Hybrid Power Plant Control with Electrolysers

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Abstract:

After a frequency event occured in the grid, frequency services will be activated in order to restore the frequency back to its nominal value. In this thesis, technologies aiming to restore the frequency during the third stage of ancillary services is looked into. Also, technology related to electrolysers are analysed in depth to provide a suitable response for the hybrid power plant. The hybrid power system will comprise of a 24.6 MW wind farm and a 12 MW electrolyser stack in DK1 region, with the hybrid power plant control being the top level controller controlling the dispatch strategy of the sub assets. A control strategy aiming to imitate the up and down regulation during the frequency service is done and tested in simulation environment.

The results shows that the designed controller managed to dispatch the reserved volume according to the input signal and the controller is stable for this purpose. The finding and conclusion are summarised in the conclusion.

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Preface

This report was written as a part of the Wind Power Systems Master's programme which was from Febuary to June 2023 in Aalborg University. The theme of this project is to coordinate and control the active power with different assets in a hybrid power systems to provide frequency support service. The project involve in coordinating a wind farm and electrolyser to provide active power in order to support the grid frequency, and designing control structures for the hybrid power plant and sub-assets.

The author would like to express his gratitude towards the main supervisor, Associate Professor Florin Iov for providing guidance, help and more importantly, his insight and knowledge towards this topic and more. The author would also like to thank Alin George Raducu from Vattenfall for offering his support, giving a chance to the author for gain insight in a company and more. Also a huge thanks to Kanev Stoyan and the rest of the SCADA team for providing support as well. Last but not least, the author appreciate all the help and support provided by his family, friends and colleagues during this time.

Reading guide

The contents that were related to other sources are cited with IEEE style. The numbering of the tables and figures are according to the chapter. If the figure and table belongs in chapter 2, it will starts from table/figure 2.1, 2.2 and so on. Description for tables are found on top of the table and below for figures.

Jun Chen Hoo

Preface

The theme chosen for this project is based on the proposal from Vattenfall, where they had managed to develop and implemented their own HPP controller in their assets. The main focus on this project is related to active power and frequency and the controller design and the hybrid power plant system will only be dealing with these.

The content of the report is divided into 6 different chapters and the overview of the chapter will be summarised in this summary. Chapter 1 state the overview of current renewable energy system in Denmark, including hydrogen. Also included in this chapter are the state of the art regarding electrolysers, motivation, related grid codes for frequency services, problem statement, objective, methodology and limitation are clearly stated in this chapter.

In chapter 2, the sizing of the system is done based on analysing the data provide by Vattenfall. The logic for the sizing is explained based on the capacity factor and location of the system. Also, review of aFRR frequency services is presented based on the literature from Energinet along with the minimum requirements of reaching up to 90% of the reserved volume in less than 12 minutes. Chapter 3 shows the modelling methods for the plants, controllers and grid. The HPP controller will take information from the TSO, wind farm and electrolyser to determine the setpoint for the controller. Different dispatch strategy on both upwards and downwards regulation are explained. The external grid is modelled using Thevanin equivalent.

Model of controllers are developed in MATLAB and Simulink. These are explained in chapter 4. The controller are represented as a first order transfer function. Losses are included in the hybrid power plant and wind farm controller. It is determined by using DIgSilent PowerFactory with cable parameters. Discretised PI controller with anti windup is used to prevent the saturation. All the controller are stable considered stable with the design and tuning done. Chapter 5 shows the simulation of the whole system where up and down regulation signal is implemented along with different dispatch function. Chapter 6 contains the conclusion of the project and the possible improvement work for the future for this project.

Nomenclature

Abbreviations	Definitions
CF	Capacity Factor
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FRR	Frequency Reserve Restoration
HPP	Hybrid Power Plant
OEM	Original Equipment Manufacturer
PEM	Proton Exchange Membrane
PCC	Point of Common Coupling
PMSG	Permanent Magnet Synchronous Generator
POC	Point of Connection
PtX	Power to X
SCADA	Supervisory Control And Data Acquisition
TSO	Transmission System Operator
WF	Wind Farm
WT	Wind Turbine

Contents

1. Introduction

1.1 Background and Motivation

Denmark has been ranked top on the list of green energy transition within the European nations and recently the country has introduced a 70% reduction of in greenhouse gases in 2030 and carbon neutrality in 2050 [1]. This could be achieved with different methods, where the main focus of is on the energy production sector. Denmark has a strong wind industry along with some of the top companies for this industry in the world and this would further strengthen the country's position in the energy transition. In 2022, Denmark acquired approximately 54% of its electricity production from wind energy alone [2]. There are plans to further increase the wind energy production in the Baltic sea by 3 GW and 10 GW in the North Sea [3].

These increase in the energy production imposes several challenges to the system, and one of those is energy storage. While Denmark is well connected to the neighbouring countries through interconnectors which ensures the energy security, by building energy storage system, the country will achieve more energy security in the long term. Currently, conventional energy storage system such as Battery Energy Storage System (BESS) are used in the grid for energy storage and frequency smoothing purposes in terms of Frequency Containment Reserve (FCR) and Fast Frequency Response (FFR) as they can respond to grid disturbance in a very short time span. With the increasing energy production from wind energy, integrating electrolysers into the system will be beneficial given the production uncertainties from the wind farms. These electrolysers will convert electrical energy to hydrogen. This initiative is called Power to X (PtX) and it has gained a lot of attention in recent years due to the application of hydrogen in different industries.

Hydrogen is used in various industries, such as transport, power sector and heavy industries. Typically, hydrogen production is done via Steam Methane Reforming (SMR) with the use of natural gas. With Carbon Capture and Storage (CCS) technology, the hydrogen produced is called blue hydrogen while without CCS, the hydrogen is called grey hydrogen. Along with the growth of renewable energy, production of green hydrogen is rising. Green hydrogen is produced with renewable energy such as wind or solar power without any consumption from the grid. The percentage of each grey, blue and green hydrogen production in the year 2018 is shown in figure 1.1. Alkaline electrolyser or Proton Membrane Exchange (PEM) is used to convert electricity into hydrogen. Each technology has its own advantage and disadvantage which is shown in table 1.1.

The electrolysers can be connected in two ways, which is centralised or decentralised. With centralised connection, electrical energy is typically produced at another location and sent to a common point, where the electrolysers will be located there. This could also be explained where for e.g. the wind farm is connected to the same PCC as the electrolyser and the hydrogen will be transported to the end user via pipelines or truck. While for decentralised connection, each individual WT is connected to an electrolyser of its own at the same POC. Typically, centralised hydrogen electrolyser benefits from the scaling up of the electrolyser modules due to its increasing efficiency at scaling up while decentralised hydrogen electrolyser benefits from having a dedicated power supply of its own as shown in figure1.2.

Table 1.1: Advantage and disadvantage of Alkaline and PEM electrolysis [4] [5]

	Disadvantages	Advantages
Alkaline electrolyser	Lower lifespan Lower gas purity Slower reaction time Lower operational pressure	Well established technology Relative low cost Non noble catalyst
PEM electrolyser	Commercialisation only begin Relative higher cost Platinum based catalyst	Longer lifespan Higher gas purity Faster reaction time

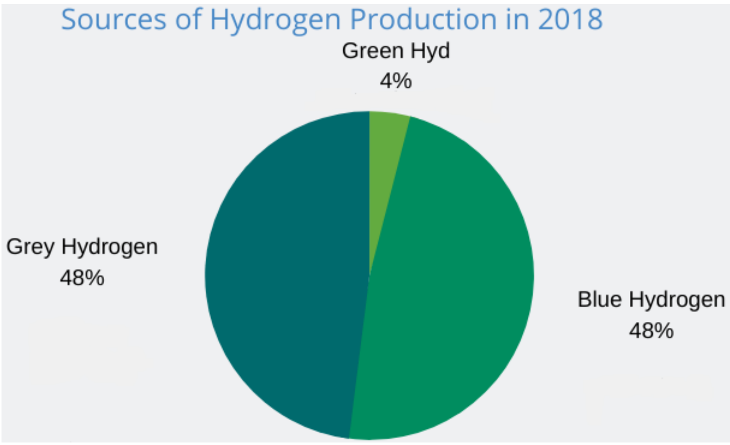

Figure 1.1: Share of hydrogen production from different sources
[6]

The addition of electrolysers present a new opportunity for it to participate in the ancillary market. Previously, there is no guideline for electrolysers to participate in these markets. Recently, Energinet published studies related to the participation of electrolysers in FCR and FRR [7]. The placement of the electrolyser is crucial due to the ancillary services requirement differences between DK1 and DK2. If the electrolyser is operating at a maximum load, it can participate in the regulation market by consuming less electricity. When the electrolyser is operating at a partial load and more electricity can be consumed to produce hydrogen [8].

With all these assets combined and the expectation of participating in ancillary services, a hybrid power plant controller is required to coordinate the active power production and frequency control while complying to the Danish grid codes. The dynamics between the WT and the electrolyser has to be considered as both WF and electrolysers will have different reaction time and the state of the electrolyser during the operation. These response time can be adjusted in the hybrid power plant controller to allow assets with faster response to dispatch first.

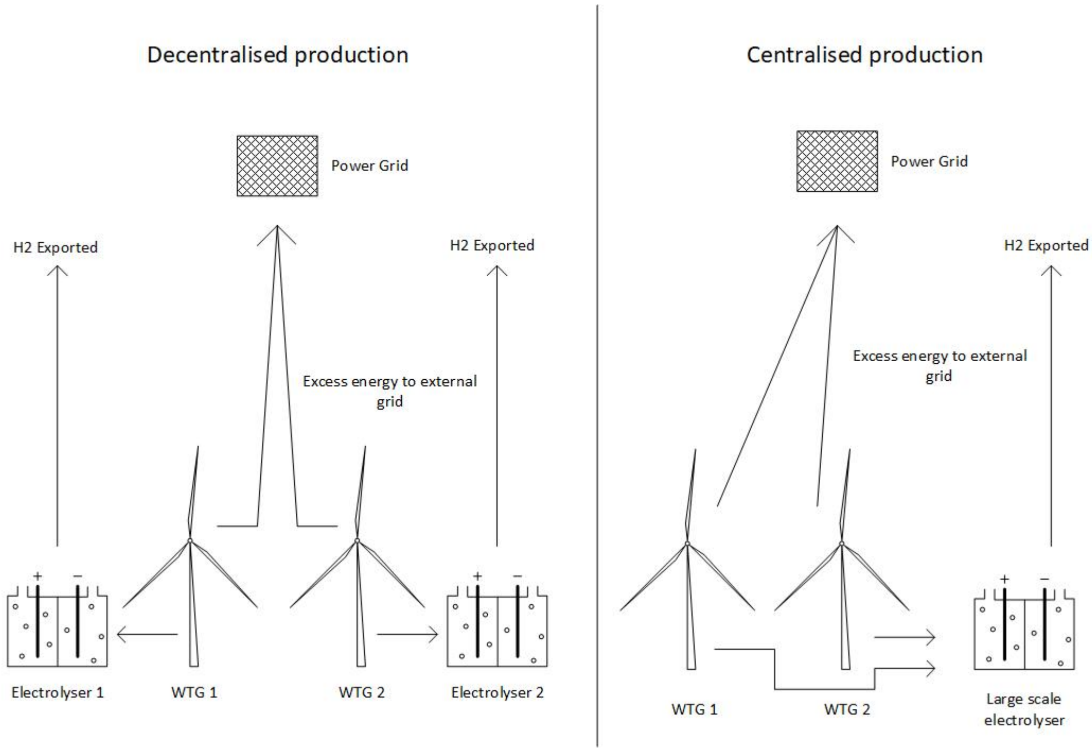

Figure 1.2: Decentralised vs centralised production of hydrogen

1.2 State of Art

When integrating electrolyser system together with wind systems, it is crucial to consider technology of the electrolyser used as this has a significant effect on the system such as response time, Balance of Plant and more. Besides, the electrolyser can have different types of converter topology and this will have an effect on the grid.

Firstly, to operate the electrolyser, the current has to be in DC current, thus a AC-DC converter is required so that it could run properly. In [9], converter topologies is discussed where 6 pulse, 12 pulse, 24 pulse rectifier and Active Front End (AFE) rectifier is discussed. 6 pulse rectifier and 24 pulse rectifier will not be further looked into, as 6 pulse rectifier introduces high total harmonics distortion (THD) into the grid while 24 pulse rectifier are too costly, thus making it less economical than AFE topology [10]. With the 12 pulse thyristor rectifier (12-TR), the electrolyser are controlled by adjusting the firing angle of the thyristor rectifier. During low power conditions, it will introduces more harmonics to the grid due to current spikes when the thyristors are turned on [11]. This is mitigated by using line frequency transformer for the 5th and 7th harmonics while passive trap filter for 11th and 13th harmonics which are common in the electrolyser converter. Reactive power compensation will be required for this topology as it consumes reactive power and this can be done via VAR compensator.

Meanwhile the AFE utilised IGBTs in the converter and this prodeces much less harmonic distortion. This is done by controlling the duty ratio of the IGBTs. A table comparing the harmonic current components is shown in table 1.2. For AFE, no reactive compensation is required. Ultimately, breaks down to the costs and complexity of the topology. With 12-TR, it is simpler to control but introduces more harmonics to the grid and require reactive power compensation, thus increasing the cost on filtering and reactive power compensation and vise versa for the AFE. Also

Table 1.2: Harmonic distortion in different rectifier topology [9]

	Fundamental	5th	7th	11th	13th
6-pulse rectifier with passive filter	100%	3%	3.3%	3.5%	2.3%
6-pulse rectifier with active filter	100%	2.3%	2.5%	2.6%	1.7%
12-pulse rectifier with double wound transformer	100%	3.6%	2.6%	7.5%	5.2%
AFE	100%	0.7%	1.4%	1.0%	0.7%

critical in the system are the type of electrolyser. The electrolyser have to be chose carefully as it will have an impact on the ramp rate, Balance of Plant (BoP) of the system and more. PEM electrolyser has a faster ramp up and down time compared to alkaline electrolyser. From [12], although the size was on kW scale, it shows that PEM has a faster ramping rate and given a larger changes of load. It shows that PEM could react in milliseconds and it is essential if the system is providing ancillary services to the grid. Meanwhile for alkaline electrolyser, it will take up to seconds for it to respond and this might cause a mismatch between the changes of wind speed and the loading of the electrolyser. However, with pressurised alkaline electrolyser, the system has a faster response time at a cost of higher degradation rate [13]. But the response time of the pressurised alkaline electrolyser is still slower than PEM. It it worth to mention also that being a pressurised system, the actual response time might be slower as it involves the pressurisation system and also the flow of the electrolytes and this might cause a further delay in real case scenario.

Regarding the BoP of the system, there are differences between the different type of electrolysers. Firstly, PEM typically operates at a lower voltage (1.75 V) compared to alkaline electrolyser (1.85 - 2.05 V) [14]. PEM also has a higher current density compared to alkaline electrolyser, at 1.0 - 2.2 A/cm^2 compared to 0.2-0.7 A/cm^2 [15]. This is the reason that PEM has a faster response time and ramp rate compared to alkaline electrolyser and it is more suitable to be used in providing ancillary services. Another aspect is the purity of water used, with PEM, the water has to be of 99.9995% and 99.99% according to [16]. Thus depending where the water treatment facility is, the BoP will be affected as higher purity water will consume more power.

