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Exploitation of Power-to-Gas for Ancillary Services Provision

(within the Context of Synergy Action TSO 2020)

Víctor García Suárez

TU Delft

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by

Víctor García Suárez

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Thesis committee:	Prof. ir. Mart van der Meijden	Full profesor, IEPG
	Dr. ir. José Rueda Torres	Associate professor, IEPG
	Dr. ir. Thiago Batista Soeiro	Assistant professor, DCE&S

TU Delft

Abstract

The progressive phase out of fossil fuel power plants and the integration of variable renewable energy sources, driven by environmental directives striving for the reduction of CO_2 emissions, is reshaping how electricity Transmission System Operators (TSOs) plan and operate the power system. The mitigation of uncertainty, which imperils the balance between generation and demand, urges the search of new sources of ancillary services, traditionally provided by bulky synchronous generators. In particular, the coupling of the electricity and gas sectors reveals promising flexibility solutions for power systems through energy conversion and hydrogen storage. The conversion of electrical energy into hydrogen, commonly known as power-to-gas, is enabled by water electrolysis in electrolyzers. Specifically, the Proton Exchange Membrane (PEM) technology can react very quickly to demand variations and thus it holds a strong potential for the procurement of ancillary services.

This thesis investigates the viability of the integration of large scale PEM electrolyzer capacity into ancillary services markets in the context of the European initiative *"Synergy Action TSO 2020"*. The current framework of Dutch frequency balancing markets, voltage control and congestion management is reviewed, as well as the future European plans for the implementation of a harmonized and common frequency market. The conducted research includes the assessment of the technical adequacy of PEM electrolyzers with respect to existing prequalification requirements and the proposal of recommendations for the optimal participation in these markets.

To illustrate the value of PEM electrolyzer support for electrical networks, a case study based on a realistic representation of the transmission grid in the north of the Netherlands for the year 2030 is presented. The case study is principally intended to examine the effectiveness of the provision of primary frequency control with PEM electrolyzers. The obtained results highlight how this technology can improve the frequency stability of the power system in comparison with synchronous generators, and more importantly for the future, how it can help alleviate the negative effects attributed to the reduction of inertia in the system.

This work has received funding from the European Union's Connecting Europe Facility (CEF) programme under the grant agreement Nº INEA/CEF/SYN/A2016/1336043 – TSO2020 Project (Electric "Transmission and Storage Options" along TEN-E and TEN T corridors for 2020). This thesis reflects only the author's views and the European Commission is not responsible for any use that may be made of the information it contains.

2020

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Nomenclature

aFRR	Automatic Frequency Restoration Reserve
CAPEX	Capital Expenditure
EFR	Enhanced Frequency Response
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible Alternating Current Transmission System
FCR	Frequency Containment Reserve
GCT	Gate Closure Time
GDP	Gross Domestic Product
HVDC	High Voltage Direct Current
IGCC	International Grid Cooperation Control
LFC	Load Frequency Control
mFRR	Manual Frequency Restoration Reserve
OPEX	Operational Expenditure
PICASSO	Platform for the International Cooperation of the Automatic frequency restoration process and Stable System Operation
PEM	Proton Exchange Membrane / Polymer Electrolyte Membrane
PTU	Programme Time Unit
RTSD	Real Time Digital Simulator
TEN-T	Trans-European Transport Network
TEN-E	Trans-European Networks for Energy
TSO	Transmission System Operator

1

Introduction

1.1. Multi-Energy Sector Coupling: Electricity and Gas

The synergy between the electrical and gas sectors has gained popularity over the last years due to the promising flexibility opportunities that power-to-gas and hydrogen storage have to offer. As exemplified by Fig. 1.1, water electrolysis is the fundamental process that enables the coupling between electricity and gas. Electrolyzers allow the exploitation of the surplus of electricity generated by renewable energy sources to produce green hydrogen. By carrying the energy in molecules instead of electrons, long term energy storage is viable. Large quantities of hydrogen are normally stored in underground salt caverns, to be used later as feedstock for industrial consumers, fuel cell electricity generation and fuel cell electric vehicles. Hydrogen can also be subjected to a methanation process in order to create synthetic gas (i.e. syngas), a fuel that is mainly used for electricity generation in gas turbines and for a handful of industrial applications. Syngas can be injected safely into the natural gas network as well, potentially allowing to manage the daily and seasonal electricity demand variations. For the electrical grid in particular, it is anticipated that the actual real-time conversion of electricity into hydrogen could end up being a valuable resource for power system operation. In this thesis, the possibility of using PEM electrolyzers for the procurement of ancillary services will be discussed in detail.

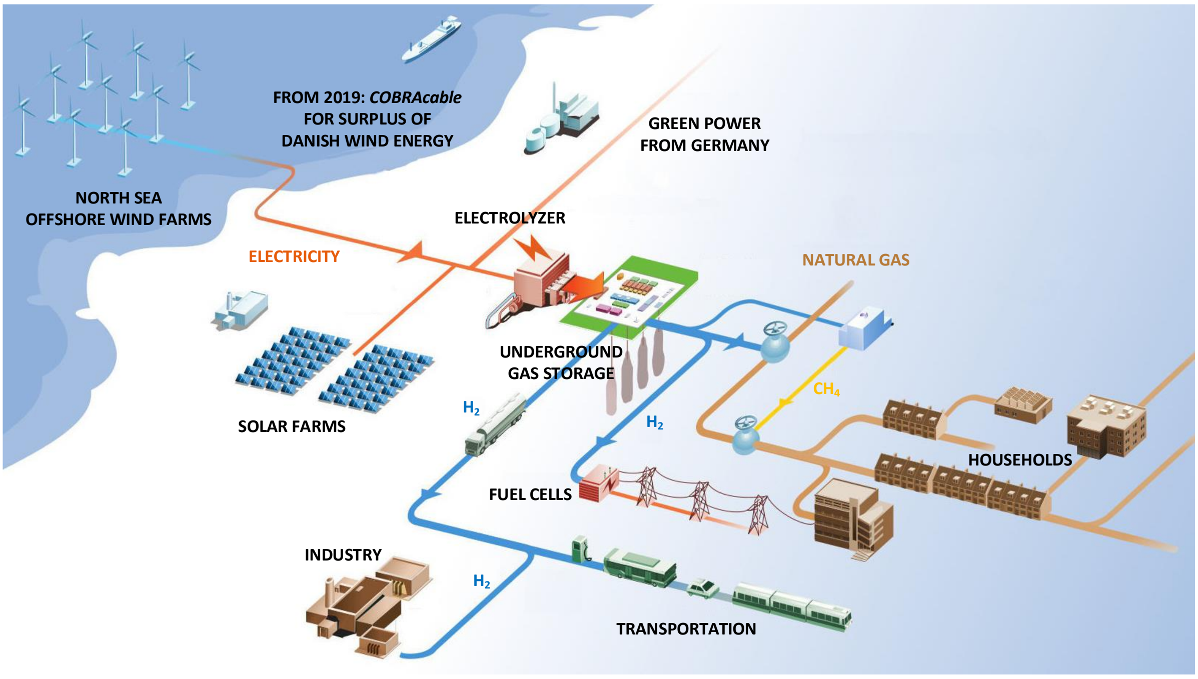
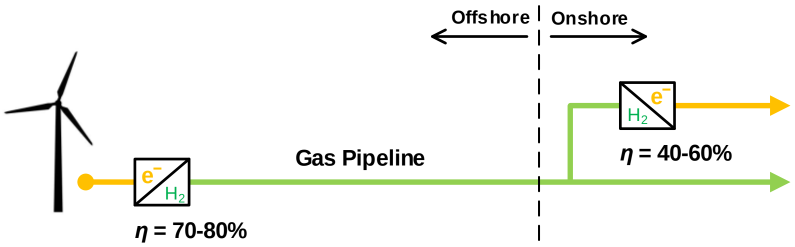


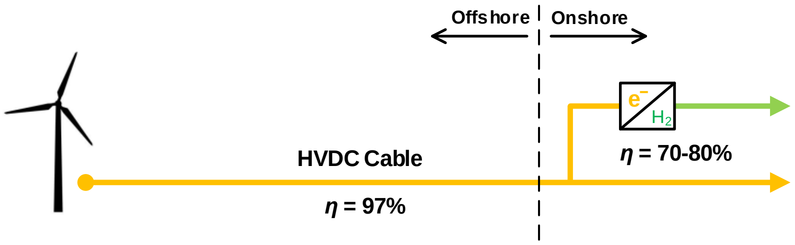
Fig. 1.1: Concept illustration of the *"Synergy Action TSO 2020"*. Adaptation from [1].

For the Netherlands, the fast growth of offshore wind energy and the existing oil and gas infrastructure of the North Sea could allow offshore green hydrogen production in the near future. Having both electrical and gas related equipment offshore opens up a discussion on how to optimally manage the transportation of wind energy back to the mainland [2]. From the example configurations illustrated in Fig. 1.2, it is clear that the end product will influence the adopted approach. If the energy is destined to hydrogen applications, it is slightly more efficient to produce the hydrogen offshore and transport it via gas pipelines. The electrical losses in a HVDC cable, typically estimated as 3%, are larger than the losses in a gas pipeline (without leaks) associated to the compressors.

