power signal can come both from measurement noise and from hydraulic transients. When analyzing a dataset from a disturbance with the data tool, the noise in the signal should not affect the result. In order to reduce the noise, a low pass filter can be used. There are several different digital filters available, but three different common filters were tested when constructing the computer tool, Chebyshev, Butterworth and fast Fourier transform. In Figure 14, the FFT filter follows the actual response closely without any shift in time. This cannot be said for the Chebyshev and Butterworth filter that both show a clear time shift in the response. The FFT filter was therefore chosen as the filter used in the computer tool.

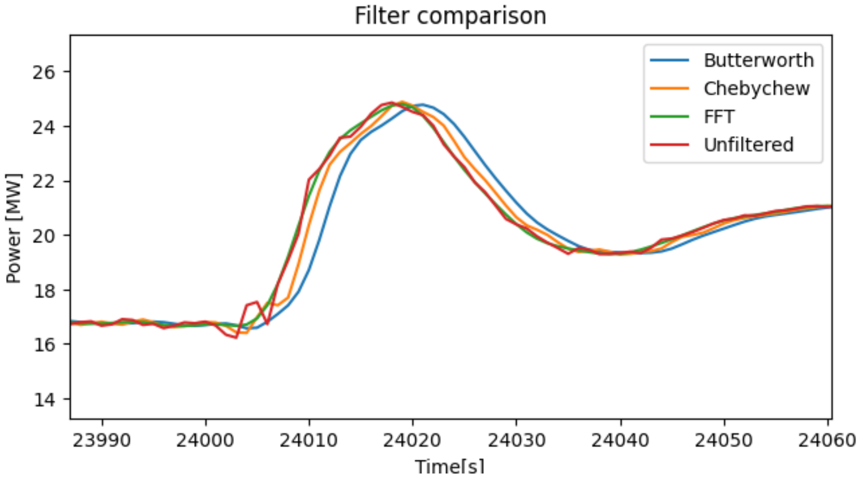


*Figure 14: Response using different filtering methods*

When choosing cutoff frequency, it is important that any of the hydraulic oscillations described in the section *Hydraulics in a hydropower plant* is taken into consideration and no important behavior is filtered out. The typical period of mass oscillations in a hydropower plant tends to be several minutes long [13]. These oscillations will therefore not be affected by the low pass filter. A medium sized hydropower plant in Sweden has a head of 15-50 m, and a large plant a head bigger than 50 m [14]. In order for pressure transients to be visible in the data the period of the pressure wave need to be more than twice as long as the sampling period. The sampling in the data is usually 1 second, meaning the pressure transients need to have a period of at least two seconds.

$$L = \frac{1000m/s \cdot T_{PT}}{4} > \frac{1000\ m/s\ \cdot 2\ s}{4} = 500m$$

The possibility of a plant having a penstock longer than 500 m is not likely. For a large plant, the penstock would be 10 times longer than the head of the plant. Pressure transients is therefore neglected when constructing the low pass filter.

The time constant of the FFT filter should not be bigger than the time constant of the water ways in the hydropower plant. In order to have optimal filtering, the two time constants should be equal. This will ensure that important dynamic behavior is kept, while all unnecessary noise in filtered out. The cutoff frequency will then depend on the time water constant $T_w$ of the plant, and can be calculated using (17).

$$f_c = \frac{1}{2\,\pi\,T_{LP}} = \frac{1}{2\,\pi\,T_w} \qquad (17)$$

One effect of the filtering however is the appearance of a slight oscillation, known as ringing, in the filtered response. This is particularly noticeable just before the disturbance occurs. This is a common artifact introduced by FFT filters when the input signal contains a sharp transition. To make the comparison between the actual response and the modeled response as accurate as possible, the modelled response is also processed using the same FFT filter. From this point on, all graphs and results in the report show the measured and simulated data after filtering, unless stated otherwise.

# 5 DEVELOPMENT OF THE COMPUTER TOOL

The idea behind the computer tool is to use the established prequalification requirements and try adapt them onto a real disturbance using modeled hydropower plants with a known prequalification result. This model will base the result on the assumption that all entities with a lower delivery than the modeled limit plant would have failed if the disturbance had the same form as in the prequalification tests. The construction of the computer tool can be divided into three main parts.

1. Finding hydropower models on the limit off passing a requirement

2. Identify the parameters of the entities transfer function

3. Compare the delivery with the modelled limit delivery

In addition to this, there is other smaller parts of the tool necessary for the analysis to work properly.

## 5.1 FREQUENCY SLICING

The frequency data from the provider is not suitable as input to the FCR models without modification. The modification of the frequency signal is different depending on which ancillary service is of interest. If the frequency on the grid is 50 Hz, there should be zero activation from both FCR-N and FCR-D.

If the frequency is higher than 50 Hz, FCR-N should have negative activation. Similarly, the activation should be positive if the grid frequency is lower than 50 Hz. This is accomplished be subtracting the frequency data from 50 Hz. At 49.9 Hz the deviation used as input will be 0.1 Hz, and at 51.1 Hz the input deviation will be -0.1 Hz. This is where the frequency band for FCR-N end and no more activation should happen. All values that deviate more than ±0.1 Hz is set to ±0.1 Hz.

For FCR-D, the activation should be zero for all frequencies in the FCR-N band. FCR-D upwards activation begins when the frequency is 49.9 Hz, and should increase linearly until 49.5 Hz. For bigger deviations, it is up to the provider if the activation should continue to increase or if the activation is maximized. To achieve this, the normalized frequency values smaller than 0.1 Hz is set to zero. The remaining values are then subtracted with 0.1 to achieve linear activation. The same is done but using over frequencies with FCR-D downwards. Providers are free to choose whether the input signal should be saturated at $\pm 0.4$ Hz or not. While the technical requirements allow both approaches, the use of a saturation limit can have a considerable effect on the response. To account for this, the computer tool also has the option of using a saturation limit or not. Since the parameters in the model is in per unit values, so should the frequency. The frequency deviation input data is therefore finally divided by 50.

$$\begin{cases} NCR - N: & u = \dfrac{50 - f}{50} & -0.1 \leq u \leq 0.1 \\ FCR - D\ up: & u = \dfrac{50 - f - 0.1}{50} & 0.0 \leq u\ (\leq 0.4) \\ FCR - D\ down: & u = \dfrac{50 - f + 0.1}{50} & (-0.4 \leq)\ u \leq 0.0 \end{cases} \tag{18}$$

## 5.2 FINDING HYDROPOWER MODELS ON THE LIMIT OF PASSING A REQUIREMENT

During a frequency disturbance, the frequency does not follow the exact pattern used as input during the prequalification process. Each disturbance is unique, so the method used to verify the delivery need to be adjusted to fit all disturbances. The dynamic properties of hydropower further complicate the task, since this will complicate the comparison. Most plants have a control system that can be compared with the system in Figure 13. A simulated response from a hydropower plant model, constructed as shown in Figure 13, can be compared to the actual response from the hydropower plant for each new disturbance registered. If all the parameters of the model are known it can be tested with the prequalification tests beforehand to know the performance of the plant, and then be subjected to the actual frequency signal from the disturbance. When verifying requirement 2 and 3, the procured power capacity is what determines what the energy and power should be 7.5 seconds after a disturbance. By finding a model that is on the limit of passing a requirement when subjected to the test sequence, it can be assumed that the plant will still be on the limit of the requirement when subjected to an actual frequency disturbance. By using the modeled delivery limit as a reference when comparing with the delivery of entities during the same frequency disturbance, it can be shown if the entity has delivered above or below the limit.

To find the limit plant, it is important that all the variables that can have an effect on the result are taken into consideration. The different parameters in the model are

$T_w, T_g, K_P, K_I$ and the droop $e_p$. To see further detail of the model, read the section *The hydropower plant* above. Each of these parameters will chance the behavior of the response. Due to the dynamic behavior in hydropower plants, it needs to be established that the effect of the parameters will not jeopardize the accuracy of the computer tool. The parameters need to be tested within reasonable limits. The limits used in the data tool was chosen by discussing with employees as Svenska kraftnät, examining entity data sheets and trial and error during the development of the computer tool and can be seen in Table 6.

*Table 6: Parameter limits in new computer tool*

| | *Min* | *Max* |
|---|---|---|
| $T_w$ | 0.5 | 2 |
| $T_g$ | 0.1 | 0.5 |
| $e_p$ | 0.02 | 0.12 |
| $K$ | 0.02 | 3 |
| $T_f$ | 0.8 | 200 |

$T_f$ is the feedback time constant of the model. This will be the time it takes for the response to reach 63% of the steady state value if the proportional part of the controller is neglected. $T_f$ and $K_I$ of the controller is closely related, and can be converted between each other using equation (19). [15]

$$K_I = \frac{1}{e_p\, T_f} \tag{19}$$

K is the static gain of the controller. It is related to the proportional gain of the controller when scaled with the droop. The equation for $K$ is shown in equation (20). [15]

$$K_P = \frac{K}{e_p} \tag{20}$$

To see the effect each of the parameters has on the response, simulations of the response from the model during a disturbance was studied. A model used as a base during the parameter testing was constructed using the model Figure 13. The base model was given parameters within the set intervals. All parameters of the base model can be found in Table 7.

*Table 7: Model parameters during disturbance simulation*

| | |
|---|---|
| $T_w$ | *1.2* |
| $T_g$ | *0.2* |
| $e_p$ | *0.05* |
| $K$ | *0.3* |
| $T_f$ | *10* |

By varying one of the parameters of the base model at a time, and keeping the rest constant, one can study the affect the parameter in question has on the power response. For each different parameter analyzed, the power response for two different models where compared. One model had the parameter on the minimum value, and the other at the maximum value in the set parameter range. All other parameters were kept according to the base model. Droop was not examined and hence kept constant for all simulations, since droop is connected to the magnitude of the response and only will scale the result. The different power responses from each model can be seen in Figure 15 to Figure 18.