Most of the electrolyser stack on the market are currently less than 1 MW in terms of scale, and the stacks have to be connected together to be scaled up. The stacks can be connected with series connection, parallel connection or a hybrid of both series and parallel connection. Depending on the application, these connections has its own advantage and disadvantage. When connecting in series, the voltage output of the stacks can be increased, which might be beneficial for electrolyser that require higher voltage such as alkaline electrolyser. This comes with disadvantages, one such problem is with series connection, the complexity and cost of the electrolyser will increase as more controls and components is required to maintain the voltage and current level. Even distribution of current has to be ensured [17]. Also, connecting it in series might decrease the operation functionality when one of the stack fails. While for parallel connection, the total current output can be increased. This is particular useful for PEM as it operates on a higher current density. This also gives higher reliability and reduces downtime when one of the stack fails as the module will still operate as it is connected in parallel configuration. However, connecting electrolysers in parallel might require more space than in series [18]. Nonetheless, in most cases, the electrolysers are connected in a combination of both series and parallel to achieve the requirement needed for it to operate.

Current studies mostly focuses on a smaller scale research, in combination with wind systems less than 10 MW. This shows that there are lack of studies in a hybrid power plant level, and no clear control strategies regarding the coordination of wind turbine and electrolysers is studied.

1.3 Grid Codes

With the increasing penetration on renewable energy into the grid, the power system face the problem on frequency balancing. A power disturbance on the grid will cause the imbalance of frequency on the grid, for example, on the 26th of April 2023, 1.1 GW of capacity was disconnected from a nuclear power plant in Sweden and this causes the grid frequency to drop to a minimum of 49.3 Hz which can be seen from figure 1.3.

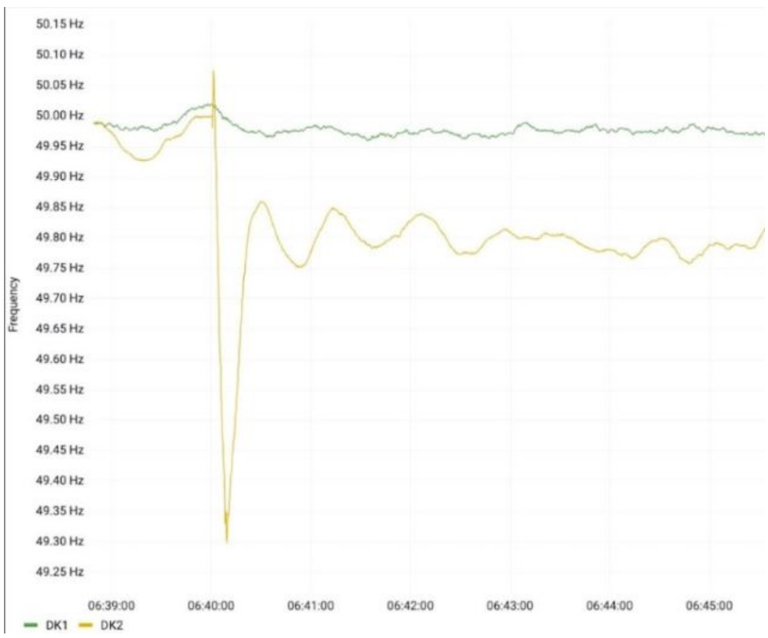

Figure 1.3: Swedish grid frequency on 26th April 2023

With event like this, a 'backup' is required and this is where the system services comes in. On an interconnected grid, assets owners can bid into the market and for a bigger 'pool' of services. Figure 1.4 shows the different stages for for frequency restoration services after a drop from the nominal frequency. When there is a frequency event, point A is depicted as the starting point in figure 1.4, FFR will first be activated until it reaches point B which is the Nadir, where the lowest point of the frequency drop. After that, FCR will kicks in until it reach steady state at point C. Do note that a second dip might occur if there is a mismatch from the demand side and generation side, and this will happens more easily in a system with a particular low system inertia [19]. Typically, the second dip will have a smaller amplitude compared to Nadir, however it will present more damage to the power system as unnecessary load shedding will occur [20]. FRR will then be activated to restore the grid frequency back to the nominal frequency.

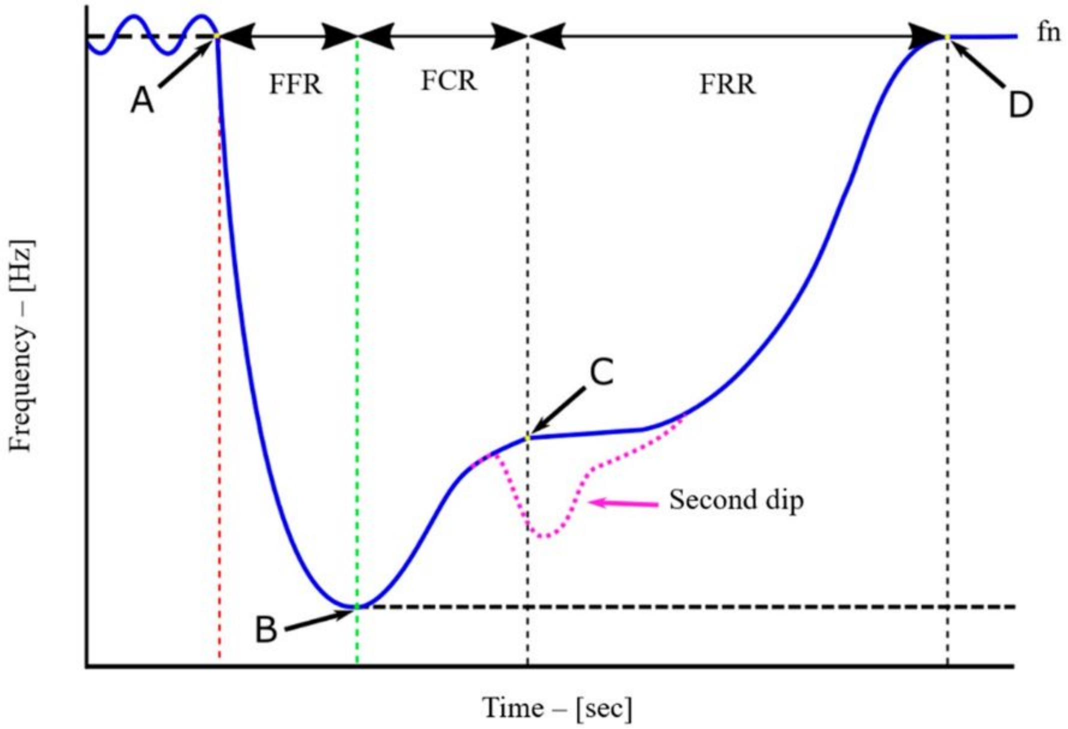

Figure 1.4: Typical frequency response curve

1.3.1 Fast Frequency Reserve

FFR is activated to reduce large frequency dips by adding fast up-regulation to the grid. Demand Side Management (DSM) could disconnects or reduce the load consumption to provide FFR services. From [21], FFR services is provided by reducing the demand from water heater or with solar PV and BESS. Otherwise, it could also be done by ramping up fast response units.

While FFR sounds similar to inertial response, they are two different services. Inertial response represents the kinetic energy stored in rotating masses such as turbines. Inertial Response resists the frequency change due to the imbalance of supply and demand and it acts in a way that it is uncontrollable due to its behaviour on balancing the generation and demand. However, with FFR, it could only provide frequency support by controlled by calculated power injection to the grid [22]. This could be achieved by using different methods including synthetic inertia, virtual synchronous machine and more [19]. When downwards frequency changes is detected, FFR has to be activated within 0.7 s to 1.3 s according to [23].

1.3.2 Frequency Containment Reserve

FCR services starts after Nadir is reached. FCR will be activated based on the frequency deviation. It must be fully activated within 30 seconds following the detection in frequency deviation and it has to be maintained for a minimum of 15 minutes. In Denmark, as the power systems is separated into 2 areas which were DK1 and DK2, and both the area have different system regarding the approach of FCR. In DK1, the grid is connected to the European synchronous area while for DK2, it provides frequency services to the Nordic grid.

FCR services in DK2 is separated into 2 different services, namely FCR-N and FCR-D. FCR-N will only be activated between 49.9 to 50.1 Hz while FCR-D will be activated from 49.5 to 49.9 Hz and 50.1 to 50.5 Hz [23]. Full activation of FCR-N has to be done in less than 150s and to be maintained for 15 minutes. For FCR-D, half of the reserve must be activated in less than 5s and another half must be activated in less than 25s subsequently. It should also be activated for a minimum on 15 minutes.

From [19], the author mentioned that the 15 minutes rule does not apply to renewables due to its dependency on weather condition. [24] also mentioned that while renewables can participate FCR services, it is less profitable than producing energy as the plant will have to run at partial load and thus assets owners are less willing to participate in the balancing market. Also from [24] mentioned that a change in the market structure has incentivised more wind energy to participate in the balancing market. Complementing together with fast reacting storage system, this could be one of the solution for this issue.

1.3.3 Frequency Restoration Reserve

FRR is separated in two different categories, with aFRR that is used to release the FCR service by restoring the grid frequency back to 50 Hz and ensuring the imbalance on other participating assets is back to the agreed level [25]. Meanwhile for mFRR, it is activated when there is an unplanned fluctuation in supply or demand to stabilise the grid. In Denmark, Energinet predicts the imbalance and activates mFRR to mitigate the fluctuations.

1.4 Problem Formulation

This project is done in collaboration with Vattenfall A/S. The company has multiple renewable assets around Europe. One such assets is Haringvliet, which is located in the Netherlands. This asset includes 22 MW of wind power, 38 MW of solar PV and 12 MW of battery energy storage system. This is similar in terms of a hybrid power plant controller providing setpoints to the assets under its control [26]. With PtX gaining more attention and based on current technology of electrolyser, it is important to determine and understand the behaviour on the electrolyser used. With many research and works done on this topic, it is time to dive further into this topic regarding the implementation of a larger scale of electrolysers, together with a wind power system. Only recently the Danish TSO drafted a technical documents regarding the requirements for electrolyser to participate in the ancillary market that will provide FCR and FFR [27]. It is known that electrolyser has the ability to participate in the market and more have to be looked into, in terms of suitability with appropriate strategies. The electroyser will have to follow the setpoint dispatched by the hydrid power plant while tracking the power output that is generated by the wind turbine. This is particularly important as the electrolyser will have a different response time compared to wind power plant.

1.5 Objectives

The objectives of the project are:

- Develop, tune and implement the Hybrid Power Plant Controller with capability to control active power and frequency according to Energinet and providing ancillary services such as aFRR by fulfilling the requirements at DK1 area.
- Optimise the operation of electrolyser through dispatch strategies.
- Verify operation of Hybrid Power Plant Controller through simulations.

1.6 Methodology

Through the projects, different methods has been used to investigate and analysed thoroughly on the main objective. Analytical approach has been utilised to determine the main challenges where the response of wind turbines along with the electrolysers. Given that the integration of electrolysers is still relative new in this field, feasible sizing and analysis is done. As the aim is to produce only green hydrogen, this will be a challenge for the HPPC. Data is obtained from Vattenfall A/S and public domain to be used in the modelling.

The model is done in MATLAB and Simulink, where the HPPC is modelled and analysed. Simplified and aggregated model is used on the wind turbine system and the electrolysers as fast reaction of the system is needed. It is deemed that complex model will slow down the simulation time and creating overruns if it was to put into HIL test, where the plant model runs slower than the controller and this will create inaccuracies.

1.7 Scope and Limitations

The project is done under some limitation due to lack of resources such as data sheet. Assumptions have to be made regarding the projects and the limitation to ensure that the HPP can be developed and run smoothly. This include:

- The model is done in RMS domain to analyse the dynamics of the grid instead of EMT simulation as the transient response is not the goals of the project.
- The impact of converter control for each individual wind turbine and electrolyser is neglected considering harmonics compensation and reactive current injection.
- Wind turbine model is modelled in first time order response and it is regarded as accurate for a system that require fast simulation time.
- Information on electrolyser such as ramp rates has to be estimated due to the lack of infromation from public domain.
- The electrolyser is modelled as a single aggregated unit.
- Details on BoP of the electrolyser such as water pumps, pressure system, cooler etc are not modelled as well as the chemical reaction that is occurring.

1.8 Content of Report

- ***Chapter 1*** of this report contains the background of the topic, problem statement, objectives, general grid codes and limitations of this topic.
- ***Chapter 2*** presents the system characterisation and sizing where how the size of wind farm and electrolyser is chosen. This chapter also contains the grid codes where the HPPC must comply with.
- ***Chapter 3*** shows the hybrid power plant model and control, including the architecture of each components and how it is modelled.
- ***Chapter 4*** consists of the tuning methods for the controller, and the definition of each parameter in the controller.
- ***Chapter 5*** includes the results based on different case studies. Analysis and discussion are based on the results are also included in this section.
- ***Chapter 6*** will states the conclusion and possible future work which will inprove the performance and accuracies of the model.

2. System Characterisation and ancillary services

2.1 System characterisation and sizing

A hybrid power systems is defined as a system that comprised of more than one source [28], and in this case, it consists of a combination of wind energy and electrolyser. Hybrid system is gaining more attention as the assets in a system typically complement to each other, as wind speed is typically lower on sunny days and vice versa.

The system is chosen based on Haringvliet configuration as an example due to the type of project it is, where a hybrid power plant controller is used to dispatch setpoints to different assets. However, multiple criteria are considered carefully before deciding a site for the WF and the electrolyser, including the sizing of the electrolyser. The criteria includes the average wind speed of the site, proximity to transportation hub, capacity factor of the site and more.

Existing site with capacity between 20 MW to 30 MW is looked into and 2 sites are looked into, which are Tjæreborg Enge WF and Nørrekæer Enge WF. Tjæreborg Enge WF consists of 8 WTs with current rated capacity of 19.5 MW and it is located near Esbjerg while Nørrekæer Enge WF consists of 13 WTs with rated capacity of 29.9 MW and located approximately 30 km east from Aalborg city.

Location wise, Tjæreborg Enge WF has more advantage as is it located in Esbjerg and with its proximity to the port, transportation cost for the hydrogen produced will be low and it can be use by the ships that potentially runs on hydrogen in the future or connected to pipelines that will be build for the energy islands. With Nørrekæer Enge WF, the location is less ideal as it is located inland and far away from ports and major city which will further increase the operation cost due to the transportation needed. Next, comparing the average wind speed of both location in year 2020, it is found that Tjæreborg Enge WF had a wind speed of 7.53 m/s at the height of 60 m. For Nørrekæer Enge WF, it had an average wind speed of 8.17 m/s at the height of 80 m. To make a fair comparison, the wind speed at Tjæreborg Enge WF is converted from the height of 60 m to 80 m by using the logarithmic height formula [29]:

$$\overline{V}_H = \overline{V}_{ref} \cdot \frac{ln\frac{H}{z_0}}{ln\frac{H_{ref}}{z_0}} \tag{2.1}$$

where:

- $\overline{V}_H$ = Wind speed at the hub height $[m/s]$
- $\overline{V}_{ref}$ = Wind speed at the mast height $[m/s]$
- H = Hub height $[m]$
- H_{ref} = Mast height $[m]$

- z_0 = Roughness length $[m]$

Thus the wind speed at 80 m for Tjæreborg Enge WF was 7.82 m/s, where there is a 0.35 m/s difference from Nørrekæer Enge WF which is not too much. Finally, the CF for both sites were also compared from year 2011 to 2018. It is found that Tjæreborg Enge WF has a lower CF, with minimum of 21.3% and maximum of 29.5%. While for Nørrekæer Enge WF, the minimum CF is 33.4% and maximum is 44.1%. However it is worth to mention that the low CF of Tjæreborg Enge WF could be caused by the lifespan of the WF, as it was built on year 1996 while Nørrekæer Enge WF was built on year 2009. Thus, CF will not be an accurate indicator but it would be useful to use as a supplement.