If the energy is intended for electrical applications, the transportation of the energy in the form of gas is not the most convenient. The maximum efficiency of the conversion of electricity into hydrogen is around 80%, while the maximum efficiency of the conversion of hydrogen to electricity with fuel cells or the conversion of gas to electricity with gas turbines is approximately 60%. This gives a maximum roundtrip efficiency of 50%, compared to the 97% efficiency of the HVDC cable. In other words, to obtain the same amount of end electrical energy, double wind turbine capacity would be required. This would be inadvisable, since the cost of offshore wind capacity per MW is significantly larger than the cost of HVDC links and hydrogen conversion equipment (e.g. Gemini offshore wind park: ≈4.5 M€/MW [3], COBRAcable HVDC interconnector: <1 M€/MW [4], PEM electrolyzers: ≈1 M€/MW [5]).



(a) Offshore conversion of electricity into hydrogen and transmission via gas pipeline.



(b) Electricity transmission via HVDC cable and onshore conversion into hydrogen.

Fig. 1.2: Different methods for the transportation of the energy produced by offshore wind parks.

The prospect of syngas is another aspect that should be taken into account when evaluating the potential coupling between electricity and gas. In Fig. 1.3, data from the year 2017 regarding the installed capacity of gas-fired power plants, the amount of electricity generated with such technology (data retrieved from the respective TSOs), the total natural gas consumption [6], and the consumption per capita is summarized for the top members of the European Union with the highest gross domestic product (GDP). In comparison with the other countries, the Netherlands would benefit the most from the production of cheap syngas, as the Dutch power system owns the generation mix with the largest share of gas-fired power plants by a wide margin (16 GW out of the 30 GW of installed capacity), and it also leads in the percentage of total electricity generated with them (44 TWh out of the 98 TWh of the gross electricity generation) [7].

All in all, from the cited solutions that the synergy between the electricity and gas systems can offer, it is clear that this multi-energy sector coupling is worth studying and evaluating. Especially in countries with a strong presence of chemical industrial activity (e.g. Germany) and/or a large generation of electricity with gas-fired power plants (e.g. the Netherlands).

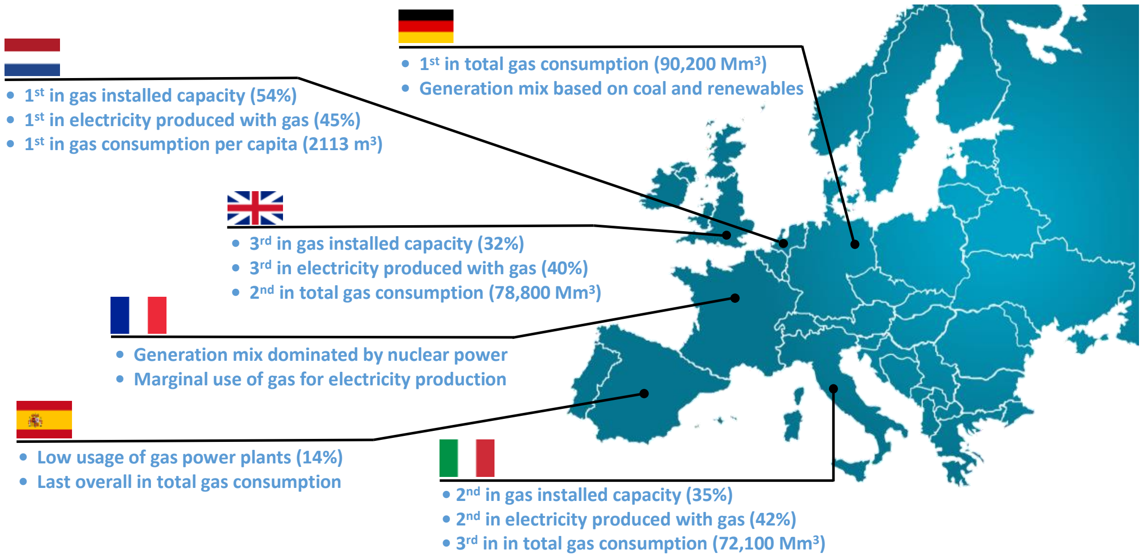


Fig. 1.3: Overview of the usage of natural gas in the top countries of Europe by GDP in 2017.

1.2. Synergy Action TSO 2020

The European project *"Synergy Action TSO 2020 (Electric Transmission and Storage Options along TEN-E and TEN-T corridors for 2020)"* [1], aims to explore the technical and commercial viability of potential power-to-gas solutions in the northern region of the Netherlands and further use the gained insight to assess the replicability of the solutions in other regions of Europe. Several partners from industry and academia are involved in the development of this project, scheduled for completion by December 2019.

The scope of *"Synergy Action TSO 2020"* comprises electrical studies, a cost-benefit analysis and two pilot activities. The impact of hydrogen conversion and storage on the electricity and gas networks is currently being investigated in Zuidwending (Veendam), where a pilot 1 MW PEM electrolyzer was recently installed [8]. Concurrently, the development of a pilot hydrogen hub is being researched in the municipality of Delfzijl, to ensure an efficient hydrogen distribution to various end costumers. The project will conclude with a detailed technical and financial outlook on the future scaling up of the studied hydrogen solutions. The list of tasks planned for the project and the participating partners are summarized below in Table 1.1.

Table 1.1: Scope of the *"Synergy Action TSO 2020"* and participating partners.

Task	Partners
Electrical power system stability studies	Delft University of Technology | TenneT TSO B.V.
Cost-benefit analysis	European Association for Storage of Energy
Pilot 1: Testing of a 1 MW PEM electrolyzer	N.V. Nederlandse Gasunie | EnergyStock
Pilot 2: Hydrogen storage and distribution	Energy Valley | Green Planet

The department of Intelligent Electrical Power Grids from Delft University of Technology, in collaboration with TenneT TSO B.V., is responsible for the development of the electrical studies within the *"Synergy Action TSO 2020"*. The research will feature extensive use of the Real-Time Digital Simulator (RTDS), which allows the simulation of power systems in real-time and the integration of analog components in the simulation. The complete list of the assigned tasks is the following:

» Modeling in RTDS of the northern Dutch electrical transmission grid (for the Groningen, Drenthe and Overijssel provinces) according to its projected future topology and operating conditions.

» Development of a generic detailed model of a PEM electrolyzer in RTDS.

» Assessment of the impact of the pilot 1 MW PEM electrolyzer on the performance of the electrical transmission network for the year 2020.

» Connection of a mock-up power rectifier to RTDS for hardware-in-the-loop testing, in combination with the implemented PEM electrolyzer model. As indicated in Fig. 1.4, the hardware is linked to RTDS via Giga-Transceiver Analogue Input (GTAI) and Output (GTAO) cards. As RTDS operates with very low voltage and current magnitudes, the output analog signals from the hardware are reduced with a current transducer, while the input signals are increased with an amplifier.

» Comparison between the performance of the electrolyzer modeled in RTDS and the data gathered from the real 1 MW PEM electrolyzer during the pilot activity.

» Investigation of the degree of flexibility and the volume of ancillary services that can be provided by 300 MW of PEM electrolyzer capacity located in Eemshaven for the year 2030.

» Study of the interaction between COBRAcable HVDC link and the modeled PEM electrolyzer (e.g. controllers, dynamic performance).

» Design of control schemes and methods for the optimal procurement of ancillary services with PEM electrolyzers and proposal of recommendations for the exploitation of the markets.

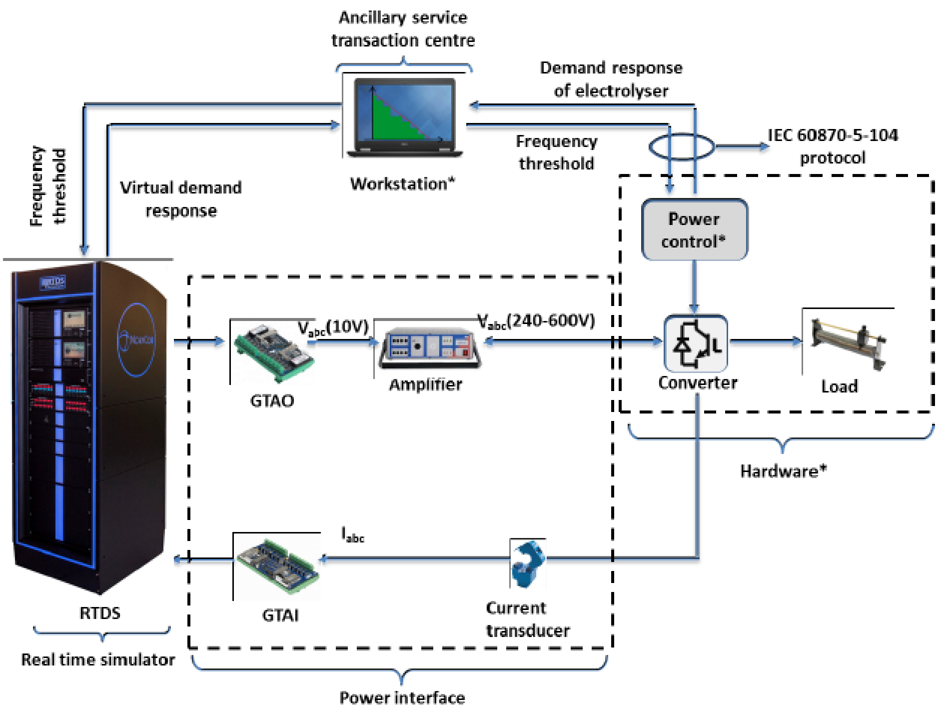


Fig. 1.4: Laboratory setup for power hardware-in-the-loop tests.