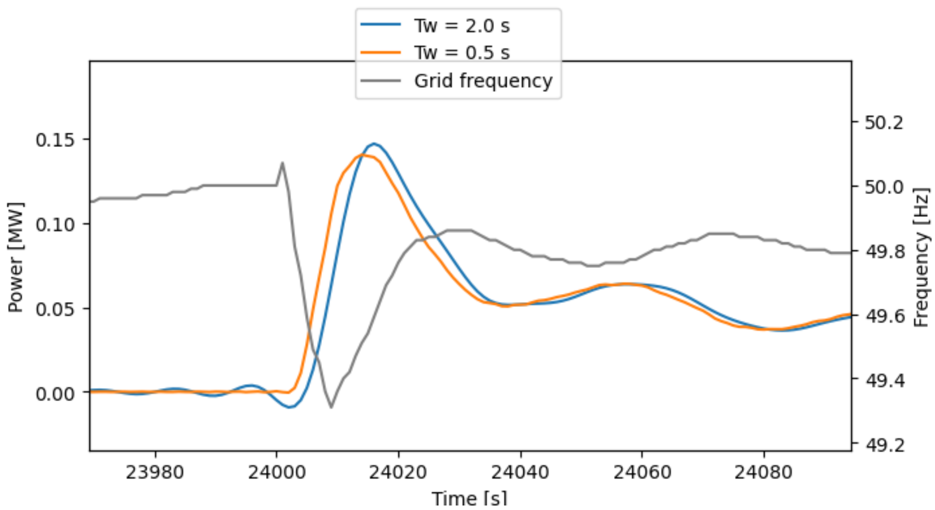


*Figure 15: Model with $T_w = 0.5$ and with $T_w = 2.0$ response during frequency deviation*

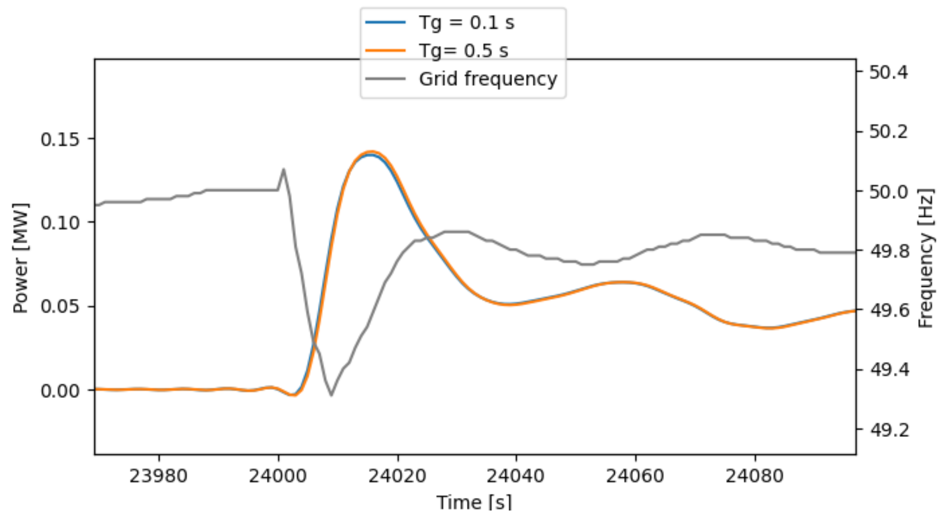


*Figure 16: Model with $T_g = 0.1$ and $T_g = 0.5$ response during frequency deviation*

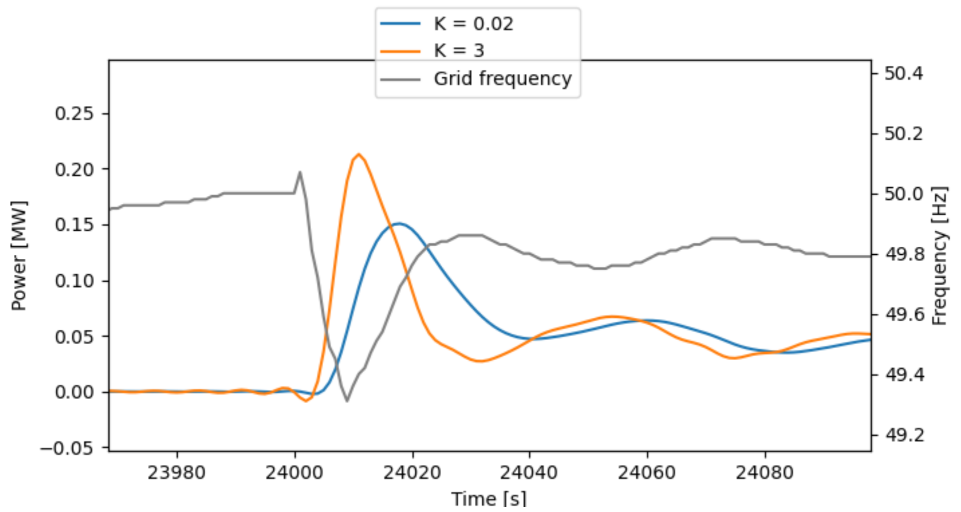


*Figure 17: Model with $K = 3$ ($K_P = 60$) and $K = 0.02$ ($K_P = 0.4$) response during frequency deviation*

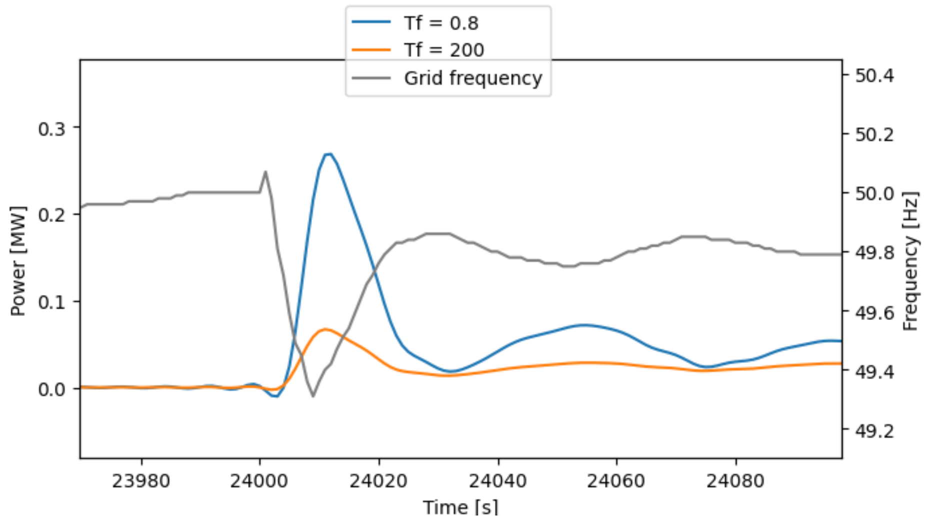


*Figure 18: Model with* $T_f = 0.8$ $(K_I = 25)$ *and* $T_f = 200$ $(K_I = 0.1)$ *response during frequency deviation*

By studying the responses seen in Figure 15 – Figure 18, the difference in response is clearly noticeable when varying the parameters $K$, $T_f$, and $T_w$. However, the difference in response when using $T_g = 0.1$ and $T_g = 0.5$ is barely noticeable. $T_g$ will therefore have a constant value in the computer tool, $T_g = 0.2$. This value will be used for all models in the tool to reduce the number of parameter combinations and by that reduce the running time of the tool. The other parameters however cannot be assumed constant since the difference is large enough to have a noticeable effect. These parameters will be varied when testing a delivery with the computer tool within the limits in Table 6.

### 5.2.1 Determining limit models

To determine a limit model, the computer tool will iterate through all compilations of parameters within the limits listed in Table 6. This will result in a large number of models with several different properties. Each model constructed in the computer tool need to be tested to see if the model will pass a requirement or not. Several different combinations of parameters can give a power response that are on the limit of passing a requirement. For example, it can be seen in Figure 15 - Figure 17 that the response will be faster both when increasing $K$ and decreasing $T_f$ or $T_w$. Which combinations of these parameters will give a response on the limit of passing will also depend on the droop of the entity. To find which models are on the limit of passing each requirement, the response of each model when using the prequalification test sequence need to be analyzed.

The power response was created using the control package in Python. To find all combinations of parameters that are on the limit of requirement 2, 3 and 4, the response was created using an iterative method. Requirement 2, 3 and 4 are all tested using the ramp sequence, which has a similar behavior as a frequency disturbance. These requirements can therefore be tested only using the disturbance data. To test requirement 8 and 9 however, the transfer function of the entity need to be known. This is discussed further in the section *Model identification* below.

The computer tool looped though all possible combinations of $K$ and $T_w$. For each parameter combination, $T_f$ was set to the upper limit of $T_f = 200$. The response of the model with the prequalification test sequence as input was simulated and analyzed using the equation for the requirement of interest. If the model failed the requirement, the loop continued but with a value of $T_f = 200/1.1$. A lower value of $T_f$ will give a faster response with a higher probability of passing the requirement. This process continued, dividing $T_f$ with 1.1 for each loop, until a value was found that did pass the requirement. If no model that pass the requirements are found for a value of $T_f > 0.8$, the process stops and continues for the next value of $K$. The process also continues without finding a limit if the model pass the requirement with $T_f = 200$, since there need to be at least one model that fails and one that passes in order to determine a limit. This was done for 10 logarithmically spaced values of K within the span. The values of $T_w$ was evenly spaced, with a distance of 0.1 s.

For requirement 4 however, the method needed to be adjusted. There were two different scenarios for passing requirement 4 found. Several spans of $T_f$ gave an approved result. When evaluating requirement 4, the loop did not break as soon as a limit was found. Instead, the loop continued and until $T_f < 0.8\,s$ to find all limits from all the areas of approved models.

For each requirement a CSV-file was created containing all models preforming on the limit of the requirement. In each file, there will be one array of different plants for each value of $T_w$. In the array, $K$ and $T_f$ is converted to $K_P$ and $K_I$ according to equation (19) and (20). The arrays contain all the different combinations of $K_P$ and $K_I$ that generated a limit plant. By knowing the $T_w$ of the entity that is tested using the computer tool, the correct array of plants can be found by choosing the correct file and row in the file.

The droop during of all models is set to 0.05. In order to scale the response of the model to the correct value, the power is multiplied with $0.05/e_p$ . $e_p$ is the droop of the entity being analyzed.

## 5.3 MODEL IDENTIFICATION

In many cases, the different parameters for each plant are not easily accessible. In case the droop $e_P$ and time water constant $T_w$ are not known for the computer tool user, there stills needs to be a way to run the computer tool. The parameters of the plant can be found by comparing the provided power data from the entity with the response of a model with known parameters during the biggest frequency disturbance in the disturbance data. Below, the strategies used in the computer tool in order to deal with missing data is described.

Droop is calculated using equation (1). To calculate the droop setting of the entity, the FCR capacity and rated power of the entity has to be known. FCR capacity of each entity is provided in the disturbance data. Depending on how the provider choose to measure the FCR capacity of the entity the data can contain variations in time when the capacity should be constant. When the amount of procured FCR capacity changes, so does the droop setting. The amount of procured capacity should not change often in the data, since FCR is bought on an hourly market. Small changes in the stated capacity however occur regularly in the provided data for some providers, resulting in difficulties when simulating a response. To avoid this problem, the average FCR capacity over the whole disturbance is used.

Rated power however is not provided in the data, but is provided together with prequalification documents. If the rated power is not entered by the user of the computer tool, the tool will identify the rated power as the maximum total power capacity throughout the data set. Total power is calculated as the reference power, added with FCR-N and FCR-D upwards capacity. This will not give the exact rated power, and hence not the correct droop. In the computer tool however, droop is used as a scaling of the response. FCR capacity is what is important in the response, so the wrong rated power will therefore have no effect and the scaling of the response will remain correct.

Once the droop and rated power is known, the data tool will loop through all the different parameters from minimum value to maximum value, shown in Table 6. By comparing the disturbance data from the provider with all possible combinations of hydropower models, it is likely to find the model that has the closest match and therefore similar behavior and time water constant as the entity. In order to have a good enough accuracy and a short runtime, an array of 30 values of $K$ and $T_f$ was used in the simulation. $T_w$ need to match the same $T_w$ values used when determining the limit models (see *Determining limit*) and an array of 16 values where used. This will result in an array of $T_w$ values that is spaced with a difference of 0.1 s and therefore match the model limits. The values of $T_w$ and $K$ spaces linearly, and values of $T_f$ logarithmically. Each model was then subjected to the same frequency disturbance as the frequency disturbance registered in the entity data. The goal is for the identified model to precisely follow the activation of FCR-D and FCR-N activation from the entity. A constant over or under delivery in the steady state response should not affect the model identification.