With all the factors above Tjæreborg Enge WF will be chosen, however with some modification and assumptions. The WTs will be replaced with a newer Vestas V112 3 MW model according to [30] and the CF from Nørrekæer Enge WF will be used as it is assumed that there will be less down time. With the max CF at 44.1%, the electrolyser sizing will be given 5% more based on the CF of the WF, as based on the past data the WF's CF is unlikely to be more than 50%. Thus, the system will consists of 24.6 MW of wind energy and 12 MW of electrolyser system, which is 50% of the WF.

The market for electrolysers is growing and more growth is expected in the future due to the role that hydrogen plays in. However choosing the right type of electrolyser is important based on the application. As the market is still relative new, there is not much MW scale electrolyser stack yet. Electrolyser from Nel hydrogen [31] and HyBalance [32] are compared. Also, with a PEM electrolyser, it will have a fast ramp up time but the detailed ramp up and down time still has a large difference based on the research done. As mentioned earlier from [12], the analysis shows that the electrolyser can respond in milliseconds. However it is worth to mention that the report uses ramp rate of current per second as a measurement whereas other uses ramp rate in p.u. per seconds. In [33], where a 6 MW PEM electrolyser is used in industry, the report mentioned that the electrolyser has a average ramp time of 0.014 p.u. per second and it could more than 0.033 p.u. per seconds and even faster response time could be done for a load up to 4 MW. In [33], the efficiency

Table 2.1: Technical specification of electrolyser [33]

Stack size	2x6 MW
Efficiency at rated power	64%
Ramp up/down rate	0.014 p.u. per second

curve also mentioned that it includes the power consumption of all ancillary components including transformers, rectifiers etc. This is important as the converter topology will present losses up to 6%. With MW scale electrolyser, this will have a huge impact on the output of the electrolyser.

Typically, the topology of a HPP can be defined into 2 categories, which were AC coupled system and DC coupled system. For a DC coupled hybrid system, assets will be connected together at and form a hybrid units, which were then connected to an inverter that is linked to a AC bus and the external grid. With a DC coupled system, WTs will require rectifier to connect to the DC bus. While for electrolyser, only DC-DC converters is required. Typical layout of a DC coupled hybrid system can be seen from figure 2.1.

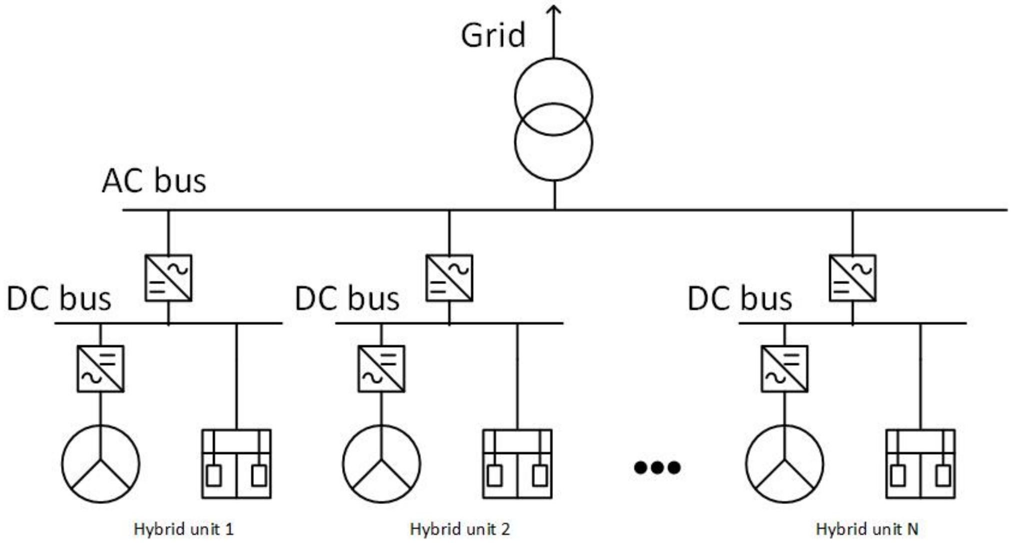

Figure 2.1: Electrical configuration of a DC coupled hybrid system

For an AC coupled hybrid system, depending on the WTs, back to back converter might be required. For the electrolyser, it will be connected with an inverter as electrolyzer only consumes DC current. The layout of a AC coupled hybrid system can be seen from figure 2.2.

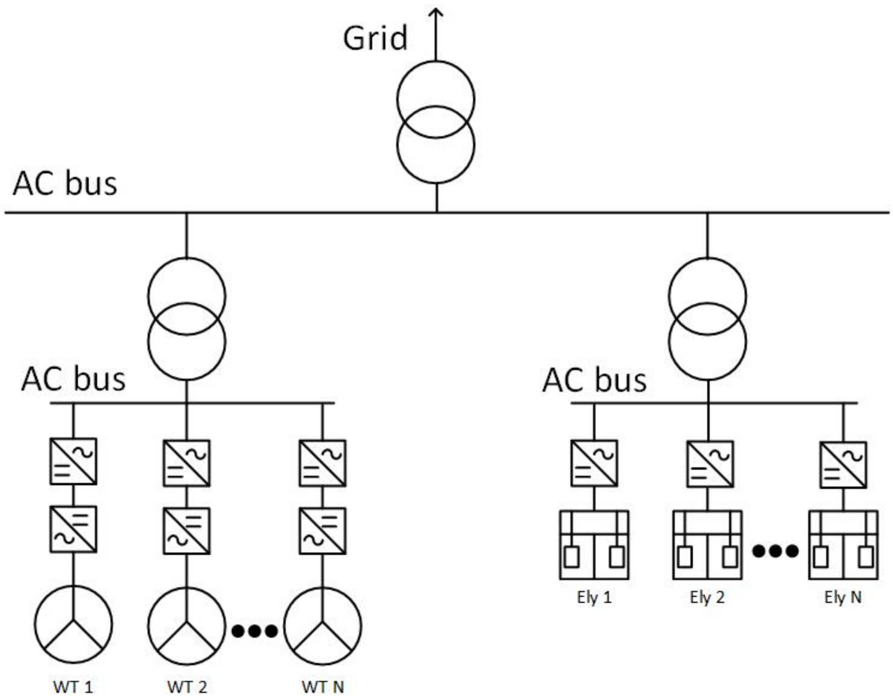

Figure 2.2: Electrical configuration of an AC coupled hybrid system

Each type of topology will have its own advantages and disadvantages. With AC coupled system, it could be expanded more easily as assets can be added in parallel to increase the overall HPP capacity. Also, the usage of plant controllers such as wind farm controller, PV farm controller etc. in AC coupled system is more common, thus it is a more mature topology and could be deployed more easily [34]. For DC coupled system, different control strategies at asset level are required to be coordinated and integrated with the plant controller. However the advantage of DC coupled system is that less power conversion components is required in the system, and thus reducing the costs for a hybrid system containing WTs, PVs and BESS [35].

2.2 Automatic Frequency Restoration Reserve (aFRR)

While the system could participate in different frequency services, aFRR is chosen because as of the time period from January 2021 to September 2022, only +/- 6 MW was purchased locally in DK1 area according to [25] and the prices remains low, less than 500 DKK per MW except for summer 2022 in the time period. Meanwhile for aFRR, it presents a better business case for the asset owner, due to the lack of competition and higher profit by providing this service. Currently, Energinet purchase 100 MW of aFRR volume, with 10 MW send to DK2 area. It is projected that the market for aFRR will grow up to 150 MW in 2032.

When participating in aFRR service, the plant will have to reserve a symmetric volume for both up and downwards regulation. Since the aFRR market in DK1 is linked to the German grid, the exchange of load schedule will be done within the participants that take part in this services. Each participants, or Balance Responsible Parties (BRP) will have a controller of their own for the participating assets. For FRR, the controller takes a power reference setpoint as an input which is coming through TSO, where compared to FCR, it takes frequency as an input to activate the frequency controller with droop settings. The frequency measurement is also measured locally at the participating plant for FCR. Figure 2.3 shows the simplified aFRR controller principle for DK1 area. The sum of ΔP1, ΔP2 and ΔP3 must be equal to ΔP*. After receiving the power reference setpoint from the TSO, assets owners could further split the setpoint by themselves.

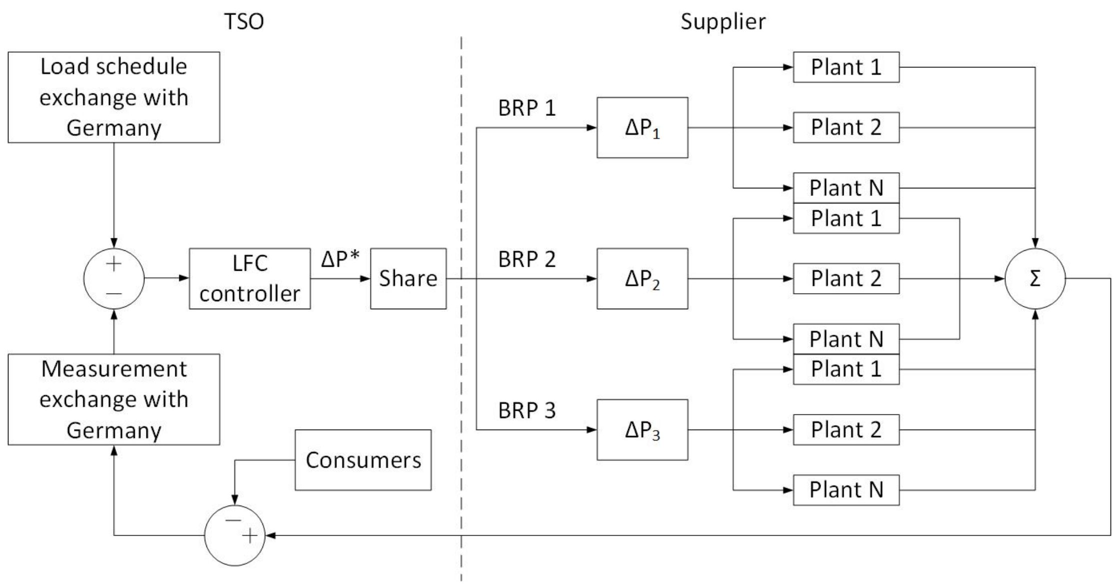

Figure 2.3: Simplified overview of aFRR controller principle in DK1

The electricity wholesale market, it can be split into 3 sub markets which were day ahead market (DA), intraday market and balancing market which can be seen from figure 2.4. The aFRR volume that will be contributing to the system is determined based on these market. In these market, the bidding volume cannot be more than 10 MW as a single unit. If more than 10 MW is bid into the market, it will be split into 2 different units, for e.g. 15 MW will be split into 10 MW and 5 MW instead. For FRR, it will only take place in the balancing market. FRR volume are secured and dispatched in almost real time due to the nature to ensure the grid frequency is within the limit.

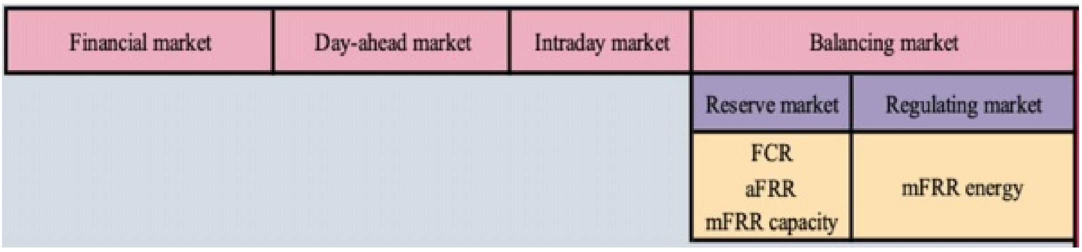

Figure 2.4: Overview of electricity trading market [36]

The controller must comply with the grid code set by Energinet. In DK1 area, a step test is applied. When a step signal is applied, the maximum time for between the receiving the signal and a measured change is detected must not exceed 135 s, and 90% of the full activation must be achieved within 12 minutes when the step signal is applied.

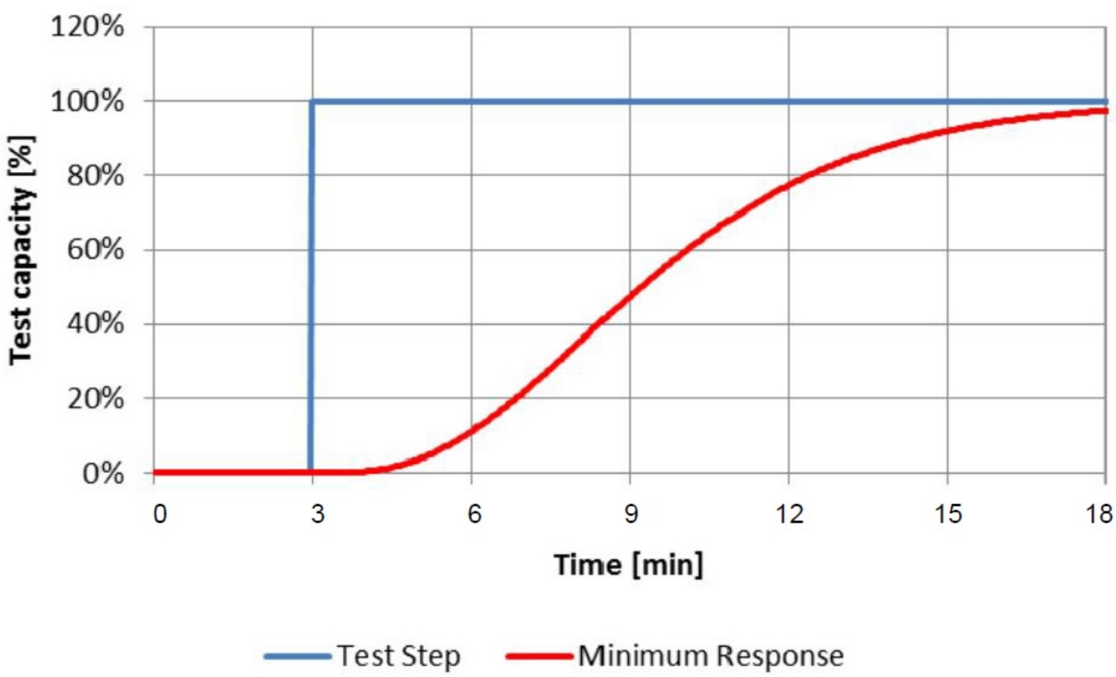

Figure 2.5: Required response for aFRR in DK1 when increment in setpoint is detected [37]

2.3 Summary

This chapter presents how the system is selected and the sizing of electrolyser as well, including the logic behind choosing the specific system. Also, more in depth of aFRR service is discussed and looked into, including a brief market overview and the test for the controller to comply with the grid codes.