1.3. Scope of the Thesis and Research Questions

From the previous list of tasks, Delft University of Technology will have completed the first three items by the time this thesis is defended. The work presented in this report is classified in the later stage of the project. The primary objective of the research is to investigate the feasibility of the provision of ancillary services with large scale PEM electrolyzer capacity and to suggest several recommendations on the optimal exploitation of ancillary services markets. The remainder of the report is divided into three main chapters and a closing chapter that gathers the conclusions drawn during the course of the research (Chapter 5). In line with the structure of the report, the research questions and the contributions of this thesis to the ongoing development of the *"Synergy Action TSO 2020"* within Delft University of Technology are the following:

- **Which are the fundamental mechanisms of ancillary services markets? What modifications can be expected for the future?**

  This research question is addressed in Chapter 2. A comprehensible review of the framework of current ancillary services markets in the Netherlands and the latest European harmonization plans expected for the next years is provided. The review summarizes the most relevant information about the framework of ancillary services in a few pages, becoming a valuable source for consultation in any future project or thesis regarding this topic.

- **Do PEM electrolyzers comply with the technical requirements of ancillary services markets? If so, which services should be favored according to the business model of power-to-gas conversion?**

  After a brief overview of the state of the art of PEM electrolyzers, Chapter 3 focuses on the assessment of the technical adequacy of this technology for the procurement of ancillary services. By also taking into consideration the business model of power-to-gas conversion, the most attractive market integration strategy is identified. Last, the dynamic model of the PEM electrolyzers used for the electrical studies in this thesis is discussed.

- **How does the participation of PEM electrolyzers in frequency balancing markets influence the dynamic performance of the power system?**

  The case study developed in Chapter 4 looks into the impact that PEM electrolyzers can produce on the power system when participating in primary frequency control. Different future scenarios that account for the gradual phase out of CO_2 emitting traditional power plants are analyzed, further comparing the behavior of the PEM electrolyzers with the one of synchronous generators. The case study also addresses the voltage control and congestion management needs of the transmission network in the north of the Netherlands, plus a method to mitigate the variability of renewable energy by using the PEM electrolyzers. The simulations planned for this thesis were initially going to be performed in RTDS. However, due to a delay in the schedule of the overall project, attributed to unexpected circumstances in the parallel development of the initial tasks within the department, the simulations had to be performed in a different power system analysis software. Therefore, the analytic results shown in the present research should be approached as a preliminary reference to be contrasted with the future RTDS simulations.

2

Dutch Ancillary Services Markets

Real-time power system operation is challenged on a daily basis by numerous disturbances such as faults, fluctuating renewable energy or demand alterations, which can induce undesired frequency, voltage or congestion issues in the grid. Ensuring an effective and reliable operation is handled by TSOs, in part, through the procurement of ancillary services. Up until the last few years, the framework of ancillary services in European countries has been subjected to the specific rules of the corresponding national TSOs, which traditionally define the offered services, contracting methods, instructing procedures, pricing settlement rules and prequalification requirements [9].

This chapter reviews the current framework of ancillary services in the Netherlands, namely frequency balancing markets, voltage control and congestion management. For the beginning of the 2020s decade, the development of a single common European frequency balancing market is being pursued [10], aimed to improve the effectiveness of the mitigation of the variability of renewable energy and to create a harmonized market playing field across Europe. This future framework is also discussed, along with further plausible developments for the year 2030.

2.1. Frequency Containment Reserve (FCR)

Commonly known as primary frequency control, FCR serves as the first barrier against sudden imbalances between generation and demand. This service is essential to guarantee the dynamic stability of the power system, as it is designed to limit frequency excursions. The working principle behind the supply of FCR is based on the regulation of electricity generation or consumption in response to frequency deviations. For balancing services, upward regulation is activated when frequency is below the nominal value, while downward regulation is requested when frequency sits above the nominal value.

2.1.1. Current Framework of the FCR Market

According to ENTSO-E, an overall FCR capacity of ±3000 MW is currently allocated in the interconnected synchronous area of Continental Europe, further divided proportionally between the member states [11]. In the Netherlands, FCR is auctioned on the common trading platform Regelleistung [12]. This joint market has an approximate total size of ±1400 MW, and it gathers the TSOs from Germany (50Herzt, Amprion, TenneT TSO GmbH and TransnetBW), the Netherlands (TenneT TSO B.V.), Austria (APG), Switzerland (Swissgrid), Belgium (Elia) and France (RTE). In the Dutch control area, the size of FCR was originally set to ±101 MW when TenneT TSO B.V. joined the auction in 2014, and it has progressively grown up to ±110 MW in 2017 [11]. This size boost is caused by the subsequent increase in total energy demand and production in the country. Out of the required national FCR capacity, 30% is auctioned exclusively for Dutch providers, while the 70% remaining is actioned in the common market and physically exchanged through the existing cross-border interconnections [12].

The framework of the joint FCR market is depicted in Fig. 2.1. The auction takes place once a week, and it allows the participation of generators, loads and storage technologies [12]. A single symmetric capacity product is requested (i.e. upward and downward regulation are indivisible), with a minimum admissible bid size of ±1 MW, offered in steps of 1 MW and with a maximum bid size equal to the corresponding prequalified volume [13]. The product duration lasts for an entire week, meaning that the suppliers must commit for that interval of time [12]. During the selection process the cheapest bids available are awarded, and they are remunerated based on a pay-as-bid settlement rule (i.e. the units are paid exactly their offered prices) [12].

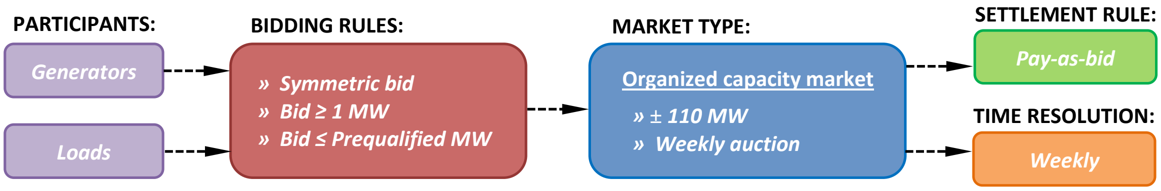


Fig. 2.1: Current FCR market framework in the Netherlands.

2.1.2. Future Framework of the FCR Market

By the year 2021, it is expected that the joint market framework will have undergone several modifications according to the latest proposal by the participant members [14]. To begin with, Denmark's TSO (Energinet) is currently involved in the FCR cooperation group and it is likely that it will have joined the market by that point. More importantly, the product duration will be shortened to 4 hours and the auction will be organized on a daily basis, with Gate Closure Time (GCT) the previous day before the actual procurement (D-1). The settlement rule will be changed to marginal pricing (i.e. every unit is paid the same price as the highest accepted offer overall), which is viewed by the TSOs to produce better price signals. Shortening the product resolution and shifting the GCT closer to the delivery time is meant to increase the flexibility of the suppliers and to help integrate renewable energy generation and other decentralized sources.

For the year 2030, it is complicated to predict how the structure of the market could vary further, as it will mainly depend on future technological developments and legislation. Ideally, the market size will reach the total capacity of ±3000 MW by the inclusion of neighboring countries. The introduction of asymmetric bids is also a plausible future implementation. Splitting the capacity product into an individual upward and downward product will enable the participation of more technologies in the market, boost the operational freedom of suppliers and allow an optimal use of their available capacity. Although asymmetric bidding is already under investigation by the TSOs, it is not planned for the next years because of the consequent increase in market complexity [14].

2.1.3. FCR Prequalification

In terms of technical requirements [13], FCR delivery relies on a decentralized linear control able to change the active power output proportionally to the frequency deviations (e.g. classic droop characteristic). For a deviation of ±200 mHz or more, the complete bid must be fully activated within 30 seconds. Similarly, for a deviation of ±100 mHz, half of the bid must be activated within 15 seconds. For providers with unlimited energy supply, the support must persist until the frequency deviation ceases.

The droop coefficient R is calculated by Eq. 2.1 [13], where Δf_{max} is the stipulated maximum frequency deviation of ±0.2 Hz around 50 Hz, f_{nom} is the nominal frequency, P_{rated} is the rated active power of the unit, and P_{bid} is the size of the offered capacity bid. For instance, a 100 MW supplier that bids 5 MW will have a droop value of 8%. The classic droop characteristic can be adapted for load demand side technologies by simply adding a minus sign to Eq. 2.1, so that the electricity consumption is lowered when the frequency drops and increased when the frequency rises.