If the deviation in frequency is more than 0.2 Hz, performance parameters are activated if the entity has mode shifting, see section *Mode shifting*. Two different results where therefore taken, both using the mean of the difference between each data point squared. For the performance parameters, the ordinary response was used. The deviation from the model was then evaluated in the first 10 seconds after the deviation goes above 0.2 Hz. When analyzing the stability parameters, the response was simulated using the actual FCR-D power as initial value. The response was found from 10 seconds after the deviation went above 0.2 Hz, and evaluated over the whole disturbance. If the plant does not have mode shifting, it is the ordinary response that is used over the whole disturbance.

For entities with mode shifting activated, only the parameters of the regulator will change during the parameter shift. $T_w$ and the delivery constant, see in section *Model identification*, should therefore have the same value for both the stability regulator and the performance regulator. The delivery constant will be of most significance after the initial peak, when the response is somewhat steady. This is where stability parameters are active, so the delivery constant is taken from the optimal stability model response. $T_w$ is the most pronounced in the initial dip in response, when the performance parameters are active. By filtering out the performance models that do not have the same constant as the one found from the stability model, the optimal response can then be found. The $T_w$ of the optimal performance is the one that is likely to be close to the actual $T_w$ of the power plant. Stability and performance regulator parameters are found to be the models with a response most resembling the actual response and with a $T_w$ and constant found from the previous analysis.

## 5.4 CHECK OF REQUIREMENTS

The requirements for FCR-D are verified in the case of a frequency disturbance bigger than the threshold entered by the computer tool user is found. If a deviation is found that lasts for 8 seconds or longer, the sliced frequency data for FNC-N, FCR-D upwards and FCR-D downwards is used as input to find the response of the limit model. This is evaluated over the whole disturbance, plus with an extra 30 seconds before and after the disturbance event.

As described in the section *Finding hydropower models on the limit of passing a requirement*, several arrays of limit models with different properties are found. The $T_w$ and $e_p$ of the FCR providing entity found during the model identification, or entered by the computer tool user if the parameters are known, is used to find the array with the limit models corresponding to the entity. This will result in an array of limit plants with different combinations of $K_P$ and $K_I$ that has a response on the limit of passing, one for requirement 2, one for requirement 3 and one for requirement 4. The different combinations will all show a behavior that is on the limit for the test sequence, but is not certain that they all will deliver the same energy and power during another disturbance. In Figure 19 and Figure 20 the response from limit plants but with different configurations between $K_P$ and $K_I$ are shown. Both models have the same droop, $T_w$ and are almost equally far from passing the requirement when subjected to the test signal. The full parameter list is shown Table 8. Error is given in percent and shows how much the delivered energy and power differed from the power and energy stated by the requirements during the simulation with the test sequence.

*Table 8: Limit models for requirement 2 and 3*

| | High $K_P$, low $K_I$ | | Low $K_P$, high $K_I$ | |
|---|---|---|---|---|
| *Requirement 2* | $K_P$ | 3.715 | $K_P$ | 0.399 |
| | $K_I$ | 1.919 | $K_I$ | 2.555 |
| | $T_w$ | 1.3 | $T_w$ | 1.3 |
| | $e_p$ | 0.05 | $e_p$ | 0.05 |
| *Requirement 3* | $K_P$ | 6.488 | $K_P$ | 0.399 |
| | $K_I$ | 6.024 | $K_I$ | 8.820 |
| | $T_w$ | 1.6 | $T_w$ | 1.6 |
| | $e_p$ | 0.05 | $e_p$ | 0.05 |

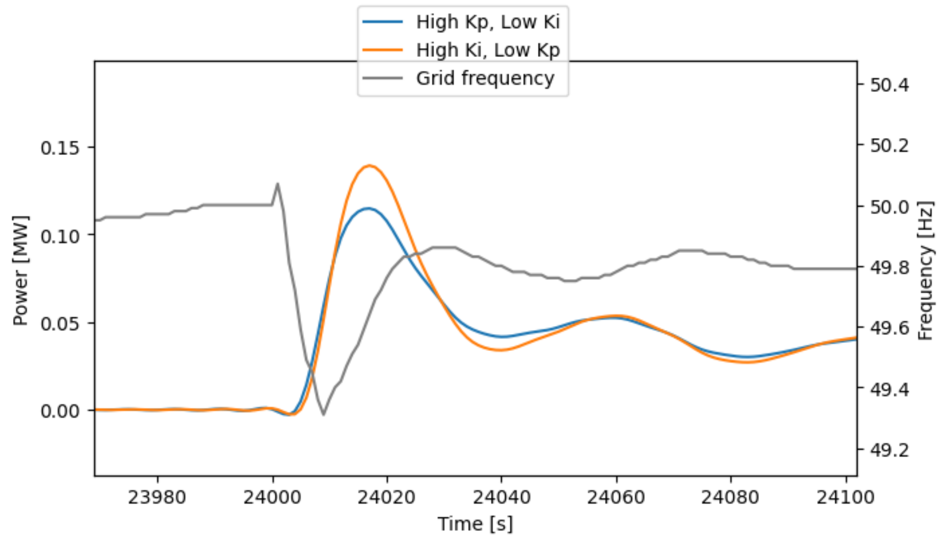


*Figure 19: FCR-D activation during disturbance with High $K_P$ and low $K_I$ vs. Low $K_P$ and High $K_I$ for requirement 2 limit entities*

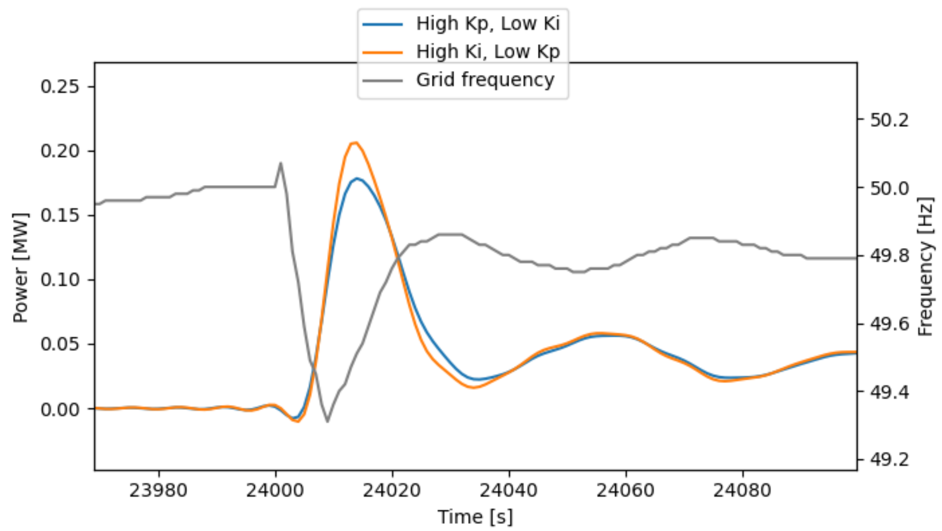


*Figure 20: FCR-D activation during disturbance with High $K_P$ and low $K_I$ vs. Low $K_P$ and High $K_I$ for requirement 3 limit entities*

As can be seen in Figure 19 and Figure 20, there is clear difference in the amplitude of the initial peak. A higher value of $K_I$ gives a higher peak both for the requirement 3 and 2 limit models. An as clear difference in energy and power after 7.5 seconds is not as easily seen, but was calculated in Python using the trapezoidal method in Numpy. This was done both for the original frequency disturbance as input, and with an input limit at 49.5 Hz. The result can be seen in Table 9. The results were generated using an FCR-D capacity of 1 MW.

*Table 9: Power and energy delivery for requirement 2 and 3 limit plants*

| | *Frequency cut at 49.5 Hz* | | *No frequency cut* | |
|---|---|---|---|---|
| | P at 7.5 s [MW] | E at 7.5 s [MJ] | P at 7.5 s [MW] | E at 7.5 s [MJ] |
| *High $K_P$, Low $K_I$* | 0.0575 | 0.2059 | 0.0668 | 0.2044 |
| *Low $K_P$, High $K_I$* | 0.0557 | 0.2028 | 0.0613 | 0.2035 |

The difference in power and energy is relatively small, but not small enough to be neglected. This especially applies when there is no cut in the frequency signal. For another disturbance with a different behavior the difference in power and energy can be even larger.

When comparing the limit plants with the actual disturbance, it is the limit plant that delivers the lowest power and energy after 7.5 seconds that will be used. The reference plants should describe the lowest possible level of approval, in order to not fail any entities that actually would have been approved if the disturbance looked different. To achieve this, it is the worst preforming model for each disturbance that should be used.

When examining the stability and performance of the delivery however, another approach needs to be taken. There is no good way to see if the delivery is approved by only studying the activation, since stability and performance cannot be seen in the response in a good way. To see the stability and performance of a plant, the plants need to be tested using the sine-tests described in the section *Technical requirements for FCR*. By using the performance and stability model found in the model identification, sine tests on the entity model can be performed. The accuracy of this method can however be discussed, since the model identification is very simplified compared to the sometimes very complicated controllers in hydropower plants. The model identification does not take into consideration time delays, backlash, a derivative part of the controller and other unknown parameters that can affect stability and performance. The sine test analysis on the performance and stability parameters can at best provide a guess on requirement 8 and 9.

## 5.5 ACTIVE POWER COMPONENTS

Most entities deliver both FCR-N and FCR-D. In the data from the provider with the delivered power from each entity it is often only the total power delivered that is provided. To know how big the amount of that power is FCR-N, FCR-D and the base power production is channeling, especially since entities can have a different base power production than stated in the provided data.

### 5.5.1 FCR-N

Instead of trying to remove the FCR-N power from the provided data, a simulated FCR-N response is added to the FCR-D response of the model. As stated in the requirements for FCR-N, the time for the delivery to reach 63% should take a maximum of 60 seconds after a frequency step from 50 Hz to 49.9 Hz or 50.1 Hz. The FCR-N delivery is modeled using a controller with a transfer function $G_N(s)$ shown below in equation (21).

$$G_N(s) = \frac{P_{FCR-N} / \frac{0.1}{50}}{60.35\ s + 1} \tag{21}$$

### 5.5.2 Baseline Power

In order to evaluate the FCR-D delivery, it is important that the base power is chosen correctly. There is however no perfect way of knowing the exact baseline power, since providers often has a constant delivery that is much lower or higher than the reference power stated in the provided disturbance data. The power can often vary right before the disturbance occurs, and FCR-N delivery and FFT filtering can further cause variations in visible when analyzing the power in the data tool.

There are several different approaches that can be used to determine the baseline power. The methods considered in this report is the stated reference power, the mean power over 10 seconds, the mean over the last oscillate period, the mean power between the two last power nadirs, the power zenith during the last oscillation and the power nadir during the last oscillation.