3. Hybrid Power Plant Model and Control

3.1 Wind power plant model

In chapter 2, it is mentioned that the wind turbines will be replaced with a model with higher capacity. However, with the V112 3 MW model that will be used in the model, it is a turbine that is made for offshore purposes and in this case, the wind farm is located onshore. Typically, onshore WT have its rated wind speed from 7 m/s to 9 m/s while offshore WT have a rated wind speed from 11 m/s to 15 m/s. The WTs is equipped with a PMSG and full scale converter to convert the variable frequency power into what the grid desire. As now, for MW scale WT, type 3 and type 4 are the most popular choices. Type 3 WT being called Doubly Fed Induction Generator (DFIG) and type 4 being full scale converter WT. Being fully decoupled from the grid, type 4 WT does not contribute to the system inertia but it could be controlled easily which allow easier integration to the grid [38].

To model a WT in detail, typically details such as aerodynamics, gearbox and power electronics dynamics will be included [19]. In [39] presents the effect of different components in the gearbox to the WT model, with a small WT. From the validation, it is shown that the gearbox will have an larger effect only if a large change in input is applied. As the aim is not to simulate and gather results on EMT simulation, a simpler model that does not include all the parts mentioned above is considered sufficient. This is deemed enough to capture the general dynamics of the WT with a simplified WT model.

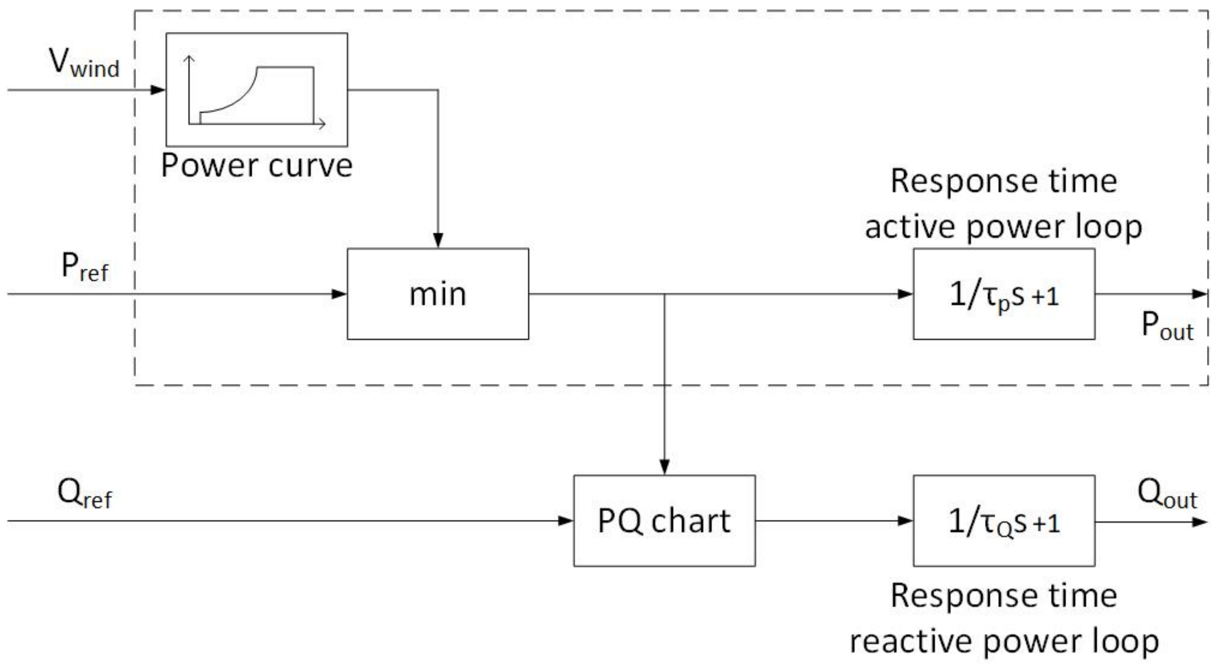

Figure 3.1: Block diagram of the WT model [40]

The model takes in wind speed, active power reference and reactive power reference as inputs. The wind speed is measured with an anemometer located at the rear side of the WT, and it will have a lower wind speed compared to the actual wind speed due to wake effect. For the active and reactive power reference, these will come from the wind farm controller. The two outputs of the model are the active and reactive power generated by the WT. The relation between wind speed and active power can be formulated by using equation 3.1:

$$P = \frac{1}{2} \cdot \rho \cdot Cp \cdot \pi R^2 \cdot V_{wind}^3 \tag{3.1}$$

Where ρ = 1.225 Kg/m^3 is the air density, Cp is the power coefficient, πR^2 represents the swept area and V_{wind} is the wind speed.

A minimum block is implemented, as only one of the signal can be prioritised. The WT could not be producing more than what the setpoint requests or vice versa. PQ chart is implemented to compensate for the losses that originated from the transformer and converter inside the WT [41]. The active and reactive power loop are treated as a first order system. For the time constant for the active power loop, τ_P, 1 s is taken for this value as this is the approximate value [42]. Meanwhile, the time constant for reactive power loop, τ_Q, 0.2 s is taken. The maximum ramp rate for the active power is 300 kW/s or 0.1 p.u./sec and 60 MVAr/s or 0.20 p.u./s for reactive power.

3.2 Electrolyser model

With electrolysers that is used solely for green hydrogen production are still relative rare in industries, the model of the electrolyser is done with the aim only to capture the overall dynamics of the electrolyser. Same as the WT model, the actual electrolyser is more complex with the internal components including the converters, pumps, compressor etc. These components will affect the BoP of the plant, as they consume power as well. Fig 3.2 shows all the components that an electrolyser will need to operate.

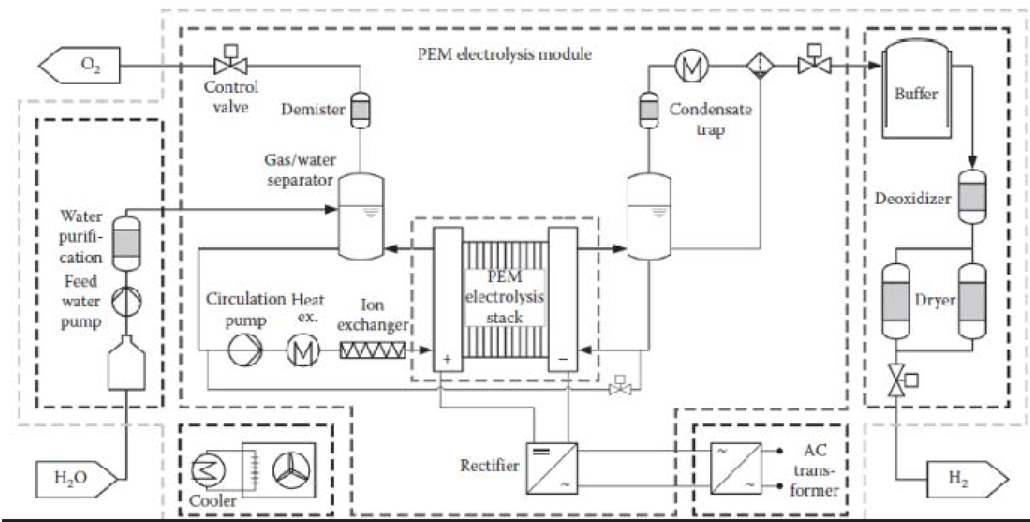

Figure 3.2: PEM electrolyser system with power electronics included [43]

In the model used, the power electronics of the electrolyser is not modelled, with the same reason for the WT model. The electrolyser is modelled as a load, as it only consume power to produce hydrogen. Due to difficulties obtaining detailed information on the electrolysers, the relationship between power consumption of the electrolyser, hydrogen produced and the stack efficiency are obtained from [33]. In publicly available datasheets, OEM only provides the general efficiency, however it is worth to mention that the efficiency curve for electrolyser is not linear. It will decreases after the optimum operation point is reached.

The input for the model are the electrolyser power reference and the hydrogen demand which is translated into MW. The ramp rate of the electrolyser is also found in [33], where 0.014 p.u. is taken, however higher ramp rates could be achieved if required. For the efficiency of the plant, it has a maximum efficiency of 64% at 4 MW and 59% at 6 MW. In the base model, the efficiency of the electrolyser is extrapolated linearly, with the maximum efficiency at 8 MW instead of 4MW and maximum capacity of 12 MW instead of 6 MW. This is due to the fact that the electrolyser stacks is done as an aggregated model. The efficiency curve also includes the losses from all the components of the electrolyser, thus it is considered to be accurate as it also account for the BoP. The time constant for the active power loop is considered to be 2.5 s and it is modelled as a first order transfer function.

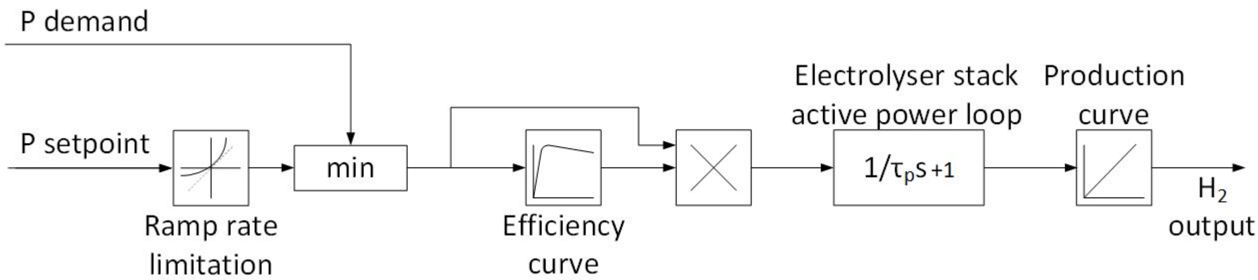

Figure 3.3: Block diagram of electrolyser model

The operation of electrolyser can be separated into different stages, namely off state, cold startup, warm startup, standby mode and normal mode and it is explained more in depth in [12]. In off state, the electrolyser does not consume any power and no hydrogen is produced. For cold startup, the electrolyser start to ramp up from off state. In this phase, additional time will be required, as the components will need longer time to raise its temperature. This stage is associated with low or no production from the wind farm, thus the electrolyser will have to start from off phase due to it not being grid connected for green hydrogen purposes. Next is warm startup, and this could be that the electrolyser is ramping down from normal mode and the components are at a higher temperature compared to cold startup mode. It will take a shorter time for it to ramp up compared to cold startup. In standby mode, the there is no production happening, but the electrolyser is ready to ramp up immediately. Finally is the normal mode, where the electrolyser is producing based on the setpoint given. In this model, the electrolyser is assumed to be running at normal mode.

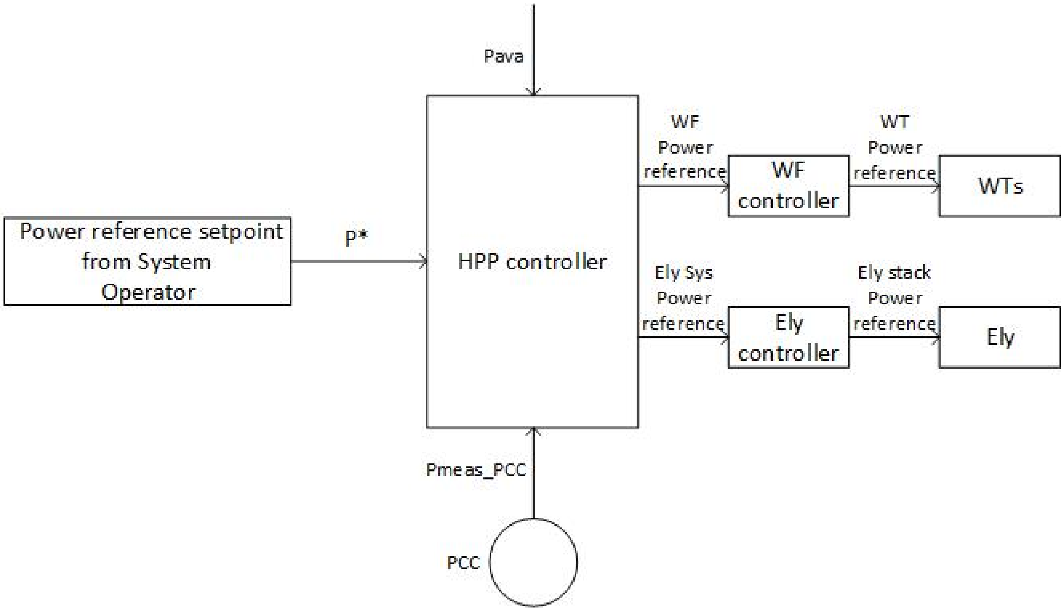

Figure 3.4: Overall hybrid power plant control scheme

3.3 Hybrid Power Plant Control Architecture

Figure 3.4 shows the general scheme of the hybrid power plant, which consists of a WF and an electrolyser stack. The HPP controller receives a power setpoint from the TSO, which is Energinet in this case. The setpoint received by the HPP controller in this case could either be a higher or lower setpoint than the current setpoint to activate the upwards or downwards regulation. The controller then will dispatch the power reference setpoint depending on the dispatch strategy to the WF and the electrolyser sub-controller based on the information that is related to the WF and electrolyser, including the available power produced by the wind farm, the demanded power for the electrolyser, reserved volume for aFRR and the measured power at PCC. The sub-controller will then dispatch the setpoint reference based on the plant's own dispatch strategy. For e.g. the WF could run on a dispatch strategy that reduced wake effects, or a dispatch mode that prioritising the overall lifespan of the WF. For the electrolyser, it could be equal dispatch or increasing the lifespan of the electrolyser stacks. These are just a few examples of the dispatch strategy that is proposed, it does not necessary to be equally dispatch among all the assets. Finally, the summation at the POC is important, as the electrolyser is a load, the rating of the POC will be lower as the electrolyser is always consuming power from the wind farm. By reducing the rating of the POC, the asset owner could reduce the cost, as the final amount to the grid will be lower which means a cable with lower ratings is applicable. Also, the cost of connection will be lower as well. The detailed model of the control architecture can be seen from figure 3.5.