The implemented FCR controller can establish a maximum deadband of ±10 mHz around 50 Hz, and it must measure the system frequency with an accuracy of 10 mHz or better. During the prequalification testing protocol, step frequency deviations of ±100 mHz and ±200 mHz are simulated to check that the required activation times are fulfilled. Additionally, an evenly increasing frequency deviation from 0 Hz to 200 mHz and an evenly decreasing frequency deviation from 0 Hz to -200 mHz are simulated to check that the change of the active power output follows a linear and even course.

$$R\,[\%] = 100 \cdot \frac{|\Delta f_{max}|}{f_{nom}} \cdot \frac{P_{rated}}{P_{bid}} \quad (2.1)$$

In line with the regulatory market modifications planned for the next years, it is probable that the technical requirements of FCR will eventually become more stringent, either by shortening the full activation time or by incentivizing the participation of faster technologies. Few countries are already exploring the development of exclusive products for fast regulation purposes. For example, United Kingdom's TSO (National Grid) launched the Enhanced Frequency Response (EFR) service in the year 2016. In EFR, suppliers must be able to detect a change in system frequency within 500 milliseconds and to activate the full bid within just 1 second [15].

2.1.4. FCR Prices

Since the year 2015, the increased level of competition in the FCR market has resulted in a progressive decline of prices [11]. Based on the data published in Regelleistung [12], the evolution of the pay-as-bid capacity price in the Dutch exclusive auction from June 26th 2017 to June 24th 2018 is displayed in Fig. 2.2. During this period, the average price was 15.58 €/MW/h. Therefore, it is estimated that a supplier contracted for all 52 weeks would have had a total average revenue of 136 k€/MW. In a similar fashion, the price evolution in the joint auction from June 26th 2017 to June 24th 2018 is shown in Fig. 2.3. The average price and total revenue in this case were 12.81 €/MW/h and 112 k€/MW respectively. It is observed that the prices in the joint auction are generally lower than in the Dutch auction. This is attributed to the higher offered capacity and the larger number of competitors that participate in this auction [7].

The prequalification of new technologies in the FCR market is also having an impact on the decrease of prices. As recently seen in the United Kingdom, battery storage was the only winning technology in the first ever EFR tender. A total of 200 MW were contracted for a period of four years, with prices ranging from a value as low as 8 €/MW/h to a maximum of 14 €/MW/h [16].

For the year 2021, the reduction of the product resolution to 4 hours is expected to induce more volatile price variations, while the implementation of marginal pricing will probably lead to slightly higher prices. Hypothetically, every supplier in the Dutch exclusive auction and the joint auction would have had a total revenue in the described period of time of 148 k€/MW and 121 k€/MW respectively. These values constitute an approximate increment of 8% with respect to the average pay-as-bid price.

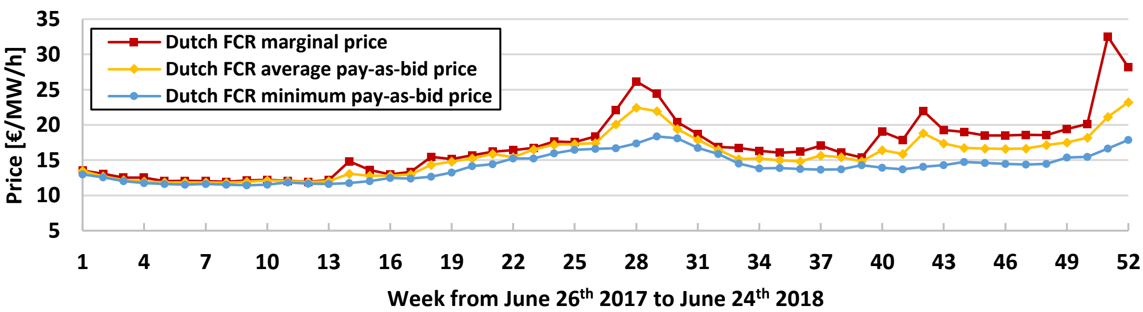


Fig. 2.2: Weekly FCR price in the Dutch exclusive auction from June 26th 2017 to June 24th 2018.

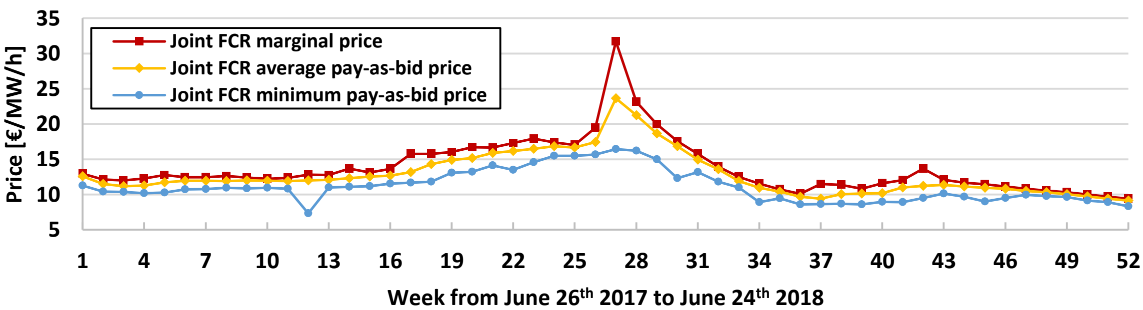


Fig. 2.3: Weekly FCR price in the joint auction from June 26th 2017 to June 24th 2018.

2.2. Automatic Frequency Restoration Reserve (aFRR)

Formerly referred to as secondary frequency control, aFRR acts right after FCR to restore the active power balance in every control area within 15 minutes after a disturbance. Currently, the framework of aFRR in Europe is entirely dependent on national legislation [9], and so far, only Germany and Austria share a pilot common aFRR market [10]. Nevertheless, all of the participants of the joint FCR market, plus Denmark and Czech Republic are part of the International Grid Cooperation Control (IGCC) initiative [17], which features advanced technical coordination to prevent different control areas from activating opposite direction aFRR simultaneously.

Manual frequency restoration reserve (mFRR), previously known as tertiary frequency control, is only activated when aFRR is not enough to alleviate the power imbalance (e.g. a severe outage occurs at a large power plant). In the Netherlands, mFRR is referred to as incident reserve. Because it is hardly ever used and due to the large minimum size required to apply for the available capacity product [18], mFRR is judged as a low interest service for electrolyzers and it is therefore not included in the present market review.

2.2.1. Current Framework of the aFRR Market

The required minimum aFRR capacity per country, typically between 3 to 4 times bigger than the one for FCR, is usually guaranteed via the specific capacity product of each territory [9]. In the Netherlands, a minimum of ±350 MW of aFRR capacity is assigned for 2018, effectively guaranteed via bilateral contracts of monthly or weekly duration [19]. The offered capacity must be symmetric and must have a minimum size of 1 MW and a maximum size of 999 MW [20]. Suppliers are remunerated on a pay-as-bid scheme [7].

The daily deployment of aFRR is divided into 96 Programme Time Units (PTUs) of 15 minutes each. For each of the PTUs, all the contracted parties are obliged to bid their agreed capacity for upward and downward regulation. Additionally, non-contracted suppliers are allowed to send voluntary (i.e. free) capacity bids, which can be asymmetric, offered in steps of 1 MW and at least 1 MW total in size. When all the bids have been received, they are inserted into a common bid ladder, with GCT an hour before the procurement (H-1). In the event of a power imbalance, the units are activated according to a merit order (i.e. cheapest bids first) [20], and the last participant unit sets the marginal price used to settle the energy usage in the PTU [9]. The structure of the complete aFRR market in the Netherlands is summarized below in Fig. 2.4.

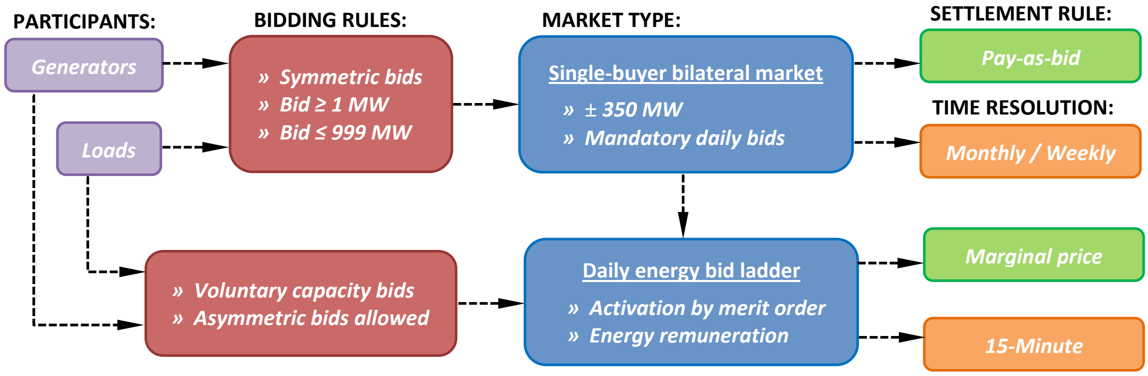


Fig. 2.4: Current aFRR market framework in the Netherlands.