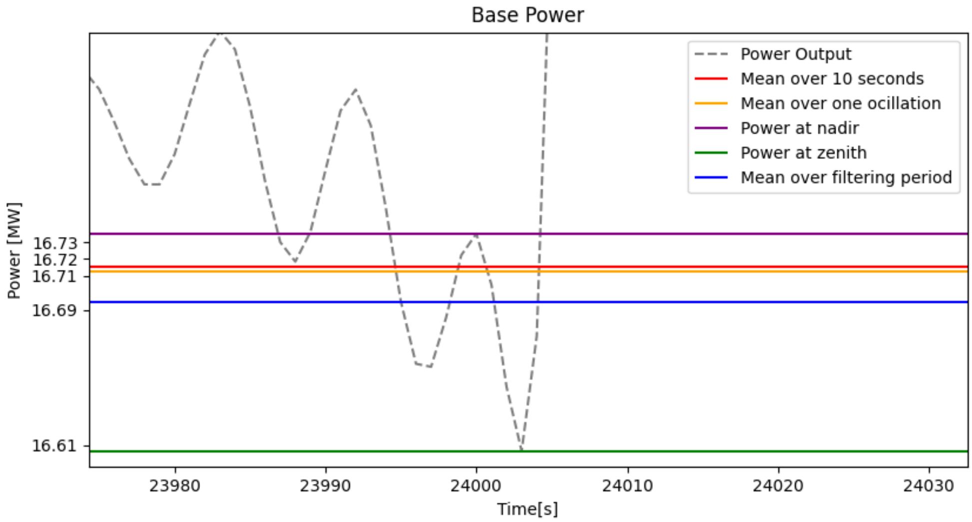


*Figure 21: Base power options for plant 1*

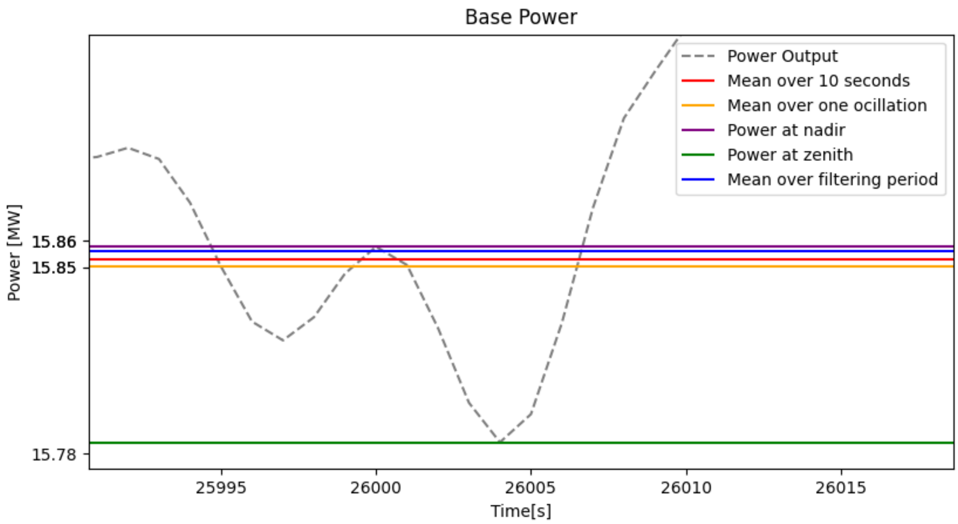


*Figure 22: Base power options for plant 2*

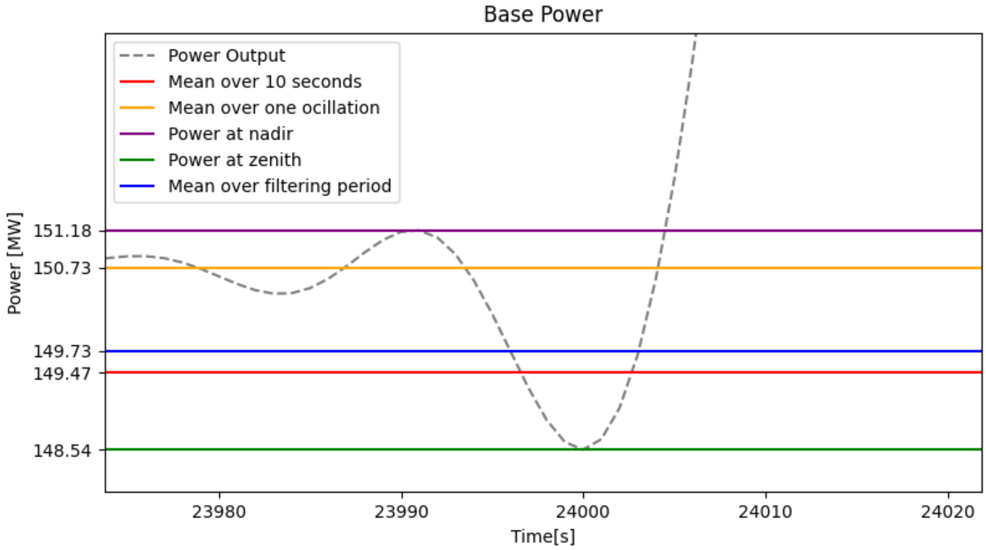


*Figure 23: Base power options for plant 3*

In most cases, the mean over one oscillation follows the power production well and is taken close enough in time to the disturbance for there not to be any major change in power from the provider except from FCR activation. The mean is evaluated between the last two power nadirs before the disturbance, so the big dip in power due to the acceleration of the water will not have as big effect on the calculation as when using evaluation over the last 10 seconds or over the last filter cut off period. This can be seen in Figure 23, where the big dip in power significantly reduces the value of the base power when evaluating over the last 10 seconds and after the filter cut off period. The mean between the last two nadirs however seems to follow the base bower well without being affected by the dip.

In case the provider is increasing or decreasing the power right before the start of the disturbance, the case of determining a base get complicated further. The mean value of the last oscillation can then have a higher value than the power at the last nadir, or lower power than the power at the last zenith. In this case, complications can arise when checking for requirement 3. The area before the initial dip begins will then be counted for whish can affect the results. To avoid this problem, the power at the power nadir is chosen during calculations of requirement 3 if the base power is bigger, and the power at the frequency zenith if the base power is smaller.

One problem with this method however occurs when there are no oscillations before the FCR activation. This can for example happen in case of a high time water constant.

## 5.6 LIMIT PLANTS

In order to accurately use the limit plants as a limit during a real disturbance, it needs to be confirmed that the model on the limit preforms worse than the models that did pass the requirement. Otherwise, there is a risk that deliveries will be failed even though the delivery would have passed the requirement. The computer tool was therefore run using the actual limit plant in addition to other plants with the same $T_w$ and $K_p$. The test then iterates over several $K_i$ over the whole span used in the tool. Since the limit was determined by iterating over $T_f$ until a plant that did pass the requirement was found, the limits will be tested by varying $K_i$, which is directly related to $T_f$, and see how it affects the result.

*Table 10: Evaluation of plant 1 limit accuracy requirement 2, 3 and 4*

| $K_i$ | 2 ($K_p$ = 0.399) | 3 ($K_p$ = 0.399) | 4 ($K_p$ = 0.697) |
|---|---|---|---|
| *0.121* | 0.347 | -3.244 | 19.760 |
| *0.145* | 0.372 | -3.207 | 22.597 |
| *0.175* | 0.402 | -3.165 | 25.819 |
| *0.209* | 0.438 | -3.117 | 29.433 |
| *0.251* | 0.482 | -3.058 | 33.427 |
| *0.302* | 0.533 | -2.987 | 37.760 |
| *0.362* | 0.594 | -2.900 | 42.354 |
| *0.434* | 0.666 | -2.794 | 47.080 |
| *0.521* | 0.753 | -2.664 | 51.753 |
| *0.625* | 0.855 | -2.506 | 56.124 |
| *0.751* | 0.976 | -2.315 | 59.884 |
| *0.901* | 1.119 | -2.085 | **62.677** |
| *1.081* | 1.286 | -1.798 | 64.123 |
| *1.297* | 1.481 | -1.457 | 63.859 |
| *1.556* | 1.707 | 2.728 | 61.579 |
| *1.868* | 1.968 | 3.153 | 57.075 |
| *2.241* | **2.267** | 3.636 | 49.777 |
| *2.689* | 2.604 | 4.192 | 46.778 |
| *3.227* | 2.982 | 4.828 | 43.650 |
| *3.872* | 3.398 | 5.562 | 40.505 |
| *4.647* | 3.848 | 6.440 | 37.136 |
| *5.577* | 4.326 | **7.487** | 33.437 |
| *6.692* | 4.821 | 8.554 | 29.254 |
| *8.030* | 5.320 | 9.698 | 25.928 |
| *9.636* | 5.807 | 10.900 | **22.146** |
| *11.563* | 6.266 | 12.132 | 18.625 |
| *13.876* | 6.684 | 13.365 | 15.226 |
| *16.651* | 7.051 | 14.566 | **12.685** |
| *19.981* | 7.363 | 15.707 | 10.650 |
| *23.977* | 7.620 | 16.529 | 9.027 |
| *28.773* | 7.828 | 17.446 | 7.578 |

All models marked green in Table 10 has passed, while the models marked red has failed the prequalification. The plants used as limit can be seen in bold. The limit is chosen as the last plant that do not pass the prequalification. From the testing one can see that all models with a higher $K_i$ have a higher delivery than the limit plant for both requirement 2 and 3. Similarly, all models with a lower $K_i$ has a lower delivery than the limit model for requirement 2 and 3. This enforces the assumption made when constructing the computer tool that the plant on the limit of passing the requirement still will be possible to use as a limit during a real frequency disturbance.

This can however not be said for requirement 4. As can be seen in Table 10, there is three different limit plants. As was explained in the section *Technical requirements for FCR,* the overshoot integral can be calculated both using half off the steady state power and the power at the frequency nadir, depending on which is smaller. For low values of $K_i$ the power at the frequency nadir will be lower than half of the steady state power due to the slow activation. The overshoot will as well be very low, resulting in the model passing requirement 4. As $K_i$ increases, so will the overshoot of the response. When the overshoot is too big the model will no longer pass requirement 4. This happens at $K_i = 0.901$ in Table 10. As $K_i$ increases even more, the model becomes faster. A faster response will lead to a higher power at the frequency nadir. As the model becomes high enough the power used to calculate the integral will be high enough for the model to once again pass the integral. It is therefore the medium high values of $K_i$ that will cause the model to fail. The last limits appear when the power at the frequency nadir is so high that half of the steady state power will be lower and therefore used to evaluate the integral. A further increase of $K_i$ will then increase the overshoot, while half of the steady state power will remain constant. The model will then one again not pass the requirement.

As can be seen in Table 10, there are models that do not pass that have a smaller overshoot then models that did pass the requirement. This will complicate he evaluation of requirement 4 using a modeled plant since there is no certainty that a lower overshoot means an approved requirement. The results of requirement 4 from the computer tool will therefore not be reliable.