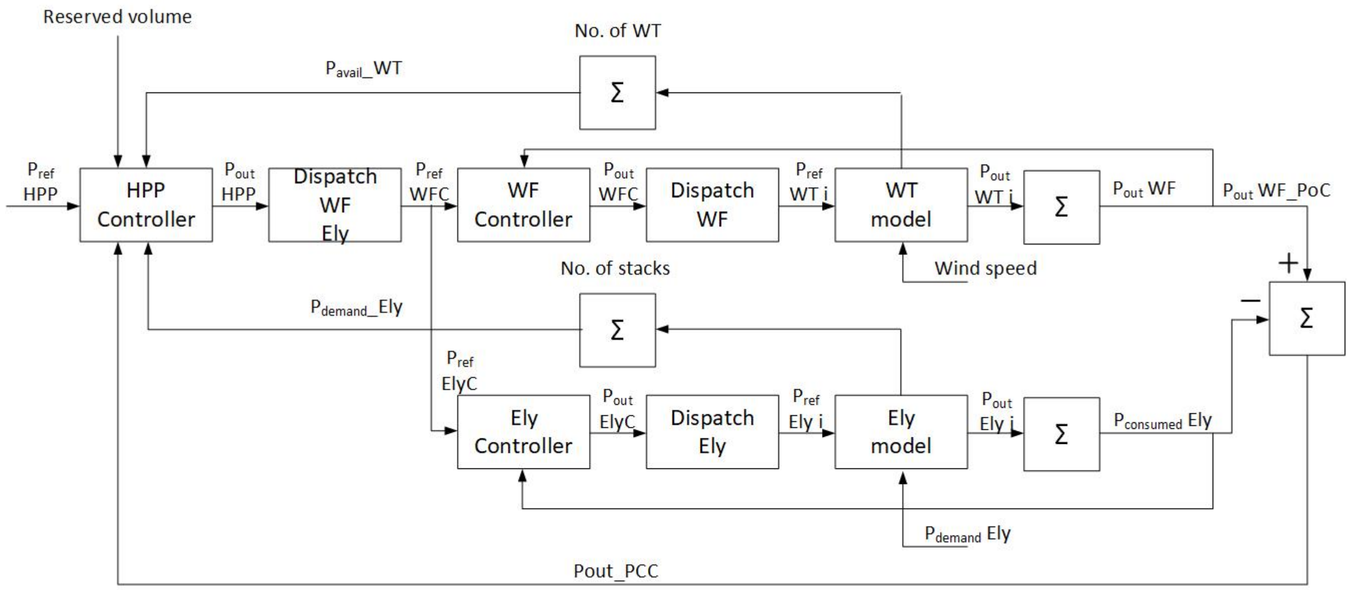

Figure 3.5: Detailed architecture of the hybrid power plant control

3.3.1 Hybrid power plant control level

The HPP controller acts as a single centralised controller, as the aim of having a HPP controller is to integrate the controller of two different assets which have a different OEM. Firstly, the power reference for the HPP must be subtracted from the demand for hydrogen as it is a load. This is then further subtracted with the measured power at PCC to obtain the error which will be fed into the PI controller. The PI controller with anti windup will serves to reduce the error between the reference power and the measured power at PCC. Figure 3.6 shows the control scheme of the HPP controller.

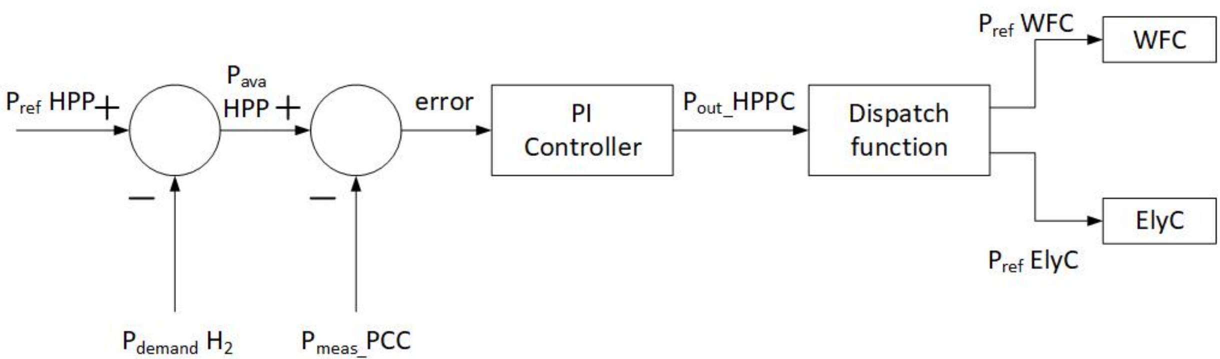

Figure 3.6: Hybrid power plant control level

Before dispatching the signal to each individual plant controller, the dispatch strategy will decide the power reference to the subplant based on the HPP power reference. The dispatch strategy will be further discussed in section 3.3.2 Communication delay of 15 ms has also been included between the measurement point of PCC and between the HPP controller, WF and Electrolyser controller as per [44]. Communication delay of 4 s are also implemented between the HPP power reference and the HPP controller as the guidance from Energinet states that the resolution from the SCADA system must be in between 4 to 10 s.

3.3.2 Hybrid power plant dispatch strategies

For the model to run, it is assumed that them model is already running at a certain fixed active power production instead of starting or shutdown phase. The HPP setpoint will start at a level which is lower than the available power that could be produced from the WF. This is due to the reserve volume for the aFRR that it might need to be ramp up or down depending on the scenario. Furthermore, the dispatch also assumed that the electrolyser is partially loaded for all the scenarios. When the HPP setpoint is higher than the available power from the WF minus the reserved volume, the dispatcher will dispatch according to the upwards regulation function. The flowchart of dispatch strategy related to upwards regulation can be seen from figure 3.7.

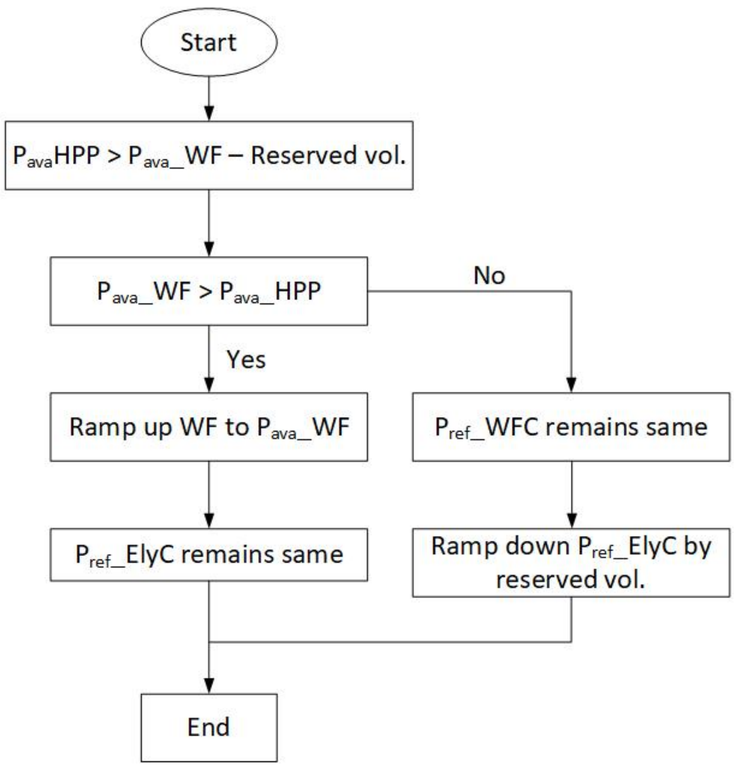

Figure 3.7: Flowchart of dispatch strategy when upwards regulation is activated

There are two options after the first condition is met. If the available power from the WF is larger than the HPP setpoint, the WF would be ramped up by the reserved volume. Meanwhile, the power consumed by the electrolyser remains the same. However if the available power from the WF is lower than the HPP setpoint, the power reference that is send to the WFC will remain the same but the electrolyser will have to reduce its consumption by the reserved volume. It is also possible to ramp up the WF even though the available power is lower than the HPP setpoint, where the WF will be ramped up to its available power and the remaining volume will be ramped down by the electrolyser. This is the most ideal case, as the assets owner would preferably avoid the ramping down of electrolyser as it reduces the profit from hydrogen production.

Next, is the dispatch strategy for downwards regulation, which is shown in figure 3.8. The dispatch for downward regulation is relatively straightforward compared to upwards regulation. When the HPP power reference is lower than the sum of available power from the WF minus the reserved volume, the setpoint that will be send to the WFC will remain the same. This is because instead of ramping down the WF, the asset owner could just increase the power consumption from the electrolyser, which in turn producing more hydrogen. It is a win win situation as the asset owner could profit from participating in aFRR and at the same time producing more hydrogen. The electrolyser will be proving support by ramping up by the reserved volume. Another situation could be to ramp down the WF, however that will be the last option as it will reduce the asset owner's profit. Unless the electrolyser is running close to full load, the WF will then only reduce the amount by the excess volume that the electrolyser could not ramp up due to reaching its maximum capacity. This dispatch strategy will only work provided that the WF is producing at least or equal to the power consumption of the electrolyser.

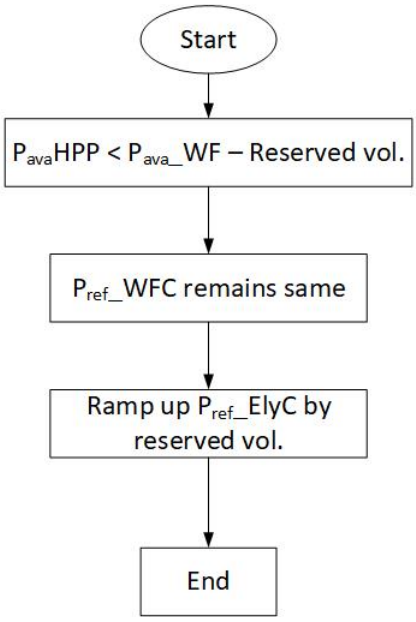

Figure 3.8: Flowchart of dispatch strategy when upwards regulation is activated

3.3.3 Wind farm and electrolyser control level

To control the active power injected and the active power consumed accurately at their respective POC, a plant controller is required for each assets. As seen from figure 3.9, the WF controller take its input setpoint from the HPP controller and the active power produced by the WF. The error signal is send to the PI controller with anti windup to be reduced. The output of the PI controller is send to the dispatch block, where the setpoint can be distributed based on the dispatch strategy. Finally, the individual power reference for each WT will be sent from the dispatch block to each individual WT in the WF.

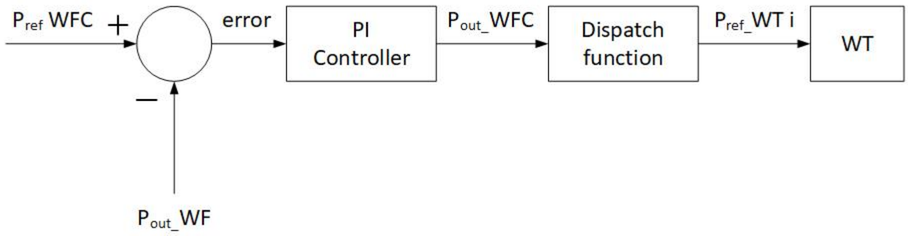

Figure 3.9: Wind farm control level

3.3.4 Wind farm and electrolyser dispatch strategies

For the WF dispatch strategy, it is set that the total set point will be distributed based on proportional distribution. This can be expressed based on equation 3.3.4:

$$P_{ref}^{WT_i} = \frac{P_{av}^{WT_i}}{P_{av}^{WF}} \cdot P_{out}^{WFC} \tag{3.2}$$

$P_{ref}^{WT_i}$ represents power reference to the WT, and i = 1:n where n is the number of WTs which is 8 in this simulation.$P_{av}^{WT_i}$ is the available power for each individual WTs. P_{av}^{WF} is the available power from the wind farm and P_{out}^{WFC} is the power reference from the WFC [45].

The total active power of the wind farm are expressed as below:

$$P_{av}^{WF} = \sum_{i=1}^{n} P_{av}^{WT_i} \tag{3.3}$$

For the dispatch function of the electrolyser, different cases had been considered. For the base case, as mentioned, it will consists only a single aggregated electrolyser that has a rated power of 12 MW, thus there is no specific dispatch function for that case.

Extra case studies are presented, where it is split into three 4 MW stacks. The possible dispatch function increases with the possibilities of controlling the stacks. The electrolyser system could run with 1, 2 or 3 stacks depending on the asset owner. One of the dispatch function is equal dispatch, where the electrolyser setpoint is dispatched equally among the stacks. The second dispatch strategy is by dispatching the setpoint with different ratios depending on the available stacks online. For e.g. a 8 MW setpoint could be distributed as 4 MW, 3 MW and 2 MW. The number of operating stack could be chosen based on different reason, such as operating the stacks at maximum efficiency, prolonging life cycle of the stacks or even offline for maintenance.

3.4 External Grid

The external grid is modelled as thevenin equivalent grid, where the grid impedance (Z_g) is taken as R_g and X_g. The impedance of transformer is taken in account with the overall grid impedance, while modelling as thevenin equivalent grid as represented in figure 3.10. Further, In order to calculate the strength of a grid can be denoted by its Short-Circuit Capacity (SCC), which is calculated as the amount of current flowing flowing through the bus during solid fault. As per thevenin equivalent model the SCC can be calculated as

$$SCC = \frac{V_g}{Z_g} \tag{3.4}$$

In simple words lower the thevenin equivalent impedance, stronger the grid is. The Short Circuit Ratio (SCR) of the bus or grid, where the plant is connected can be calculated as the ratio of SCC of the bus to the rating of plant S_P connected to the bus

$$SCR = \frac{SCC}{S_{P(s)}} \tag{3.5}$$

Generally, if the SCR of the ac system is greater than 3.0 it is a strong system. A weak system can be considered as SCR between 2.0 and 3.0, except that SCR below 2.0 is a very weak system. However, in this project a system with SCR of 5.0 is considered, Which is a strong system.

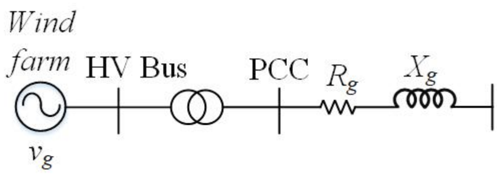

Figure 3.10: External Grid

3.5 Summary

In this chapter, the modelling method for WT, electrolyser and the HPP controller is explained. The electrolyser will acts as a load, and it follows the up and down regulation by ramping down or up depending on the scenario. The HPP controller will have different dispatch methods, depending how loaded the electrolyser is, and it is possible to ramp up/down the WF and electrolyser partially to satisfy the reserved volume. The dispatch strategy for WF is straightforward but there is multiple dispatch strategies for the electrolyser, assuming it is not a single aggregated stack.

4. Control System Design

4.1 Characterisation of Transfer Function

Transfer functions are used to depict a system overall behaviour. This further includes a controller and delay transfer function to alter a real-time system scenario. The first order transfer function are used to depict the behaviour of a plant and to avoid complexity. Therefore, first order transfer function are used for three sub-plants including the WF, electrolyser and hybrid plant controller. The first order transfer function can be represented as in eqn.4.1. Where, T_s is the settling time and the gain k has been considered to unitary.

$$G(S) = \frac{k}{T_s S + 1} \tag{4.1}$$

The T_s of the system is the time required for the response curve to reach and stay within 2% of the final value. It should be noted that steady-state error should be less than 2% of the final value. Therefore the controllers are tuned to meet the requirements and avoid instability. There should be no overshoot and the settling time to step input should be less than 10 s. The next section discusses the estimation of losses for the plant.

4.2 Estimation of Losses

The losses of the plant should be estimated to ensure an accurate is injected at PCC. The losses are derived from PCC to POC of each sub-plant consisting of cables and transformer of different power rating. It should be noted that the power-to-x is directly connected at the PCC, no losses are considered for that.