2.2.2. Future Framework of the aFRR Market

Over the last few years, the development of a joint aFRR market framework in Continental Europe has been targeted, and it is expected to be completed during the early 2020s. At the moment, PICASSO is the reference project for the harmonization of the aFRR platform [10]. The proposed market modifications according to this initiative focus exclusively on the energy product, delegating the definition of the capacity product, or lack thereof, to the corresponding national authorities. The Dutch system already follows the structure of the goal common energy market. When implemented, a common European bid ladder will be constructed for each of the PTUs and a common cross-border merit order list will determine the energy activation of the suppliers. Last, cross-border marginal pricing will become the settlement rule, once again prioritizing the cheapest bids and at the same time avoiding possible congestions in the cross-border interconnectors.

2.2.3. aFRR Prequalification

For the activation of aFRR, suppliers must follow the setpoints sent by the TSOs from a centralized Load Frequency Control (LFC), as to correctly restore the power balance in all of the control areas. In TenneT TSO B.V., the power setpoints are realized in steps of 1 MW. The units must guarantee a minimum ramp rate of 7% of the bid per minute and the full activation of the bid must be completed within 15 minutes [20]. It is expected that in the upcoming joint aFRR market the full activation time will be shortened to 5 minutes, which translates into a minimum ramp rate of 20% of the bid per minute [10]. Technologies that can achieve greater ramp rates than the minimum benefit from higher income, as the energy volume is supplied faster to the network.

2.2.4. aFRR Prices

The potential annual revenue that a supplier can earn from partaking in the aFRR market is hard to estimate, as neither imbalances nor the merit order list can be predicted. For suppliers under contract, the average price of the symmetric capacity product in the year 2017 was approximately 10 €/MW/h [7], thus totaling a revenue of around 86 k€/MW if contracted for the entire year. From the data published by TenneT TSO B.V. [21], the energy price duration curve for upward energy aFRR regulation from June 26th 2017 to June 24th 2018 is plotted in Fig. 2.5. For upward energy regulation, for which TSOs remunerate suppliers (vice versa for downward energy regulation), the average settlement price during the cited period was 80 €/MWh at peak hours (i.e. 08:00 to 20:00) and 73 €/MWh for the rest of the day. In total, 50% of the PTUs requested activation, while four out of the seven most expensive prices occurred on a single evening during the month of November.

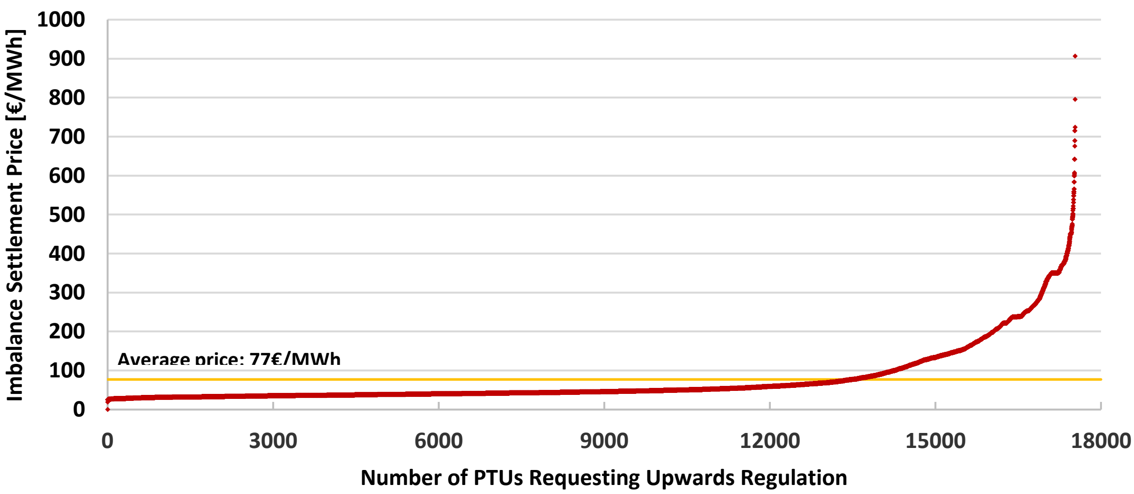


Fig. 2.5: Energy price duration curve for upward regulation aFRR from June 26th 2017 to June 24th 2018.

2.3. Voltage Control

The injection or absorption of reactive power is the main mechanism to control the voltage in power systems. Due to the local nature of voltage profiles, each country specifies its own market framework [9]. Generally, every grid code demands mandatory voltage regulation capabilities to synchronous generators and power electronic interfaced renewable energy sources connected to the transmission grid. Besides, other equipment such as power transformers, FACTS, HVDC links, battery storage and several industrial loads can also effectively contribute to the control of voltage.

In the Netherlands, the optimal use of reactive power is defined by TenneT TSO B.V. on the basis of its own experiences, studies and local needs. For generators with installed capacity larger than 5 MW, voltage control is a mandatory and contracted service [9]. A yearly tender is organized for external reactive power suppliers, where bilateral contracts for a duration of the entire year can be arranged. For every control area, price is the only criterion during the contracting phase. The remuneration is settled on a pay-as-bid rule, and depending on the contract terms, a yearly fixed fee or an hourly variable fee is agreed [22]. Concerning the technical requirements of this service, suppliers must reach the full activation of the reactive power setpoints commanded by TenneT TSO B.V. within 15 minutes [22].

2.4. Congestion Management

TSOs can approach different strategies in order to relieve the congestion of transmission lines [7]. The redispatch of power plants and large demand side response is widely used, but it comes at a combined cost of several billions of euros in Europe every year. For instance, in Germany alone the redispatch cost in the year 2017 was approximately 1.15 B€ [23]. TSOs can minimize the call for redispatch and anticipate for future transmission capacity needs by investing in infrastructural upgrades for the grid. On a European level, TSOs can opt to make use of available cross-border capacity to alleviate congestions as well [7].

In the Netherlands, the enhancement of the grid infrastructure is the action plan currently followed by TenneT TSO B.V. [7]. However, if a congestion issue is identified, bilateral contracts can be drawn with generators or large industrial consumers as an alternative [22]. As a last remark, just like in the case of voltage control, the prices settled for congestion management are not publicly available. Also, both services are fundamentally dependent on local needs, making the prospect of a market expansion highly improbable.

3

Power-to-Gas: PEM Electrolyzers

Existing research in the field of water electrolysis anticipates that PEM technology will be the industry standard for the year 2030 [24]. In comparison to alkaline electrolysis systems, PEM is favored due to its higher power density, better cell efficiency, improved hydrogen purity and faster dynamic performance. In the present day, PEM systems are already available on a commercial level, but capital costs are still expensive and their reduction constitutes the main industry goal moving forward.

This chapter serves as an overview of the state of the art of PEM electrolyzers. Topics such as the latest developments from manufacturers, the expectations for the year 2030, the evaluation of the potential contribution of this technology to power system flexibility, its adequacy to the future ancillary services markets and its modeling for dynamic electrical studies are discussed.

3.1. State of the Art

At the moment of the writing of this thesis, the maximum size of an individual PEM electrolyzer is 3 MW [25]. The electrical capacity of the unit determines how much hydrogen can be generated, as the production rate is directly proportional to the input DC electrical power. PEM electrolyzers can generate around 15 kilograms of hydrogen per hour for each installed MW, with an overall system efficiency ranging from 70-80% [5]. Efficiency is further influenced by the loading level and the electrolysis stack constitutes the main source of losses [5]. The maximum lifetime of the electrolysis stack is roughly 80,000 hours (approximately 9 years of continuous operation), whereas the rest of the equipment in the installation can work up to 30 years [26]. With regard to the finances, the CAPEX of the PEM electrolyzer technology is currently priced on 1 M€/MW, while the additional yearly OPEX is less than 5% of the initial investment [27].

Over the next years, the modular aggregation of individual units will be adopted in the pursuit of large scale systems. The larger sizes and the associated economies of scale are expected to decrease the capital costs to 500 k€/MW midway through the 2020s decade [5]. Also, the efficiency is anticipated to reach 85% as the technology improves [5]. All in all, the promising prospect of PEM power-to-gas conversion has resulted in the development of several small scale electrolyzer demonstration projects worldwide. Not only that, but few commercial projects on a larger scale have already been announced, like a 10 MW refinery in Germany [28], or a 13 MW methanation plant in Austria [29]. Others are still in the initial planning stages, as in the case of a potential 20 MW facility for hydrogen mobility in the Netherlands [30].

(a) Siemens' SILYZER300 (b) ITM Power's HGas (c) Hydrogenics' HyLYZER600 (d) Nel Hydrogen's A-Range

Fig. 3.1: Megawatt range PEM electrolyzers from different manufacturers.

3.2. Adding Flexibility to the Power System

From the point of view of the electrical network, the most interesting technical capability of PEM electrolyzers lies in the fast dynamics of the electrolysis process. Manufacturers guarantee that ramping up and down to change the consumption of electricity can be completed in less than 1 second [5,26]. Furthermore, operating at partial load with respect to the rated capacity can be sustained during long periods of time [31], as long as a minimum consumption level is respected to avoid compromising the lifetime of the stack (e.g. 30% loading). Last, PEM electrolyzers can go through a cold startup within a few minutes and completely shut down within a few seconds [27,31].