## 5.7 Model identification

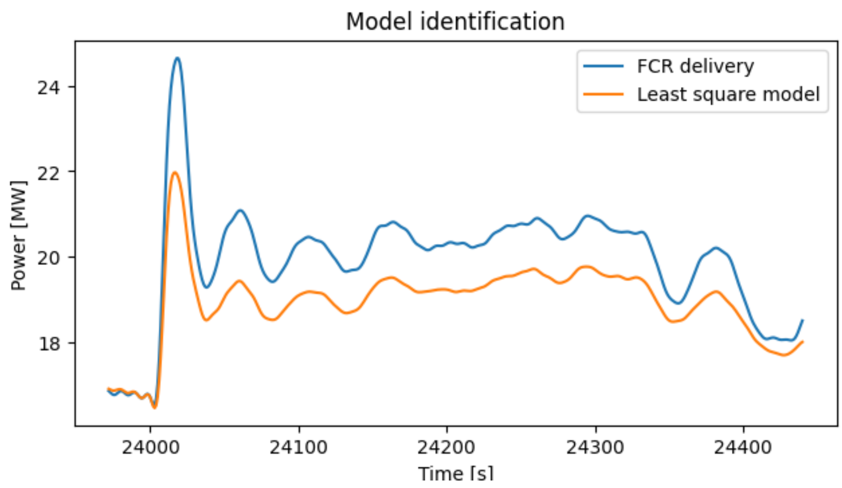


*Figure 24: Constant over delivery in power from provider*

Many deliveries analyzed had a steady state delivery that was higher or lower than the modeled delivery. This causes a problem during the model identification since the least square sum will be large even if the model fits the behavior of the delivery well. To avoid this, the model was multiplied with a delivery constant before the least square is calculated. The delivery constant was calculated using equation (22). The delivery constant can have a relation to requirement 1.

$$delivery\ constant: \ \overline{P_{delivery} - P_{baseline} - P_{FCR-N}/P_{model}} \tag{22}$$

In order to analyze requirement 8 and 9, the full transfer function has to be known. It is hard to determine these requirements solely based on the delivered activation. Thanks to the model identification, it is possible to test for requirement 8 and 9. The certainty of the result is however debatable. The actual power plant can have another characteristic than the modeled power plant, and this can have a great effect on the stability and performance without having much effect on the power response. If it is the correct model that is found is also not certain. To visualize this, two different model responses was simulated, visible in Figure 25. The two responses are from two models with the same PI-regulator, giving them a very similar response. Due to different water time constants and time constant for the guide vane servo, only one is approved. The failed model is far from passing both requirement 8 and 9, and fails even with a requirement reduction factor of 0.75. This shows that there is much that can influence the stability and performance of a plant without being visible in the power response, which affect the reliability of the computer tool when analyzing requirement 8 and 9 of a power delivery.

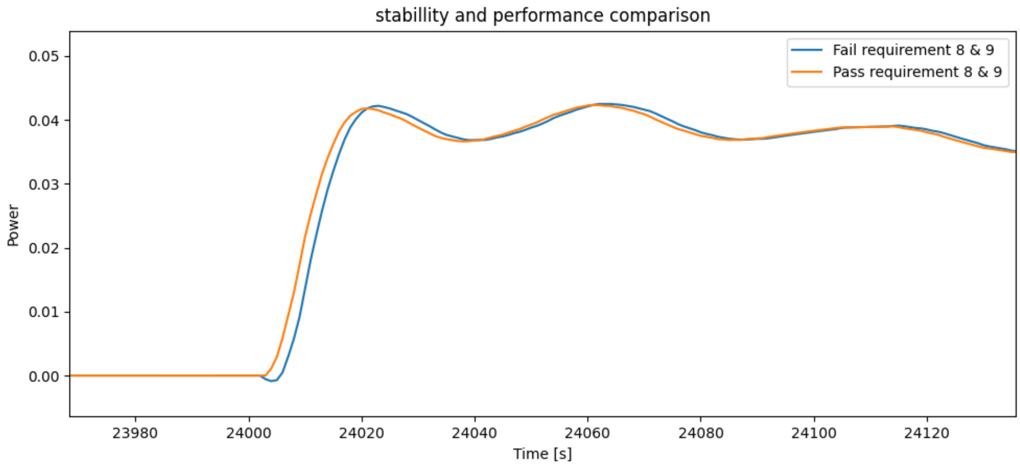


*Figure 25: Comparison of activation between failed and approved model*

## 5.8 TEST OF COMPUTER TOOL USING DISTURBANCE DATA

In order to test the computer tool and how well it works with actual data, disturbance data from recent frequency disturbances where used. The data is taken from three different hydropower entities during tree different disturbances. The hydropower entities will be referred to from now on as plant 1, plant 2 and plant 3.

### 5.8.1 Plant 1

Plant 1 was the plant used during the development of the tool. Plant 1 has a known rated $T_w$, where a participating FCR-D and FCR-N entity during a recent frequency disturbance and the provided data had no errors or complications. The response from the plant also had a very similar shape to the modeled plant response.

Running of the data tool produce several plots, and in addition a printed text in the terminal. The printed text when evaluating plant 1 can be seen in Figure 26.

```
Model identification:

Mean FCR-D power over delivery:  1.6759682299576657

        Droop:  0.04125
        Kp:  2.942528735632184
        Ki:  3.084856894450378
        Tw:  1.5

        Preformance test:

        Kred = 1        Pass =  True
        Kred = 0.75     Pass =  True

        Stabillity test:

        Kred = 1        Pass =  False
        Kred = 0.75     Pass =  False

Requirement 2: Power delivered 7.5 seconds after disturbance [MW]

Requirement 3: Total energy delivered 7.5 seconds after disturbance [MJ]

Requirement 4: Enerrgy overshooting power deleivered at frequency nadir [MJ]


Check for req2 at time: 2402

        Entity FCR-D delivery:   4.6954901555473185

        Limit model FCR-D delivery:

                Total limit model FCR energy:  916.81967347914

                Requirement evaluated after 7.5 seconds:

                Kred = 1:       2.148382727762201      Approved delivery for  req2  =  True
                Kred = 0.75     1.63110788229167       Approved delivery for  req2  with reduction factor =  True


Check for req3 at time: 2402

        Entity FCR-D delivery:   8.718964476163144

        Limit model FCR-D delivery:

                Total limit model FCR energy:  973.9098779265889

                Requirement evaluated after 7.5 seconds:

                Kred = 1:       7.2396732451869905     Approved delivery for  req3  =  True
                Kred = 0.75     5.298860938575078      Approved delivery for  req3  with reduction factor =  True


Check for req4 at time: 2402

        Entity FCR-D delivery:   151.04047104377415

        Limit model FCR-D delivery:

                Total limit model FCR energy:  974.5969628959581

                Kred = 1:       70.06777482135722      Approved delivery for  req4  =  False


Total limit model FCR-N energy 577.9134981190007

Total entity FCR energy:        1703.7953198730793
```

*Figure 26: Printout in terminal when running for plant 1*

The model response most similar to the actual response was found when using a delivery constant of 168%. According to requirement 1, a 20% over delivery is okay, which is much lower than 68%. When analyzing the results, it can be seen that it is the produced power before the disturbance that is lower than the reference power stated in the data. The power production after the disturbance is at the correct level when using the reference power as a base line. Since the tool uses the mean power of the last 10 seconds before the disturbance as base, which is lower than the reference, an increase of 68% is needed to match the delivery. The identified model has a time water constant $T_w = 1.5\ s$. The controller parameters are $K_P = 2.94$ and $K_I = 3.08$.

The controller parameters are not known beforehand, but the values found are in the reasonable span. The time water constant for plant 1 is known however, and is rated at $T_w = 1.31\ s$. The identified value, that only evaluates the response at $T_w = 0.5, 0.6, \ldots, 1.9, 2.0$ is close to the true value but not the closest possible. The response if the identified model response and the actual delivery can be seen in Figure 27 below.

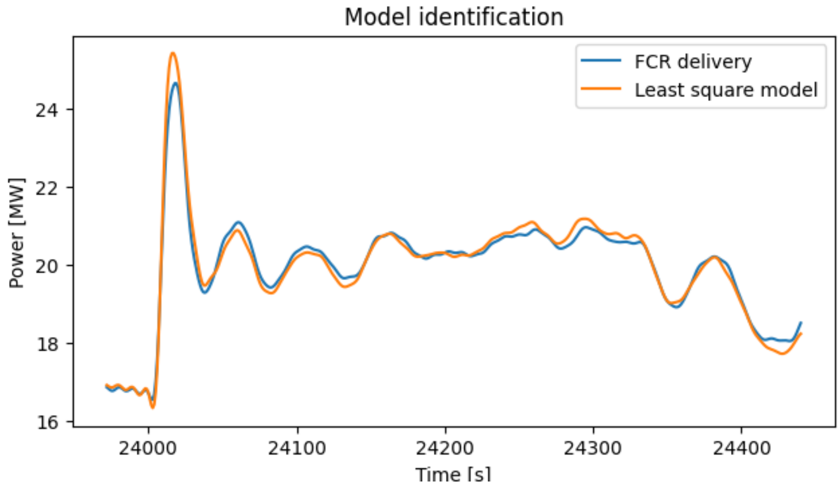


*Figure 27: Disturbance response for identified model and plant 1*

When testing the stability of the identified plant, the model fails both with and without the reduction factor. As described in the section *Check of requirements*, there are several factors that affect the stability of the plant that cannot be seen in the response alone. That the computer tool fails the plant therefore is not a certain sign that the plant is not stable when completing the prequalification test described in section FCR technical requirements. The same can be said for performance requirement 9, but according to the tool the plant passes the requirement with a good margin.

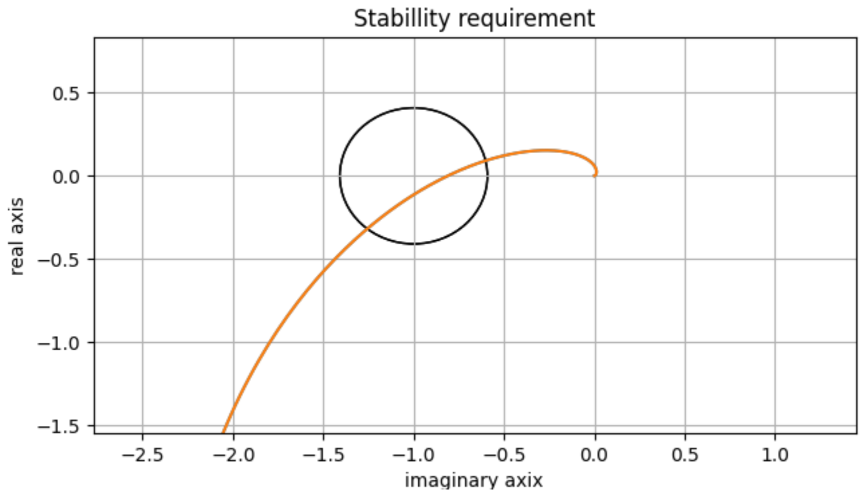


*Figure 28: Stability test for plant 1 identified model*

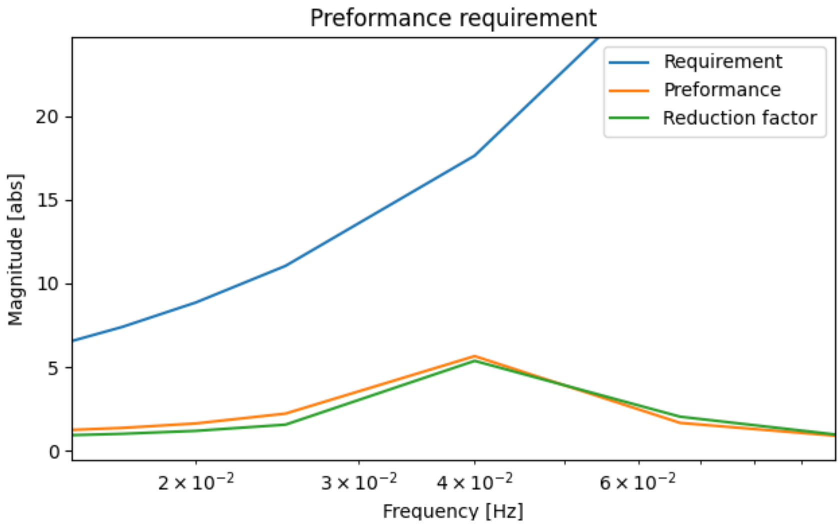


*Figure 29: Performance test for plant 1 identified model*

When analyzing requirement 2, 3 and 4, plants on the limit of passing is used instead of an identified model. If $T_w$ is unknown however, the constant is taken from the model identification. The delivered power after 7.5 seconds is 4.695 MW. Compared to the limit plant response of 2.148 MW, the power activation from plant 1 is sufficient and passes the requirement.