The losses for WF are only considered. The WF consists of 8 WTs of 3 MW each connected in two parallel branches of four WTs each. Each WT is 0.35 km away from each-other and the same distance to POC. NKT CU cables were considered for the WF with different cross section. Finally, to estimate the losses, DIgSILENT PowerFactory is used to model each parameter and calculate losses. The impact of different parameters at the PCC such as SCR, X/R and grid voltage (v_g) are not investigated in detail. The power injected at PCC can be denoted as in equ.4.2.

$$P_{PCC} = P_{POC}^{WF} + P_{POC}^{Ely} - P_{WF}^{loss} \tag{4.2}$$

Where P_{PCC} is the power injected at the PCC by the HPP, P_{POC}^{WF} is the power injected by WF at POC, P_{POC}^{Ely} is the power injected by electrolyser at POC and the losses occurring from WF are denoted by P_{WF}^{loss}. The losses occurring are always a function of several parameters and can be denoted as:

$$P_{WF}^{loss} = f(v_g, P, Q, SCR, X/R) \tag{4.3}$$

In order to estimate losses for the project certain simplifications are considered by avoiding ambiguity such as large number of busses, different wind speed for each WT, temperature etc. As discussed before the plant transfer function is considered as first order transfer function and K_{loss}, which computes for the losses occurring from the plant. However, further detail analysis can be done to estimate losses at varying grid voltage, SCR, X/R it is neglected in this project.

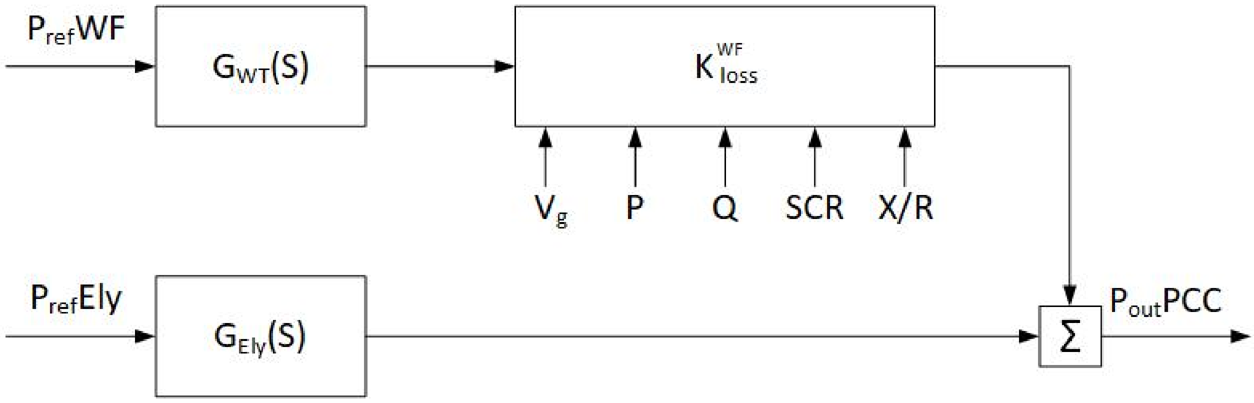

Figure 4.1: Transfer function diagram

4.3 Controller Design and Tuning

This section discusses the implementation of PI (Proportional Integral) controller for the plant and the sub-plant. The minimum requirements as per grid-code compliance will be followed. The closed loop controller of a plant can be represented as in figure 4.2. The error between the reference and the measured is taken in fed into the PI controller bridging steady-state error equivalent to zero. Further, we have the plant transfer function to take in account the losses and the delay from the grid meter.

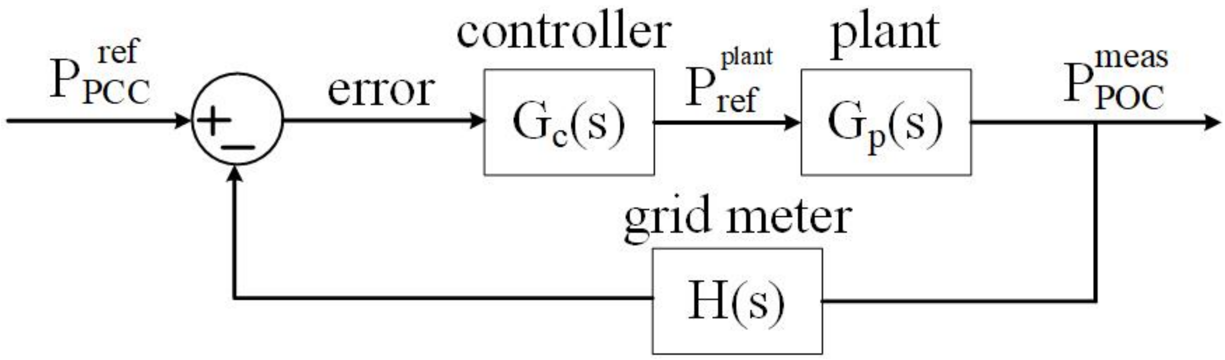

Figure 4.2: Close loop control scheme

The closed loop transfer function for the plant can be expressed as in eqn 4.3.

$$G_{cl}(s) = \frac{P^{meas}_{PCC}(s)}{P^{ref}_{PCC}(s)} = \frac{G_p(s)G_c(s)}{1 + G_p(s)G_c(s)H(s)} \tag{4.4}$$

The plant transfer function $G_p(s)$ can be obtained as:

$$G_p(s) = \frac{P_{PCC}^{meas}(s)}{P_{WF}^{ref}(s)} = \frac{K_{loss}}{\tau_p s + 1} \tag{4.5}$$

Where, the K_{loss} is defined as loss coefficient and can be defined as:

$$K_{loss} = \frac{P_{WF}^{out} - P_{WF}^{loss}}{P_{WF}^{out}} \tag{4.6}$$

K_{loss} varies depending upon the output power and the grid voltage. In this project the designed controller will under specific conditions with SCR=5, XR=10, Q_{WF}^{out}=0 p.u., P^{out}=0.8 p.u. and v_g = 1 p.u. considering that each WT and electrolyser stack has equal power. The electrolyser is connected directly to the POC so no losses will be occurring, the WF will have losses with P_{WF}^{out} = 0.8 p.u.The total losses occurring for WF P_{WF}^{loss} = 0.0088 p.u. it yields K_{loss} = 0.9891 p.u.

The delay introduced by grid meter is also taken into the consideration with delay of τ_m equivalent to 15 ms. It can be represented as:

$$H(s) = \frac{1}{\tau_m s + 1} \tag{4.7}$$

Finally, PI controller with anti wind-up following backward Euler method is utilised. The discrete form of PI is done using canonical form with modulus optimum method. This method follows the zero pole cancellation avoiding the ambiguity of closed loop controller. The transfer function of a PI controller can be represented as:

$$G_c(s) = K_P \frac{T_i s + 1}{T_i s} \tag{4.8}$$

Where, T_i is selected as the time response for each plant for WF it is taken as 1. While for electrolyser due to slow response it is taken as 2.5 and for hybrid plant controller as 0.9. Finally, the K_p is selected as:

$$K_P = \frac{T_i}{K_{loss}} \tag{4.9}$$

Table 4.1 shows the K_P and T_i value taken for each of the controller:

Table 4.1: K_P and T_i value for each of the PI controller

Controller	K_P	T_i
HPP	0.91	0.9
WF	1.011	1
Electrolyser	2.5	2.5

Further, to avoid error during saturation anti-windup is implemented. The bode-plot of the closed loop controller is represented as in figure 4.3. The bandwidth of the system in 1 rad/s. The phase margin is greater than 90 degree and gain margin is greater than 3 dB. This indicates that the system is stable. It should be noted that the same procedure is followed for tuning the electrolyser and the HPP controller.

To verify the robustness of all the controllers, a test case is done. From figure 4.4, the power reference is changed from 0.7 p.u. to 0.8 p.u.. It is seen that the HPP controller has the fastest response, followed by the WF controller then the electrolyser controller. The HPP controller and WF controller reached steady state around 7 s to 8 s while the electrolyser controller at 15 s approximately. There is no steady state error from all of the controller and no overshoot behaviour is observed. Currently, there is no requirement set for the HPP and electrolyser controller by Energinet. Even though the settling time for electrolyser controller is more than 10 s, it is considered acceptable. On the other hand, the WF controller fulfill the requirements as explained in section 4.1.

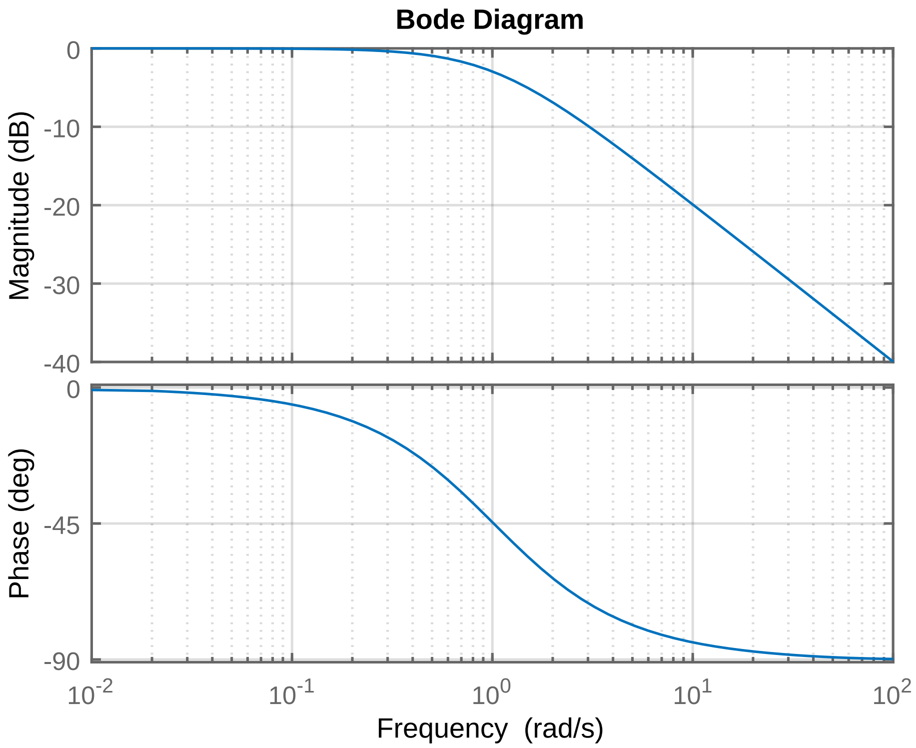

Figure 4.3: Bode Plot of Wind Farm Controller

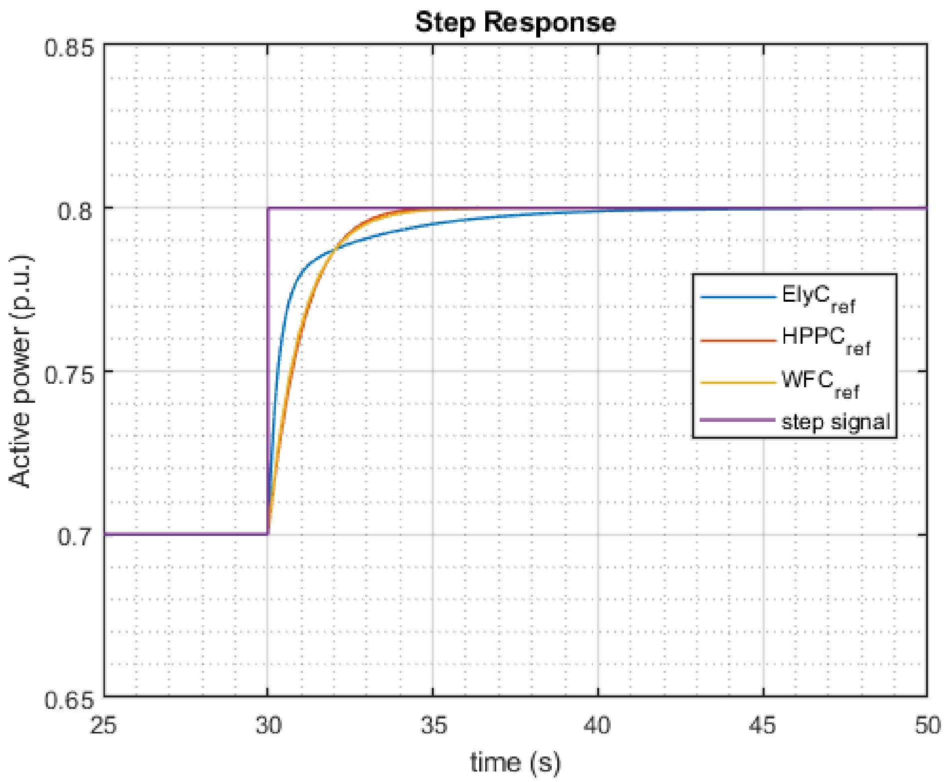

Figure 4.4: Step response of all the PI controllers

4.4 Summary

This chapter includes the controller design for the HPP, WF and electrolyser controller. All of the transfer function of the controller is represented as a first order transfer function. Losses are included for the HPP and WF in the controller but not for the electrolyser controller. PI controller with anti wind-up is implemented for all the controllers and discretisation of the controller is done with backward Euler method. All of the controllers are stable as the gain margin is larger than 90 degree and the phase margin is larger than 3 dB. A step response is implemented further to verify this.

5. Simulation

5.1 Grid compliance and testing of controllers

To test the grid compliance of the HPP controller, according to [37] as mentioned in chapter 2.2, the HPP controller must be able to reach 90% of full activation volume within 12 minutes after the activation signal, which can be seen from figure 2.5.

A same test is done for the designed HPP controller, where a step input signal is applied on the HPP power reference at t = 150 s, with a reserved volume of 0.2 p.u. or 4.92 MW. While the step signal is triggered at 150 s, due to the resolution of SCADA, the HPP controller received the signal at t = 154 s. From figure 5.1, the system started at 0.6 p.u. and reached 0.8 p.u. after the step signal. The system managed to reached 90% of the reserved volume at t = 161.5 s, which was 7.5 s since the HPP controller received the power reference signal. While figure 5.1 shows upwards regulation, the results for downwards regulation should be similar to figure 5.1 except that both of the P_{ref}^{HPPC} and the P_{meas}^{PCC} will be reaching 0.4 p.u. instead. This show that the HPP controller satisfy the aFRR requirement in DK1 region.