The cited technical characteristics open up several potential demand side response schemes to support the operation of electrical power systems. For instance, fleets of PEM electrolyzers could be commanded to quickly ramp-up their consumption at times when there is surplus of renewable energy generation, hence contributing to the minimization of electricity curtailment. On top of that, they could be coordinated with renewable energy sources to help mitigate the fluctuations of the generated power, as later explained in the case study.

3.3. Technical Adequacy for Ancillary Services Provision

The technical capabilities of PEM electrolyzers also indicate a notable adequacy for the participation in the procurement of ancillary services, especially for frequency balancing and congestion management. For FCR and aFRR, electrolyzers can provide a much quicker response to frequency variations than the minimum full bid activation times stated in the respective prequalification requirements.

For congestion management, large scale electrolyzers can contribute to the reduction of critical peak loads by curtailing their electricity demand or even by completely interrupting operation. The fast speed provided by the PEM electrolyzers becomes an advantage over other industrial loads with slower dynamics. By automating the procedure or by allowing direct control by the operators of the network, it would be possible to fully exploit the capabilities of the PEM technology. For example, to swiftly alleviate a congestion caused by the sudden trip of a transmission line.

For steady state and dynamic voltage control, electrolyzers can provide reactive power support when operating at partial load. In such scenario, the remainder capacity of the electronic converter that feeds the stack can be used to inject (or absorb) reactive power to the grid. Participating in voltage control while simultaneously working at rated active power would require an oversized electronic converter. Alternatively, it would be feasible to indirectly influence voltage by varying the active power consumption of the units. However, this method is less efficient than the use of reactive power.

3.4. The Power-to-Gas Business Model

The fundamental business principle behind power-to-gas resides in the exploitation of cheap electricity to produce hydrogen, when the entire process is more cost-effective than the direct purchase of hydrogen on the market. The hydrogen price sets the threshold electricity price for which the power-to-gas conversion is competitive, thus determining the annual number of hours of operation. The principal stream of revenue for this business comes from the sale of hydrogen and syngas, and it can be supplemented and maximized by partaking in electrical ancillary services markets [32].

The capacity factor of the electrolyzers will be crucial to decide what ancillary services markets are the best option. If the operation throughout the day is very intermittent, engaging in the energy market for upward regulation aFRR via voluntary bidding would be the most accessible way to participate in frequency balancing, mainly because of the PTU length of 15 minutes. From the year 2021 onwards, the reduced resolution of the FCR product will also allow the integration of electrolyzers in this market. When planning the bidding strategy, it is important to consider that FCR features capacity payments, a remuneration scheme that tends to be more attractive for suppliers than energy payments.

As already explained, the contracting of voltage control and congestion management in the Netherlands is negotiated with TenneT TSO B.V. bilaterally. The contract clauses (e.g. duration, availability, etc.) could be customized to satisfy both parties if there exists the need for the service. Particularly for voltage control, the owners of the power-to-gas facility may not be interested in oversizing the electronic converter if the contracting is not guaranteed beforehand.

3.5. Modeling for Dynamic Electrical Studies

A complete representation of a PEM electrolyzer unit includes the modeling of the stack, the power conversion system (i.e. transformer and electronic converters) and the balance of plant (i.e. electrical consumption of the remainder equipment of the installation) [33]. The electrolyzer is coupled to the grid via an AC-DC rectifier, followed by a DC-DC converter that controls the input power by modulating the electrical current. The electrolysis stack can be reduced to an equivalent circuit composed by the open circuit DC voltage of the stack, plus a resistor in series to represent the different internal electrical losses. As mentioned in the introduction, the implementation in RTDS of a detailed generic model of a PEM electrolyzer is currently being developed by Delft University of Technology as a part of the *"Synergy Action TSO 2020"* [1].

The main focus of this thesis is to evaluate the effectiveness of the provision of ancillary services with PEM electrolyzers and to estimate the impact they would have on the dynamic performance of the power system. Consequently, the description of the internal behavior of the electrolyzer is not strictly required, only an accurate representation of the ramping dynamics of the electrolyzer is mandatory. In literature, very limited information can be found concerning the evolution of the power curve after a setpoint change and the definition of precise settling times. For this thesis, previous research on a kilowatt range PEM unit was used as the base for the dynamic modeling [31]. These laboratory tests, displayed in Fig. 3.2 and Fig. 3.3 for different ramp-up and ramp-down step responses respectively, have proven the capability of the sample PEM electrolyzer to settle within only 250 milliseconds after the event is triggered. Moreover, the shape of the current curve can be approximated mathematically by a first order differential equation, which allows to simplify the electrolyzer model as an equivalent dynamic load able to emulate the performance of the tests.

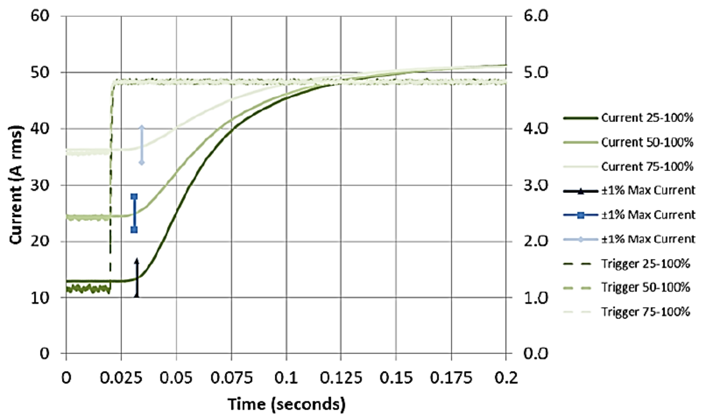


Fig. 3.2: Ramp-up laboratory tests of a 40 kW PEM electrolyzer. Retrieved from [31].

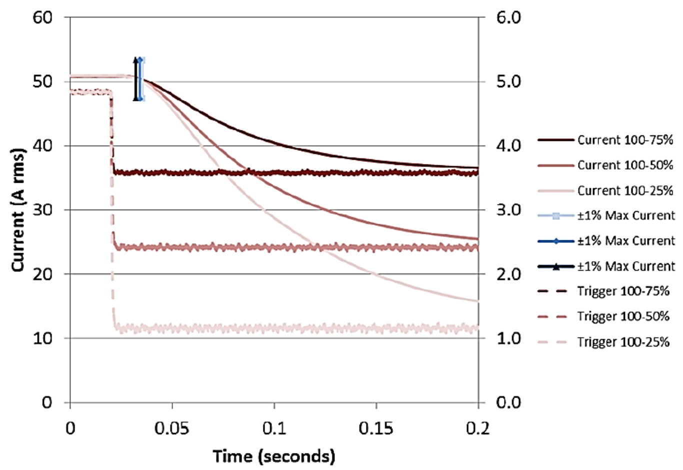


Fig. 3.3: Ramp-down laboratory tests of a 40 kW PEM electrolyzer. Retrieved from [31].

1 Detailed information about the complete modeling process of the PEM electrolyzer is available in the following TU Delft MSc thesis: *"Feasibility of Demand Side Response from Electrolysers to Support Power System Stability"*.

Additional controllers are implemented to enable the delivery of ancillary services. When the electrolyzer is not working at the rated consumption and voltage control is available, the injection of reactive power is managed via an external setpoint signal that simulates a request coming from the TSO. A similar approach is followed for congestion management, as an analogous external signal is used to modify the setpoint of the input active power.

For FCR, the designed control block diagram is portrayed in Fig 3.4. Instead of using the droop coefficient as computed with Eq. 2.1, the inverse linear characteristic can be easily simplified so that the bid size is directly an input variable. The controller takes frequency deviations *(Δf)* larger than the insensitive range of ±10 mHz and calculates how much power must be added or subtracted *(ΔP)* to the actual active power consumption *($P_{reference}$)*. The new setpoint *($P_{setpoint}$)* is bounded by a maximum *(P_{max})* and minimum *(P_{min})* power, that allows to configure if the FCR support is symmetric or asymmetric. If the upper bound is equal to the reference power *($P_{max} = P_{reference}$)*, the unit provides exclusively upward regulation. On the other hand, if the lower bound is equal to the reference power *($P_{min} = P_{reference}$)*, the unit provides only downward regulation. In order to enable symmetric support, the power bounds must ensure that the full bid can be activated in both directions *($P_{max} \geq P_{reference} + P_{bid}$* and *$P_{min} \leq P_{reference} - P_{bid}$)*. Finally, the new setpoint is fed to the simplified dynamic description of the PEM electrolyzer.