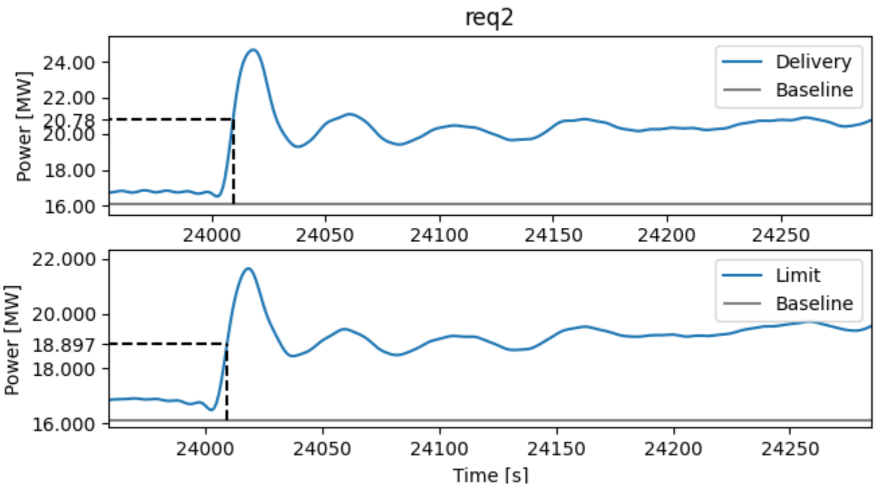


*Figure 30: Requirement 2: Power after 7.5 seconds for plant 1*

The plant delivers 8.719 MJ in the first 7.5 seconds from the disturbance. This value is evaluated from the time that the power goes below the base line, and not from the time instant the disturbance starts. This because the filtering smooths out the signal, including the initial dip. Due to the smoothing, the dip will start just before the actual start of the disturbance. In case of plant 1 and for this disturbance, that means the evaluation begins 2.25 seconds before the start of the disturbance. The limit plant has a total energy of 7.240 MJ, evaluated from 2 seconds before to 7.5 seconds after the disturbance. The actual delivery has enough energy to pass the requirement for activation energy.

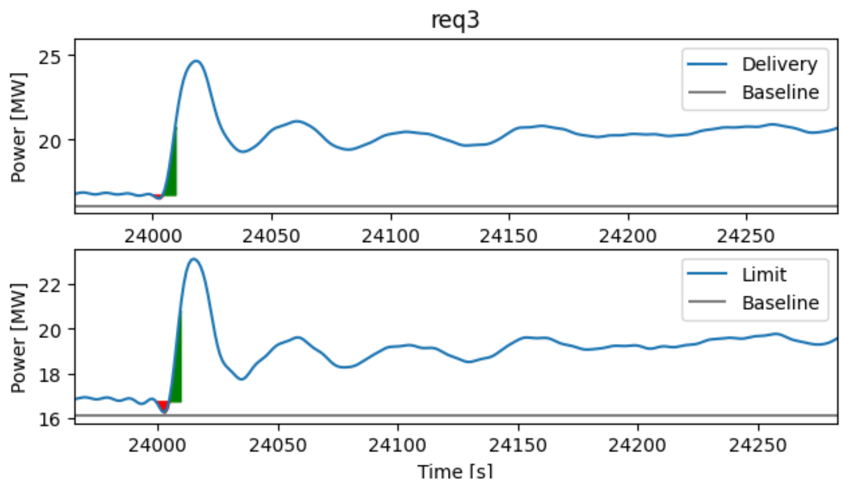


*Figure 31: Requirement 3: Energy after 7.5 seconds for plant 1*

When analyzing requirement 4, the plant does not pass the requirement according to the data tool. The limit plant has a higher base power, $P_{base} = 17.97\ MW$, whereas the actual delivery is evaluated using $P_{base} = 17.57\ MW$. A higher base will reduce the area over the base and hence lover overshoot energy.

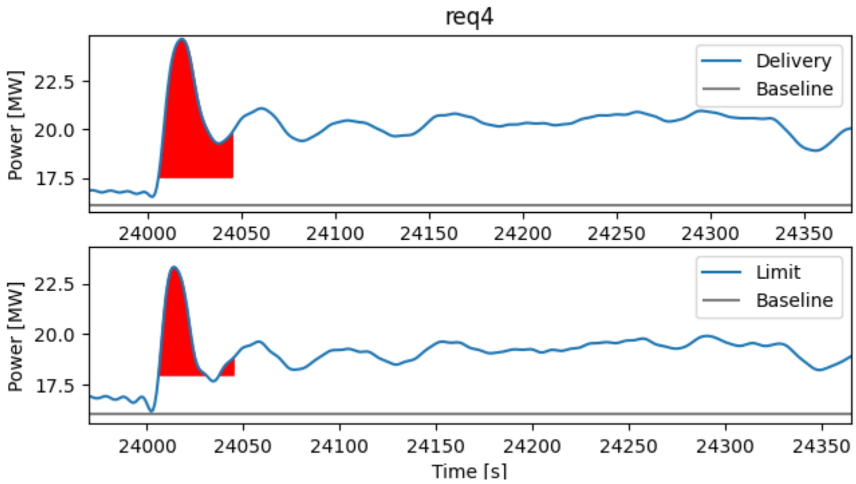


*Figure 32: Requirement 4: Overshoot energy for plant 1*

The total energy activated during the disturbance is 473 kWh. Each of the modeled limit responses had a lower energy. The modeled requirement 2 response had a total energy of 255 kWh, the requirement 3 model had 271 kWh, and the requirement 4 model had 271 kWh.

### 5.8.2 Plant 2

```
Model identification:

Mean FCR-D power over delivery:  1.6750439146129992

        Droop:  0.02666666560555561
        Kp:  10.293103857855597
        Ki:  3.260731860220943
        Tw:  1.2000000000000002

        Preformance test:

        Kred = 1        Pass =  True
        Kred = 0.75     Pass =  True

        Stabillity test:

        Kred = 1        Pass =  True
        Kred = 0.75     Pass =  True

Requirement 2: Power delivered 7.5 seconds after disturbance [MW]

Requirement 3: Total energy delivered 7.5 seconds after disturbance [MJ]

Requirement 4: Enerrgy overshooting power deleivered at frequency nadir [MJ]


Check for req2 at time: 4410

        Entity FCR-D delivery:   2.2702959565598135

        Limit model FCR-D delivery:

                Total limit model FCR energy:  19.028091666548274

                Requirement evaluated after 7.5 seconds:

                Kred = 1:       1.236230528216471     Approved delivery for  req2  =  True
                Kred = 0.75     0.9816462826748681    Approved delivery for  req2  with reduction factor =  True
g:\Division System\Systemutveckling\SYV\06 Projekt och linjearbete\11 Examensarbtete Emma\Utveckling kod\req3.py:108
  1/(test + np.abs(test))                    #If start=0 it moves to expect


Check for req3 at time: 4410

        Entity FCR-D delivery:   7.1263037826832

        Limit model FCR-D delivery:

                Total limit model FCR energy:  25.01918635294462

                Requirement evaluated after 7.5 seconds:

                Kred = 1:       5.039220782537331     Approved delivery for  req3  =  True
                Kred = 0.75     3.9524794815944597    Approved delivery for  req3  with reduction factor =  True


Check for req4 at time: 4410

        Entity FCR-D delivery:   16.566074972463156

        Limit model FCR-D delivery:

                Total limit model FCR energy:  44.087747671268296

                Kred = 1:       13.544998050281192    Approved delivery for  req4  =  False


Total limit model FCR-N energy 4.631253484841998

Total entity FCR energy:        46.00962414327728
```

*Figure 33: Printout in terminal when running for plant 2*

The second plant was analyzed using another disturbance, occurring after the new FCR requirements were put into action. The water time constant of the entity is not known. The plant does however consist of two entities, both with the same head. According to equation (14), the water time constant of two entities with the same head only depends on the initial speed of the water in each entity. The other entity in the plant has a $T_w = 1.92\ s$. The other plant, if the speed of the water is somewhat similar, should therefore reasonably have a similar water time constant.

When running the model identification in the data tool, the time water constant $T_w = 1.2\ s$ was found. Below, the response from the identified model both using $T_w = 1.9\ s$ and $T_w = 1.2\ s$ is shown. The model with a $T_w = 1.2\ s$ (Figure 34) follows the actual response very closely compared to the model with a higher $T_w$ (Figure 35), and is therefore considered a successful result even though it is far from the initial guess of time water constant.