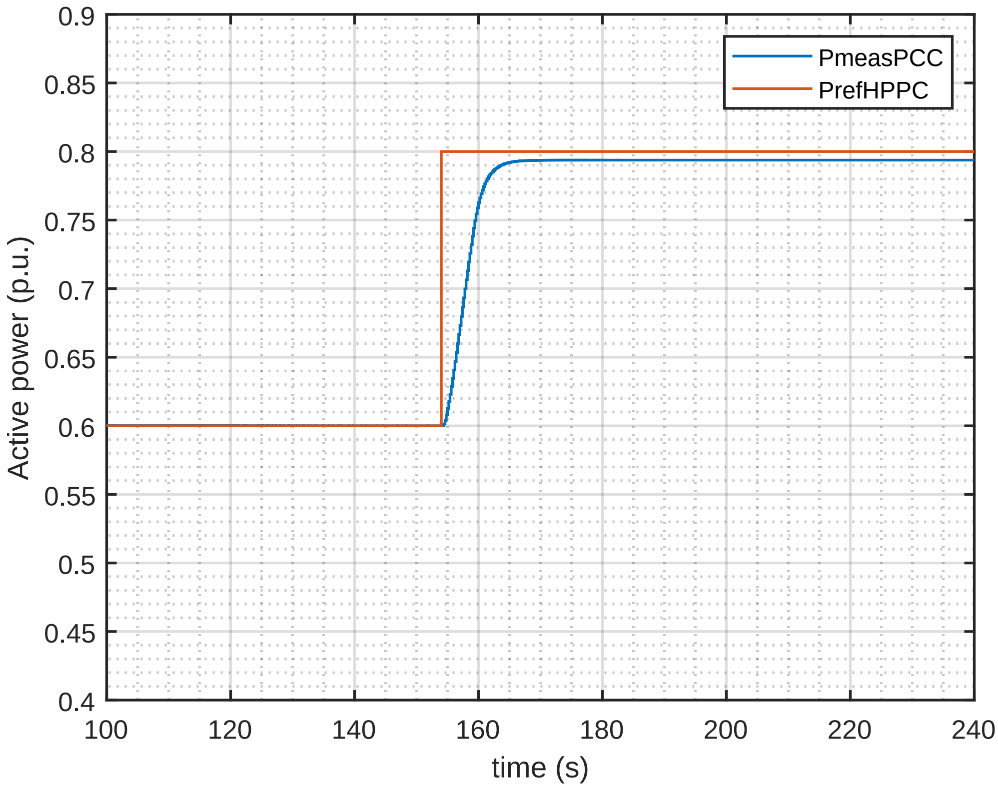

Figure 5.1: P_{ref} and P_{meas} for upward regulation

Next, a similar test is done for the WF controller to test the capability of the controller designed. Similarly, a step input is applied on the HPP controller power reference and the response for the WF controller is observed. The final results is similar to that of the HPP controller, however from both figure 5.1 and figure 5.2, there is a steady state error for the active power measured at the PCC. This is caused by more grid losses than anticipated in the grid model and assumed to be acceptable as at 1p.u., the losses is 0.01 or 1% and 0.00625 p.u. or 0.625% at 0.8 p.u..

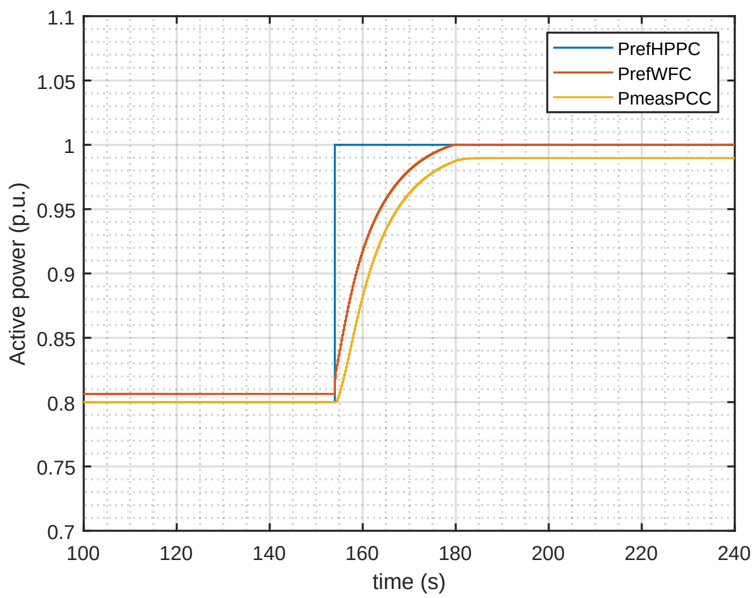

Figure 5.2: Wind farm controller step response during upwards regulation

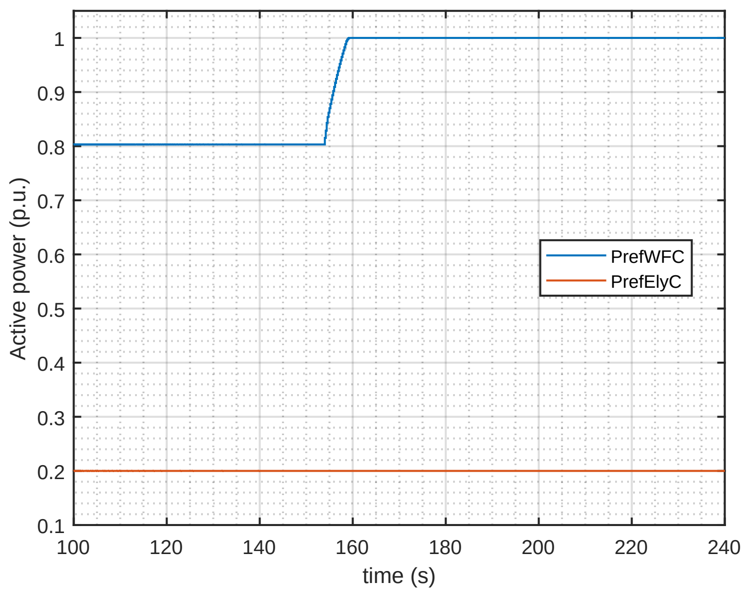

Figure 5.3: PrefWFC and PrefElyC during upward regulation

5.2 aFRR: Upwards regulation

The system response for the step input test coincide with the aFRR upregulation scenario, where only the WF will increase its output as it is running at a reserved capacity, while the production from the electrolyser will remain constant. This can be seen from figure 5.3. However another scenario will be considered.

5.2.1 Up regulation by ramping down electrolyser

This is not an ideal case for the asset owner as ramping down the electrolyser would reduce the profit, however this case study could be used due to the low wind speed and the electrolyser had to be ramped down. This case is only possible when the WF is generating the same amount of active power that the electrolyser is consuming. Reserved volume of 0.2 p.u. or 4.92 MW is implemented. After receiving the up regulation signal, the electrolyser is ramped down from 0.488 p.u. or 12 MW to 0.288 p.u. or 7.08 MW while the WF setpoint remains constant. The active power injected to the grid can be seen from figure 5.5. Initially, there is no active power injected to the grid as the electrolyser is consuming all of it, after the up regulation signal, the power injected to the grid was 0.2 p.u. due to the ramping down of electrolyser.

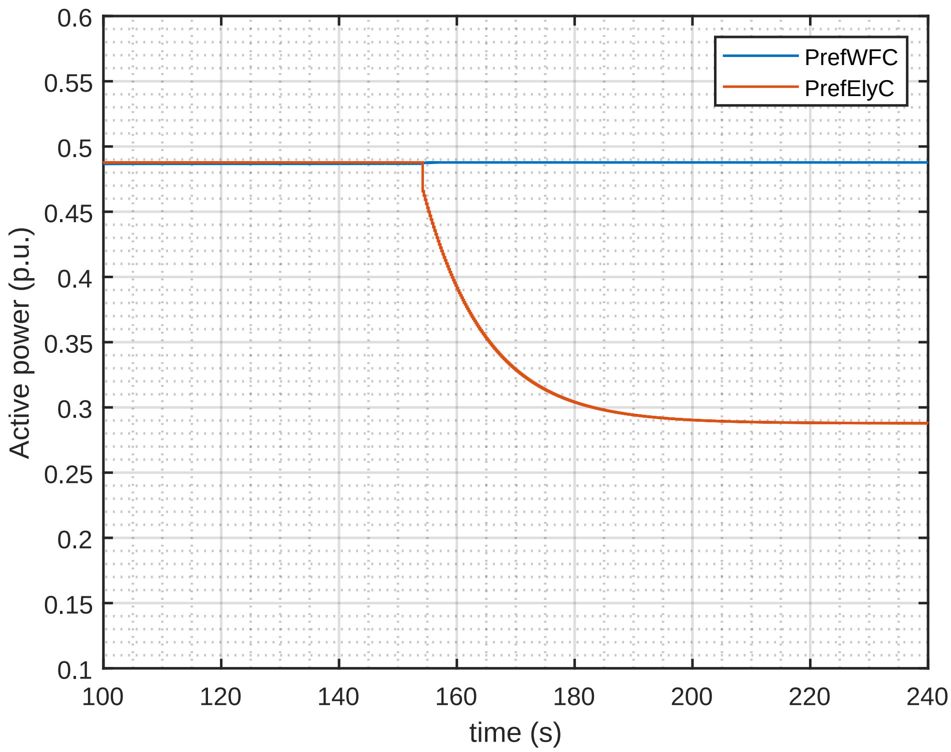

Figure 5.4: Up regulation with electrolyser being ramped down

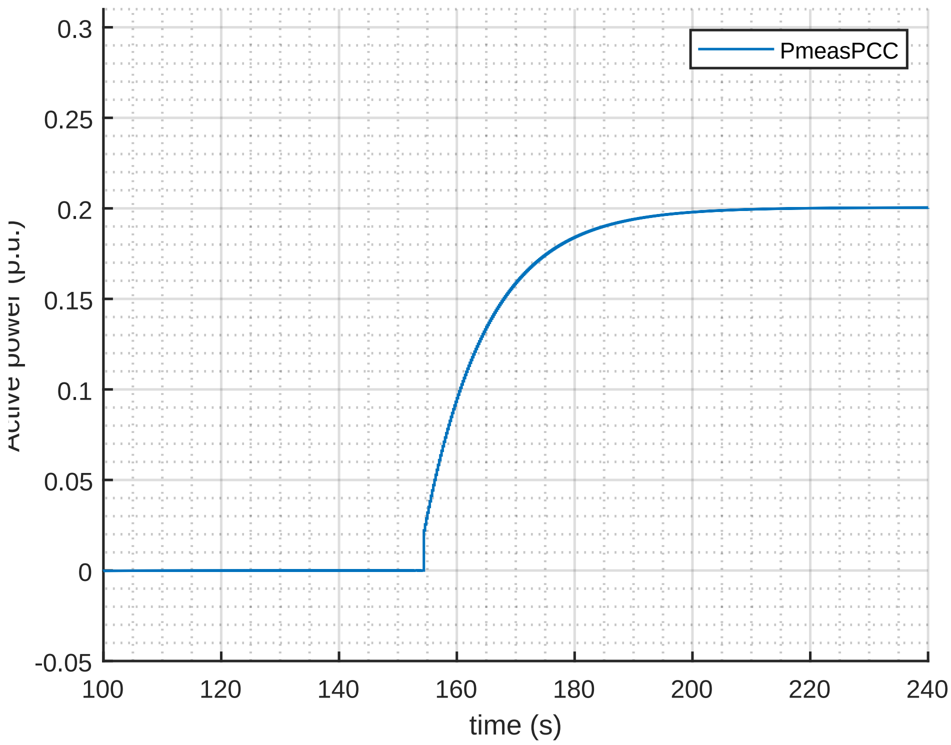

Figure 5.5: Active power injected to the grid during upregulation

5.3 aFRR: Downwards regulation

For the downwards regulation, multiple scenarios are implemented to measure the system response. As in downregulation, the electrolyser stacks could operate in different methods according to the dispatch strategy chosen.

5.3.1 Down regulation with aggregated electrolyser stack

In this case, the downregulation is done jointly by both assets. The electrolyser is modelled as an aggregated model with a single stack of 12 MW. While the available power is 1 p.u. from the WF, the WF was running at 0.8 p.u. due to the reserve. Initially, the electrolyser is producing at 0.82 p.u. of its capacity which were 9.84 MW and the reserved volume is 0.2 p.u. or 4.92 MW while the WF is running at 0.8 p.u. or 19.86 MW. When the HPP controller received the down regulation signal from SCADA, the system will prioritised on ramping up the electrolyser first, as increasing the electrolyser production will generate more profit for the asset owner since it is generating more hydrogen while fulfilling the grid demand. From figure 5.6, the electrolyser was ramped up by 2.16 MW while the remaining 2.76 MW will be fulfilled by ramping down the WF. The HPP system will inject 0.4 p.u. of active power into the grid, as 0.4 p.u. is consumed by the electrolyser. After receiving the down regulation signal, the system reaches 90% of its reserved volume at t = 167 s. The final active power that will be injected into the grid was 0.2 p.u. due to the ramping down of the WF and the increase consumption from the electrolyser.

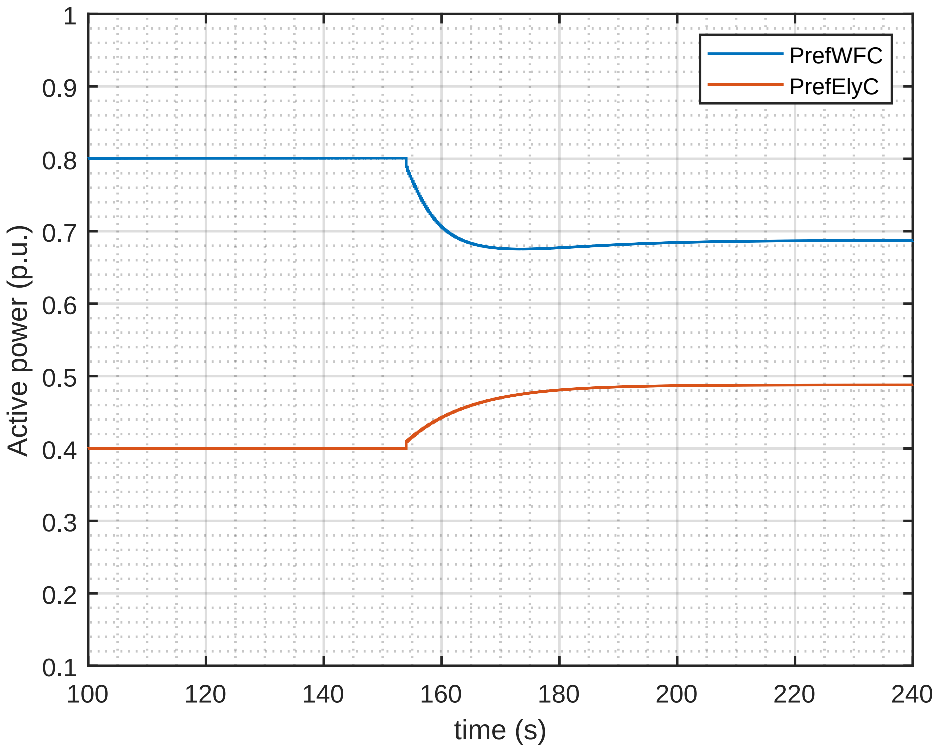

Figure 5.6: Down regulation with aggregated electrolyser model

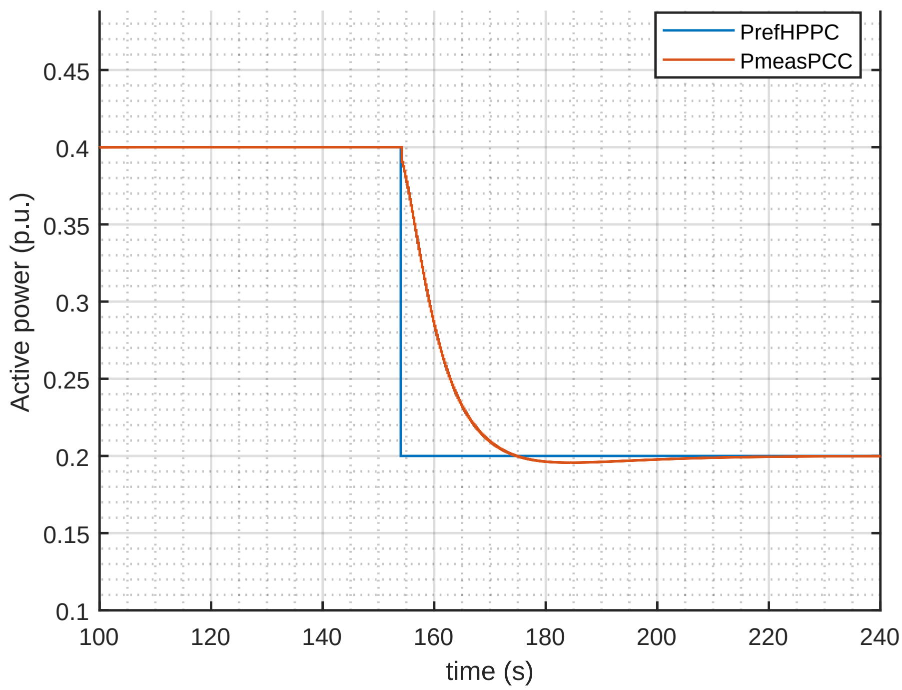

Figure 5.7: Pref and Pmeas for downward regulation (base case)

From figure 5.7, it is shown that there is a undershoot in the measured active power at PCC. This is due to the slower response time of the electrolyser when ramping up compared to the WF which react faster and thus creating an undershoot. This will not affect the overall required response because it went to steady state in approximately 40 s while the grid code allows up to 12 minutes.