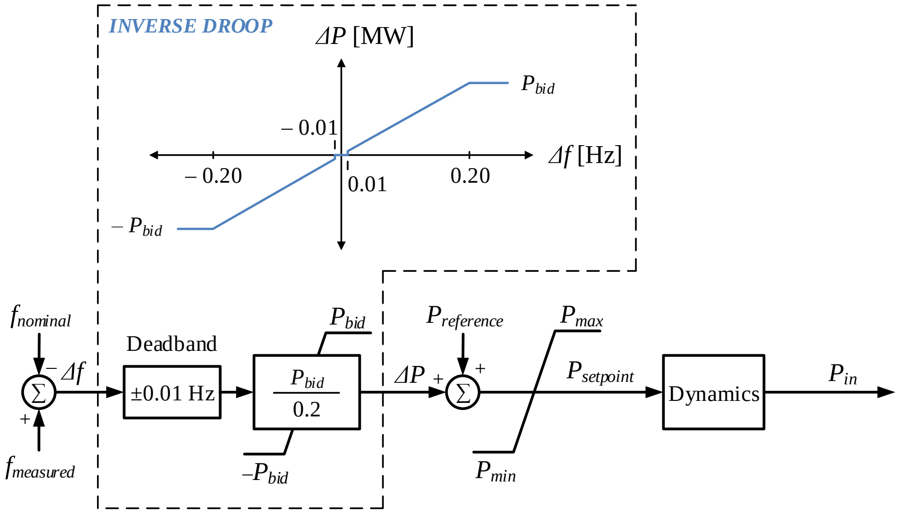


Fig. 3.4: Frequency control and inverse droop characteristic implemented to the PEM electrolyzers.

4
Case Study: Northern Dutch Grid in 2030

In the context of *“Synergy Action TSO 2020”*, the Groningen region is considered to be the most promising location for the installation of large scale power-to-gas capacity. This area features the Eemshaven seaport, a pivotal infrastructure in the Netherlands that gathers several gas-fired power plants, wind parks and one of the endpoints of the HVDC interconnections with Norway (since 2008) and Denmark (planned for commissioning in 2019).

The main objective of the proposed case study is to evaluate how the procurement of ancillary services with PEM electrolyzers influences the dynamic performance of the electrical power system. In accordance to the *“Synergy Action TSO 2020”*, a total electrolyzer capacity of 300 MW is hypothetically installed in Eemshaven for the year 2030. The modeled network, highlighted in Fig. 4.1, covers key sections of the 380 kV and 220 kV high voltage transmission grid in the Groningen, Drenthe and Overijssel provinces.

Previous research has pointed out that the integration of large shares of fast demand side response with PEM electrolyzers will produce a positive effect on power system stability [31,34]. This chapter focuses primarily on the potential contribution of electrolyzers to FCR. The impact of the bid sizes, the location in the grid and the level of rotational inertia in the system are thoroughly examined. The case study also discusses the prospect of voltage control and congestion management in the area and concludes with the interaction of PEM electrolyzers with renewable energy sources to help mitigate their inherent variability.

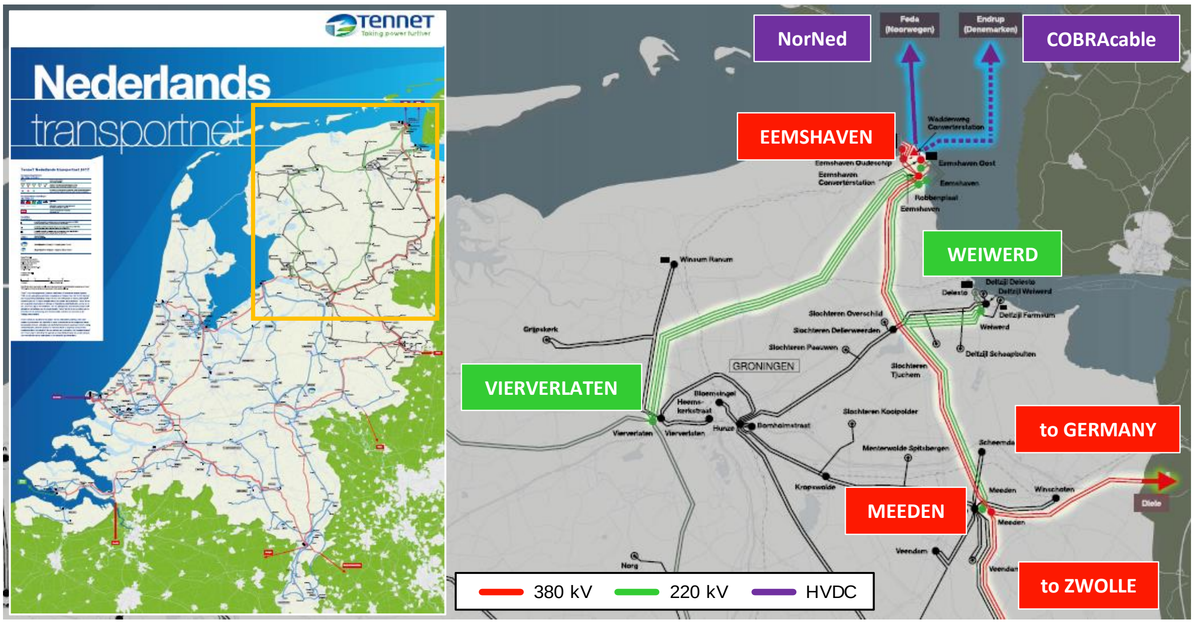


Fig. 4.1: Modeled section of the electrical transmission network in the north of the Netherlands. Adaptation from [35].

4.1. Description of the Test System

The single line diagram of the test system is illustrated in Fig. 4.2. The topology, the power flow conditions and the electricity demand were derived from the guidelines of the ten-year development plan of TenneT TSO B.V. [36]. The installed generation capacity in the network is divided between a gas-fired power plant (600 MVA) and the Gemini offshore wind park (600 MW). In the considered scenario, a substantial share of the total electricity demand comes from the excess hydro and wind power from Norway and Denmark respectively, and it is imported via NorNed (700 MW) and COBRAcable (700 MW) HVDC links.

The test system was modeled in DIgSILENT PowerFactory 2018 SP1. Generic models already available in the software were used to describe the different elements in the grid [2]. For this case study, it is assumed that only the gas-fired power plant and the PEM electrolyzers participate in the regulation of the system. Accordingly, a generic gas turbine-governor with droop control, an exciter and a power stabilizer were implemented to the synchronous generator to enable dynamic control. The PEM electrolyzers, as explained in the previous chapter, were modeled as an aggregated dynamic load able to partake in the provision of ancillary services. The HVDC interconnectors were simplified as constant negative loads to merely depict the power transfer. Likewise, the connections to other parts of the transmission network and the local demands were also modeled as constant loads.

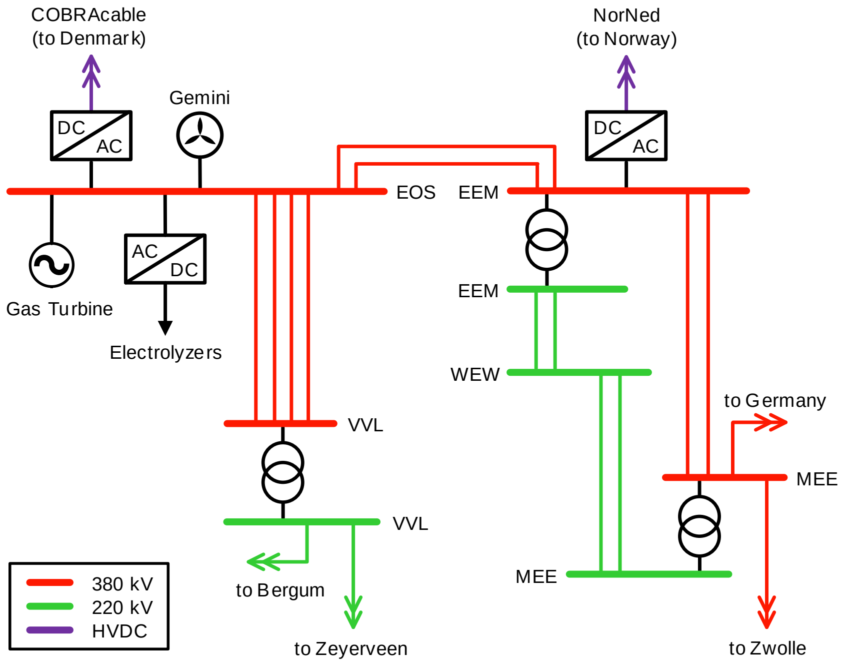


Fig. 4.2: Single line diagram of the modeled section of the northern Dutch transmission network for the year 2030.

4.2. Assessment on Voltage Control and Congestion Management

In order to assess the voltage control and congestion management needs of the transmission network in the north of the Netherlands, a preliminary contingency analysis that covered the N-1 and N-2 criteria (i.e. sudden loss of one or two elements respectively) was performed for different grid topologies and power flow conditions for the year 2030. According to the simulations, no significant voltage or congestion issues were identified, which indicates the strength of the future transmission grid.

The infrastructural reinforcements planned for the next years [36], such as the new 380 kV lines connecting Eemshaven with Vierverlaten, will add enough capacity to successfully integrate COBRAcable and other potential new projects. Besides, the presence of synchronous generators, wind parks and HVDC links in Eemshaven is expected to guarantee enough voltage support in the region. Therefore, the provision of voltage control and congestion management with the PEM electrolyzers installed in that area will not be imperative, yet it should be considered as a feasible possibility for other parts of the network.

[2] Due to confidentiality reasons, the parameters of the components of the modeled network are not provided.