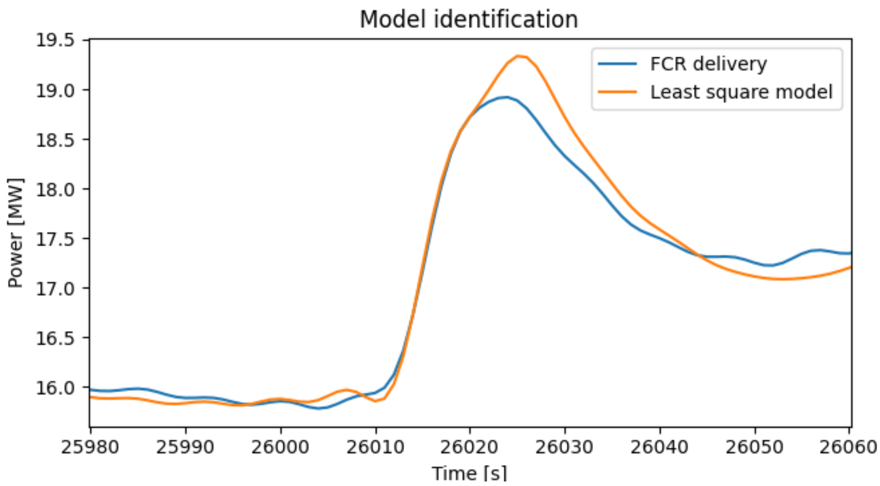


*Figure 34: Disturbance response for identified model with $T_w = 1.2\ s$ and plant 2*

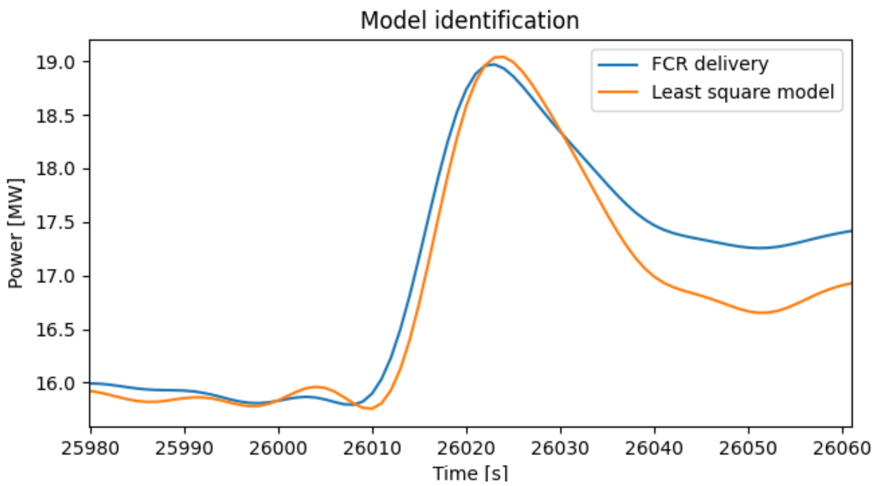


*Figure 35: Disturbance response for identified model with $T_w = 1.9\ s$ and plant 2*

As can be seen in the plot, the disturbance last for a shorter period of time compared to the disturbance used when analyzing plant 1. The plot cuts off when the frequency deviation no longer is big enough to reach the FCR-D band. The identified model pass both the stability and the performance test, which do not necessarily mean the plant would pass the sine tests, but is a good indicator that the model is reasonable. The over-delivery found by the model identification is 68%.

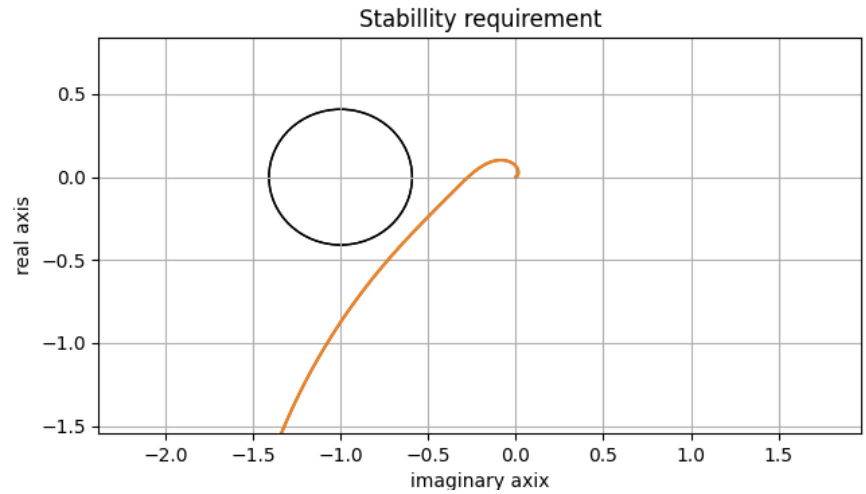


*Figure 36: Stability test for plant 2 identified model*

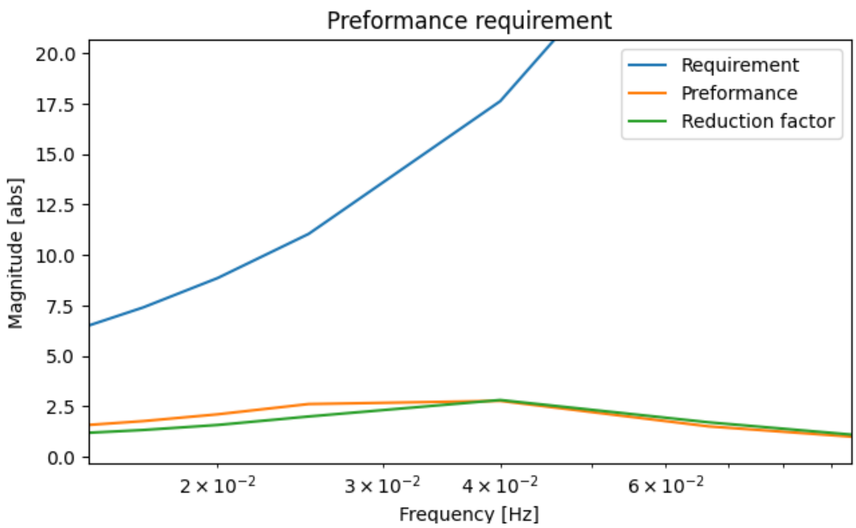


*Figure 37: Performance test for plant 2 identified model*

The plant does pass requirement 2, and with a good margin. 7.5 s after the disturbance, the modeled plant has increased the power production with 1.24 MW. The actual delivery from plant 2 has increased with 2.27 MW, more than 1 MW more than the limit. The response can be seen in Figure 38.

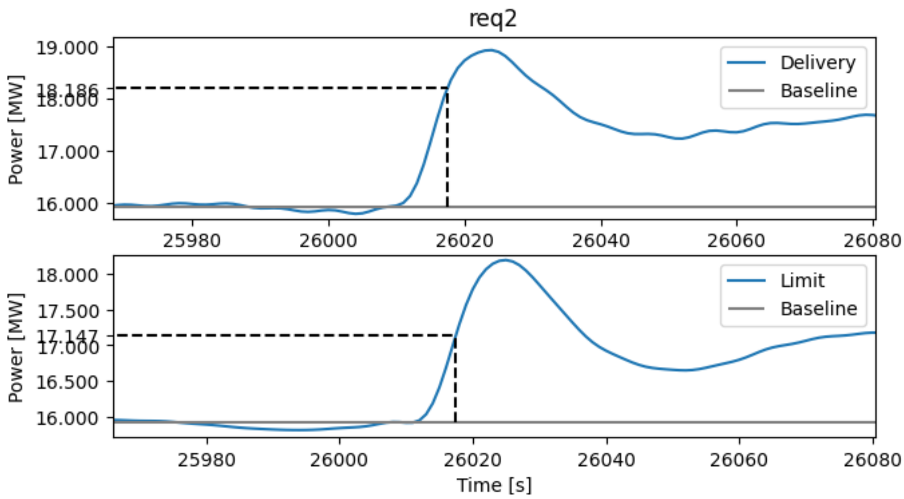


*Figure 38: Requirement 2: Power after 7.5 seconds for plant 2*

The energy from the plant is 7.13 MJ in the first 7.5 seconds, compared to the energy from the modeled plant which is 5.04 MJ. This requirement is passed with a good margin as well.

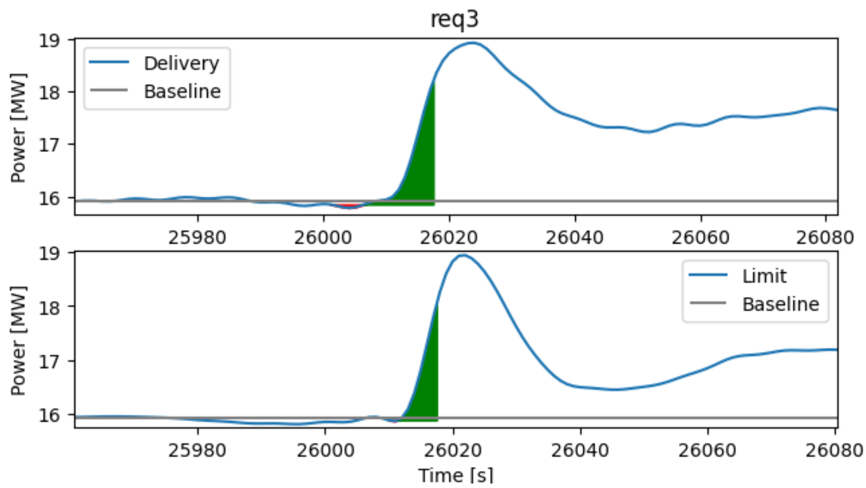


*Figure 39: Requirement 3: Energy after 7.5 seconds for plant 2*

The plant, just like plant 1, do not pass requirement 4. The overshoot in the actual delivery result in an extra energy of 16.57 MJ, which is more than the 13.58 MJ extra delivered by the modeled limit.

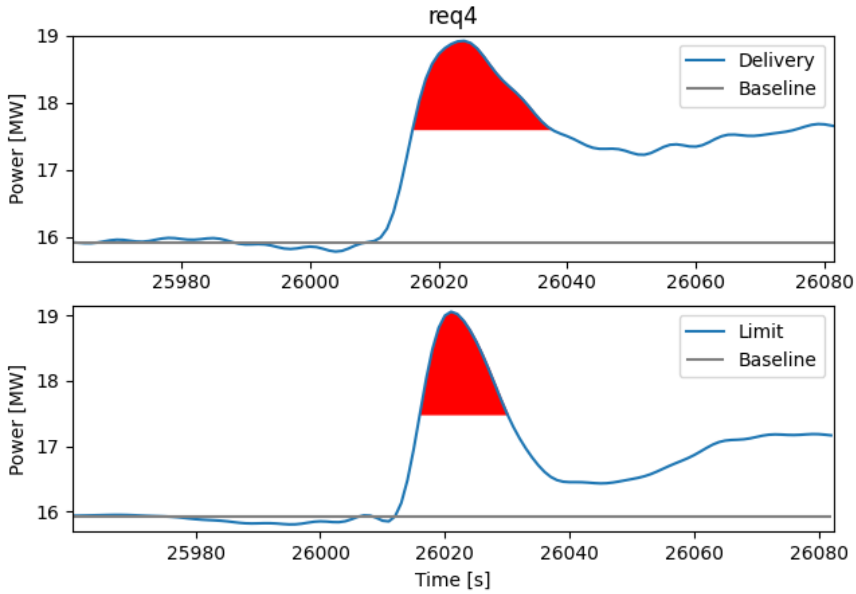


*Figure 40: Requirement 4: Overshoot energy for plant 2*

### 5.8.3 Plant 3

```
Model identification:

Mean FCR-D power over delivery:  0.7911669585396134

Preformance parameters:

        Droop:  0.08109390960985449
                Kp:  4.592376849200433
                Ki:  0.6056654549992665
                Tw:  2.0

        Preformance test:

        Kred = 1        Pass =  True
        Kred = 0.75     Pass =  True


Stabillity parameters:

        Droop:  0.08109390960985449
                Kp:  3.661144877001457
                Ki:  0.5006626770973512
                Tw:  2.0

        Stabillity test:

        Kred = 1        Pass =  True
        Kred = 0.75     Pass =  True

Requirement 2: Power delivered 7.5 seconds after disturbance [MW]

Requirement 3: Total energy delivered 7.5 seconds after disturbance [MJ]

Requirement 4: Enerrgy overshooting power deleivered at frequency nadir [MJ]


Check for req2 at time: 2403

        Entity FCR-D delivery:   19.96650662905361

        Limit model FCR-D delivery:

                Total limit model FCR energy:  5297.661068571015

                Requirement evaluated after 7.5 seconds:

                Kred = 1:       5.108944067933921      Approved delivery for  req2  =  True
                Kred = 0.75     3.7380344174136813     Approved delivery for  req2  with reduction factor =  True


Check for req3 at time: 2403

        Entity FCR-D delivery:   26.176945514377138

        Limit model FCR-D delivery:

                Total limit model FCR energy:  5442.749907702968

                Requirement evaluated after 7.5 seconds:

                Kred = 1:       6.276009963692777      Approved delivery for  req3  =  True
                Kred = 0.75     3.5043124224105386     Approved delivery for  req3  with reduction factor =  True


Check for req4 at time: 2403

        Entity FCR-D delivery:   453.21804039815447

        Limit model FCR-D delivery:

                Total limit model FCR energy:  5327.455367789307

                Kred = 1:       182.6311671809982      Approved delivery for  req4  =  False


Total limit model FCR-N energy 6692.7712445529905

Total entity FCR energy:        9173.49488741285
```

*Figure 41: Printout in terminal when running for plant 3*

The third plant was evaluated using the same disturbance as plant 1. The third plant uses mode shifting for frequency deviations bigger than 0.2 Hz. Using the mode shifting in the model identification, the response can be seen in Figure 42: Disturbance response for identified model with mode shifting, $T_w = 2\ s$ and plant 3. The response differs a lot form the actual delivery from the plant. The model found has a time water constant $T_w = 2.0\ s$, when the time water constant stated by the provider for the entity is $T_w = 1.3\ s$. The model identification finds an under delivery of 21%.