5.3.2 Down regulation with three electrolyser stacks

To further optimise the system, the electrolyser is divided into 3 stacks with equal rated power. The initial condition remains the same as the aggregated stack scenario, only that the electrolyser setpoint is distributed equally among three of the electrolyser stacks. From figure 5.8, each stack of electrolyser is running at a capacity of 0.13 p.u. or 3.28 MW which amounts to 9.84 MW in total. Meanwhile for the WT, each of the WT is running at 0.1 p.u. or 2.46 MW and with 8 WTs in total, the total active power produced are 19.68 MW. After receiving the down regulation signal, each electrolyser stack ramps up to its maximum capacity which were 0.163 p.u. or 4 MW while each individual WTs ramps down to 0.086 p.u. or 2.115 MW respectively. The measured active power response are the same as figure 5.7, since they have the same inputs but with only the distribution of power reference to individual electrolyser stacks.

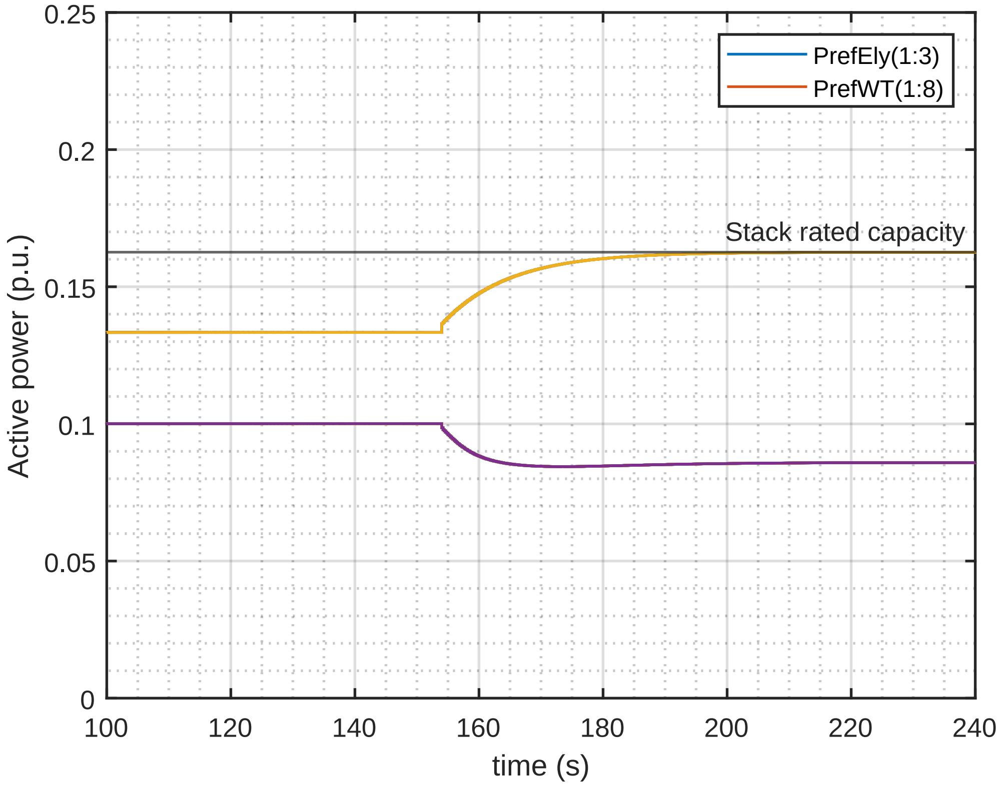

Figure 5.8: Downward regulation with electrolyser stack loading at equal ratios

Furthermore, another case study with multiple electrolyser stacks but with different dispatch strategy is done. On this case study, during down regulation, the electrolyser stacks will be ramped up, while WF output remains constant. The reason for this dispatch strategy is explained in section 3.3.2, instead of reducing the WF output and producing the same amount of hydrogen through the electrolyser, it is more profitable for the asset owner to just ramp up the electrolyser stacks instead and the WF output remains constant. However, this is done with the assumption of that there is still enough capacity for the electrolyser to be ramped up. If there is not enough capacity for it to be fully ramped up, it would be equal to the case study done before, where the electrolysers stacks will be ramped up partially and the WF would be ramped down partially.

The initial conditions for this case study is the same as before, except for the initial setpoint of the electrolyser stacks is 0.1 p.u. or 2.46 MW, where electrolyser stack 1 is operating at 0.044 p.u. or 1.093 MW, stack 2 at 0.033 p.u. or 0.82 MW and stack 3 at 0.022 p.u. or 0.546 MW. When the downwards regulation signal is activated, the electrolyser in stack 1 is operating at 0.13 p.u. or 3.28 MW, stack 2 at 0.1 p.u. or 2.46 MW and stack 3 at 0.067 p.u. or 1.64 MW. These can be seen from figure 5.9. The output for the WTs remains the same all the time. The active power injected to the grid and the HPP controller setpoint which is shown in figure 5.10.

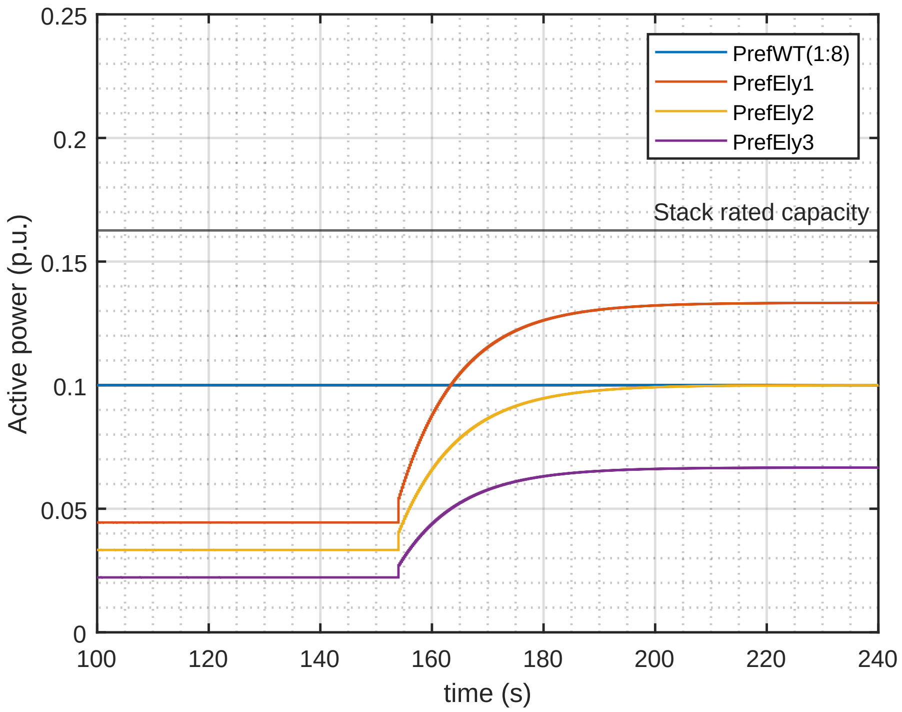

Figure 5.9: Downward regulation with electrolyser stack loading at different ratios

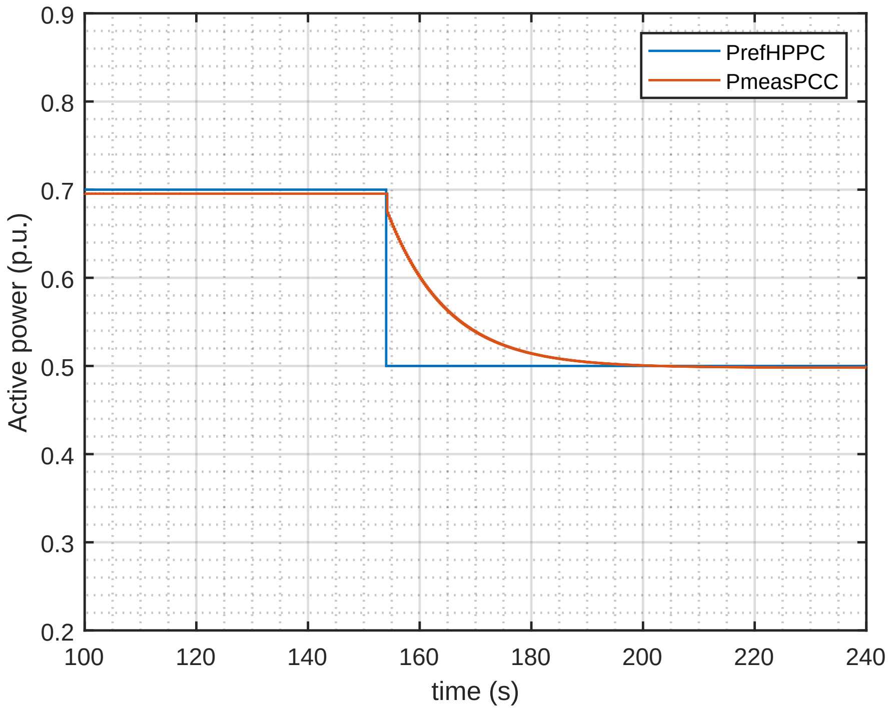

Figure 5.10: Pref and Pmeas for downward regulation with multiple electrolyser stacks

5.4 Summary

In this chapter, the results shows that the system managed to ramp up a reserved volume of 0.2 p.u. within 7.5 s when the HPP controller receive the upwards regulation signal by ramping up the production of the WF. The functionalities of a WFC is also tested by having a step input and it is found that the losses value in the grid model is higher than expected, thus it did not reach the controller value. However the steady state error is considered acceptable as it is a minor deviation. Different down regulation scenarios are also tested, with both aggregated electrolyser model and multiple electrolyser stacks.

6. Conclusion and future works

6.1 Conclusions

This thesis has presented the problems of providing frequency services with renewable plants, especially with electrolysers, where this emerging technology is gaining more attention. The main objective is to develop aFRR strategy that could be implemented in a HPP system, in this case, a 24.6 MW of WF and 12 MW of electrolyser.

In chapter one, the background of Danish renewable energy, especially with hydrogen and wind energy is discussed. Different type of hydrogen technology is looked into and compared as they offer different dynamics when combined with other sources of renewable energy sources. Different stages of frequency services such as FFR, FCR and FRR were also researched thoroughly to determine which stages of frequency services this project should be participate in. Problem formulation, objectives, methodology and limitations of the project are also included in this chapter. Chapter two consists of the sizing of the HPP system, on how the WF and electrolyser system is chosen based on available data. It is also found that AC coupled hybrid system is more advantageous in this project and it will be used in the modelling. aFRR frequency service is explained more in depth to determine the difference between other frequency services and tests that should be conducted on the HPP controller so that it comply with the grid code.

Chapter three introduces the modelling method for the WT, electrolyser and the controllers. For the WT and electrolysers, more detailed model could be done as per other literature, but as it is not in the scope of the project, these components are not strictly necessary as the overall dynamics of the plant will suffice. The time constant for the WT is 1 s and 2.5 s is taken for the electrolysers. For the HPP controller, it will take in power reference from the TSO, available power from the assets, reserved volume and the measured active power at the PCC as inputs. The controller will then dispatch the setpoints based on its dispatch strategy to both the WF controller and the electrolyser controller. The working principle for the sub controller is the same as the HPP controller, however with a different dispatch strategy compared to the HPP controller, especially for the electrolyser as it will be modelled in three different stacks instead of one aggregated model as per the base case. The dispatch strategy for the WTs is proportional dispatch.

Chapter four describes the control system design and tuning. The controller transfer function is described as a first order transfer function. To compensate for the losses, DIgSilent power factory is used to determine the losses occurring from the cables connecting the WTs. The project could be improved by analysing other parameters by varying the reactive power, SCR and X/R value. For the tuning of the HPP and WF controllers, it have a K_{loss} of 0.9891. The K_P for the HPP, WF and electrolyser controller are respectively 0.91, 1.011 and 2.5. All three of the controller are stable as the phase margin is greater than 90 degree and gain margin is greater than 3 dB. The model is then converted to discrete form by using backward Euler method. Chapter five includes the results on how the controllers will react in the whole HPP system. Firstly, a step input is applied to the HPP controller and the results shows that the system comply to Energinet grid codes as it managed to ramp up the reserved volume within 12 minutes. For up regulation, one case study is done where the output from the WF remain constant while the electrolyser is ramped down. No extra cases for up regulation is done as the results is the same as the step input test, where ramping up of WF is the more profitable choice compared to ramping down of electrolyser. For the down regulation, several case studies were done such as ramping up the electrolyser partially and ramping down the WF partially and only ramping up the electrolyser while the WF output remains constant. This is also done with multiple stacks of electrolysers instead of one aggregated model where different dispatch strategy is implemented.

In general, the objective set in the beginning of the project is achieved. Even though the simulation is done with simplified models, it shows that the plant behaves as expected and the HPP controller designed and tuned by using modulus optimum satisfy the aFRR requirements by performing up and down regulation. The electrolyser is also optimised by introducing different strategies which will extend the lifecycle of the stacks.

6.2 Future works

The project had managed to developed a aFRR controller for a HPP system, which it consists of a wind farm and a electrolyser system. Currently, the literature regarding the combination of these two assets are still not common, however that the assets involving other type of renewable plant are more common and also regarding the type of services provided. Different services will have a different design criteria and architecture for the controller. Further works can be improved by:

- Implement other frequency services such as FCR, FFR is not suitable due to the slow dynamics of the electrolyser provided.
- Tune the controller to accommodate for the losses at all operating range, instead of just 0.8 p.u. and this could be done by using a lookup table.
- Implement different dispatch strategies for the WF, and more dispatch strategy for the electrolyser stacks.
- Including more of the electrolyser dynamic when it was in different state such as off state, cold startup, warm startup, standby mode and shutdown mode.
- Evaluate the model by implementing Hardware In the Loop test in Opal-RT.
- Include more sources of renewable plant, such as battery energy storage system (BESS) and solar PV. Especially with BESS since it can provide active power to the grid as well as consuming it.
- Simulate the HPP system with variable wind speed.
- Include reactive power and voltage control in the controller.

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