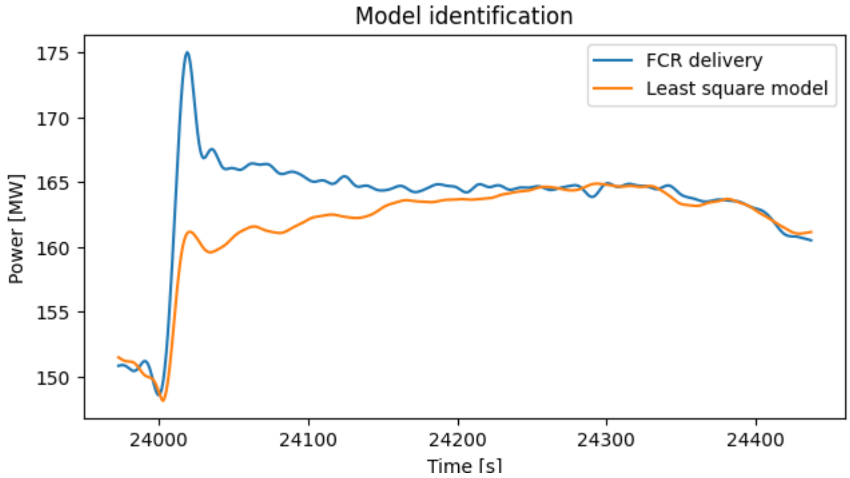


*Figure 42: Disturbance response for identified model with mode shifting, $T_w = 2\ s$ and plant 3*

The identified model has both stability and performance parameters. It is the performance parameters that has to fulfill the performance requirement, and the stability parameters that should fulfill the stability requirement. This is the case for the identified model. Performance is approved, and the plant fulfills the stability parameters. The stability and performance can be seen in Figure 43 and Figure 44.

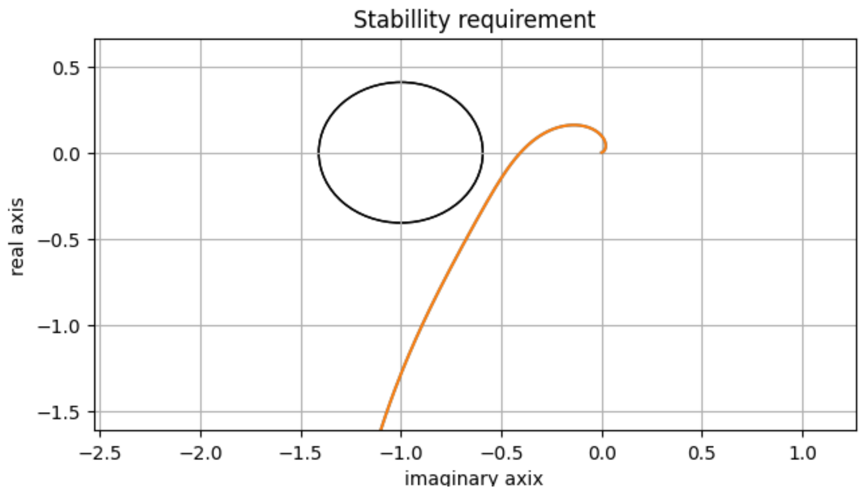


*Figure 43: Stability test for plant 3 identified model*

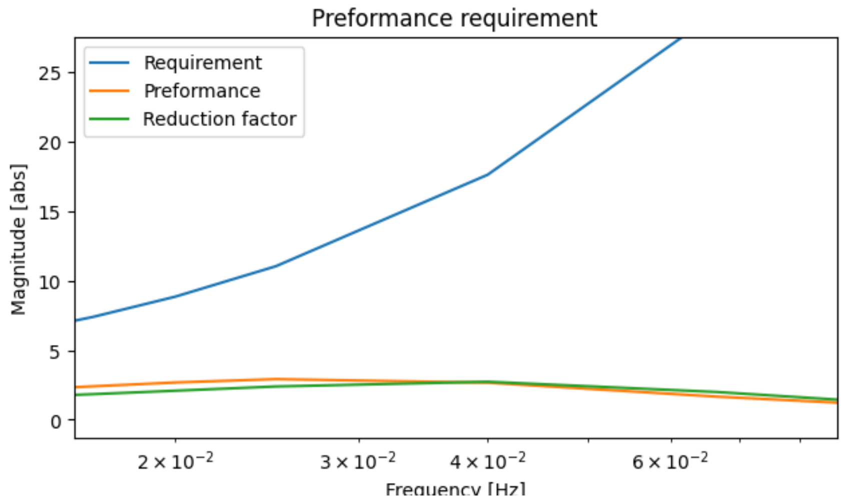


*Figure 44: Performance test for plant 3 identified model*

The plant pass both requirement 2 and 3. When evaluating requirement 2, the limit model has an activation of 5.11 MW, whereas the actual delivery is 19.97 MW. During the evaluation of requirement 3 the model has an energy of 6.28 MJ, and the actual delivery is stated to be 2618 MJ.

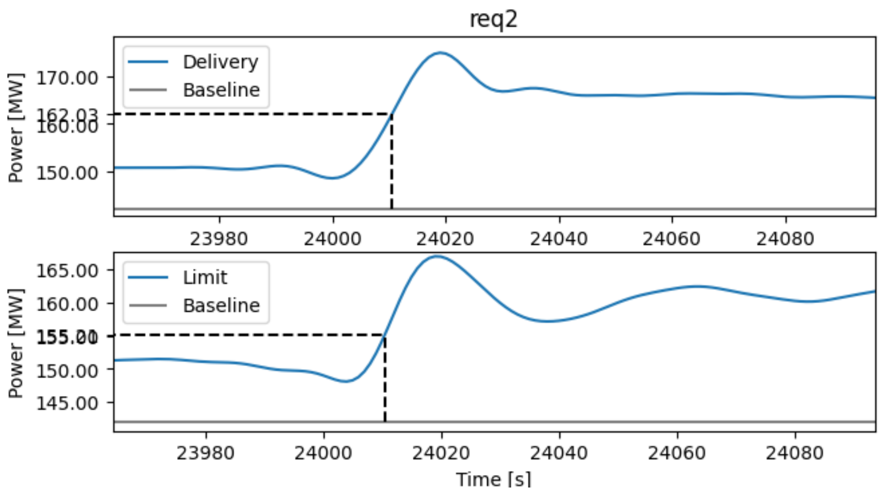


*Figure 45: Requirement 2: Power after 7.5 seconds for plant 2*

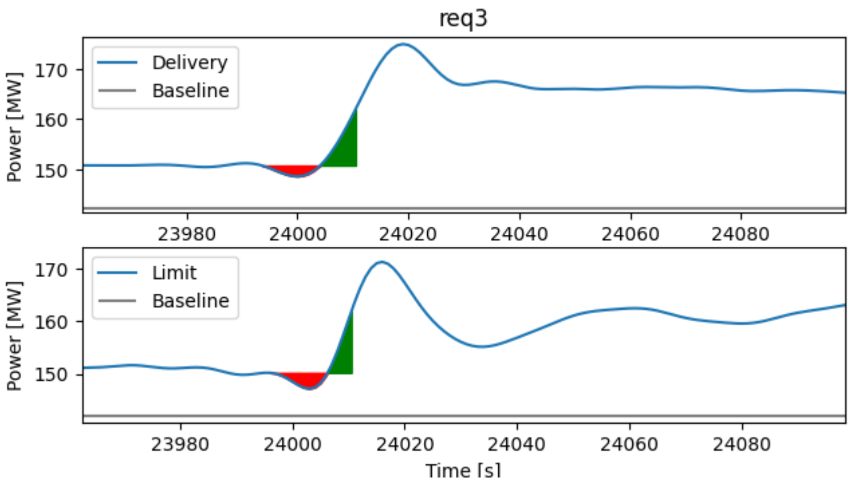


*Figure 46: Requirement 3: Energy after 7.5 seconds for plant 2*

The actual power during the frequency deviation peak is lower than the steady state FCR-D response, leading to a very large overshoot energy that continues to grow for the whole 40 evaluated seconds

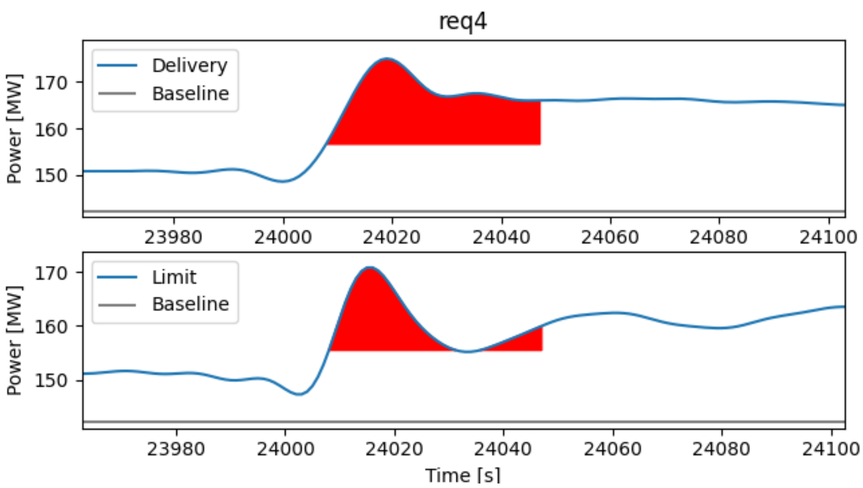


*Figure 47: Requirement 4: Overshoot energy for plant 1*

# 6 Conclusion

The computer tool seems to work for requirement 2 and 3. In order to properly determine the accuracy of the tool a larger amount of data need to be tested. It would also be interesting to test the tool together with the old method of verification to compare the difference in results. For requirement 4, 8 and 9 however there is great uncertainty in the results and the new method cannot be used for an accurate verification.

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