4.3. Procurement of FCR: Effects on Frequency Response

To analyze how the provision of FCR with PEM electrolyzers influences the frequency response of the power system, the network is subjected to a sudden decrease in generation at Eemshaven Oudeschip (EOS). An event of such characteristics could be originated by the disconnection of several wind turbines or by the loss of imported power from the HVDC links. The overall FCR capacity available in the test grid was set to a constant value of 30 MW for all the simulations, approximately 27% of the actual total support assigned to the Netherlands and 1% of the total capacity of the synchronous area of Continental Europe [11]. The initial conditions in every case are identical (e.g. power flow) to ensure a fair comparison of the results.

First, the frequency response for different bid size ratios between the gas turbine and the electrolyzers is tested. Both providers operate at a reference power setpoint that allows the participation in the FCR market via symmetrical bidding. In general lines, the results plotted in Fig. 4.3 show that the introduction of PEM electrolyzers improves the frequency response. Better frequency nadir is obtained (i.e. largest frequency deviation), the oscillations of the turbine are reduced and the network reaches steady state faster. Comparing the frequency response when the 30 MW of FCR support comes exclusively from the gas turbine with respect to when it comes exclusively from the electrolyzers serves as an accurate representation of the dynamics of both technologies. The speed of the dynamic response of the PEM electrolyzers is unmatched by the gas-fired power plant, and given that gas turbines are the fastest turbine technology coupled to synchronous generators, the differences would be more noticeable if using traditional steam turbines.

Next, the values of the frequency nadir for different bid size ratios when the network is subjected to different disturbances sizes are explored. In this case, the results displayed in Fig 4.4 further emphasize the effectiveness of PEM electrolyzers to limit frequency excursions in comparison to traditional power plants. Notice that the difference between the plotted lines is larger as the size of the disturbance increases. It can also be observed that the betterment of the results is not linearly proportional to the bid size of the electrolyzers. For instance, for the 20 MW disturbance, the frequency nadir for a electrolyzer share of 0% is 49.80 Hz, while for a 50% share the value improves by 46 mHz, and for a 100% share it improves by 67 mHz. This can be attributed to the fast dynamics of the PEM technology, which become more dominant than the dynamics of the gas turbine even for small bid size ratios.

During the course of the simulations the sensitivity to the electrolyzer locations was also tested, but due to the high strength of the grid, the results did not deviate significantly. For weaker grids and more severe disturbances, the impact of the location of the FCR capacity gains more importance and positions closer to critical buses in the network tend to produce an improved dynamic performance [34].

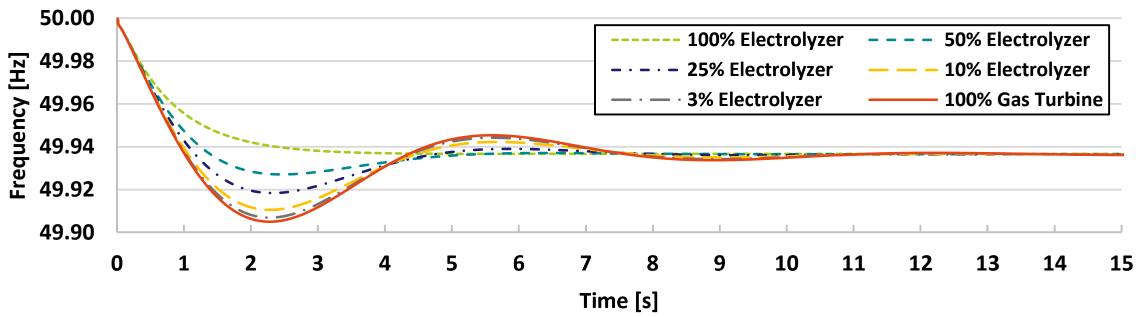


Fig. 4.3: Frequency response for different FCR bid size ratios.

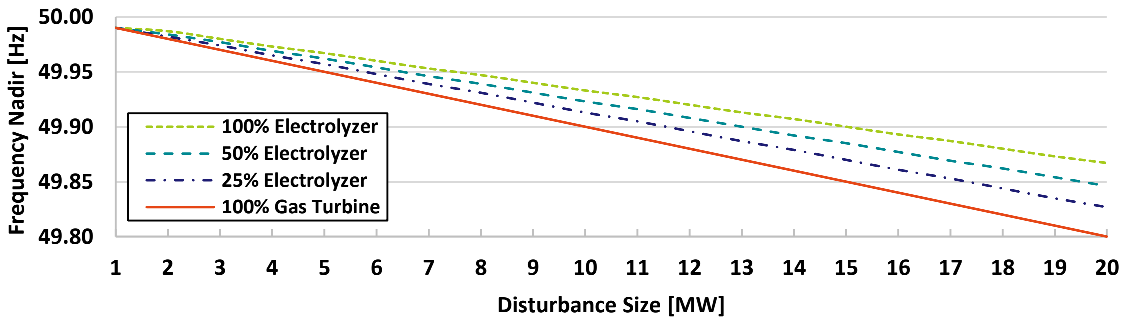


Fig. 4.4: Frequency nadir for different disturbance sizes and FCR bid size ratios.

4.4. Dealing with Low Inertia Grid Conditions

For the power system, the reduction of CO_2 emissions is being achieved by gradually substituting traditional thermal synchronous generators with stochastic renewable energy sources. In such scenario, the frequency stability of the grid is jeopardized, as a consequence of the decrease of the rotational inertia associated to synchronous generators [37]. Although a certain level of inertia will remain in hydro power plants and some rotating loads, it is necessary to explore how renewable energy and other new technologies can make a contribution to this area.

In this part of the study, the possible role of PEM electrolyzers to mitigate the detrimental effects of low inertia in the grid is investigated. In the modeled system, the only source of rotational inertia comes from the synchronous generator of the gas-fired power plant, which has an inertia constant *(H)* of 5.74 seconds. Since the phase out of this single generator would result in zero inertia in the test network, the value of the inertia constant can be modified instead to create different scenarios, as summarized in Table 4.1. The base case is derived from the base grid conditions. Rotational inertia is set to the original value and FCR support comes exclusively from the gas turbine. In the second and third scenarios, the rotational inertia is cut down to half to represent the energy transition of the power system, while the provision of FCR incorporates PEM electrolyzers. Finally, the fourth case features the exclusive procurement of FCR with PEM electrolyzers in a grid with low rotational inertia, linked to the extensive decommissioning of thermal power plants.

Table 4.1: List of scenarios, FCR bid sizes per technology and results of the frequency indicators.

Scenario	Inertia	Gas turbine	PEM electrolyzers	Nadir [Hz]	RoCoF [mHz/s]
Base case	100%	30 MW FCR bid	No FCR support	49.905	66.464
Energy transition | Base	50%	30 MW FCR bid	No FCR support	49.868	130.431
Energy transition | Mix	50%	15 MW FCR bid	15 MW FCR bid	49.915	110.228
Low inertia | H_2	10%	No FCR support	30 MW FCR bid	49.914	552.539

The frequency response for each case is shown in Fig. 4.5. The comparison of the first two scenarios gives an idea on the effects of rotational inertia in electrical networks when synchronous generators are the only participants in FCR. First and foremost, inertia is directly related to the initial slope of the frequency drop, technically known as rate of change of frequency (RoCoF) [37]. Thus, the reduction of the inertia in the system translates into a steeper RoCoF (measured in the first 500 milliseconds) and a worse frequency nadir. For the gas turbine, the smaller inertia constant induces larger oscillations to the response.

In the third scenario, half of the FCR support is provided by PEM electrolyzers. Despite having almost the same initial RoCoF as in the previous case, due to the identical inertia value, the fast dynamics of the PEM technology still improve the frequency nadir with respect to the base case. In the fourth scenario, the frequency drop right after the disturbance is extremely steep (around 8 times faster than the base case), because of the lack of dominant inertial behavior. Yet once again, the fast recovery by the PEM electrolyzers is able to limit the frequency nadir to a better value than in the base case.

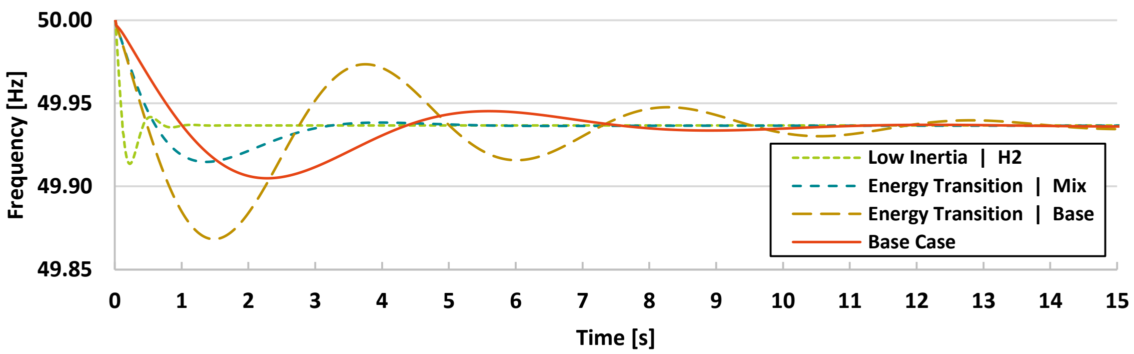
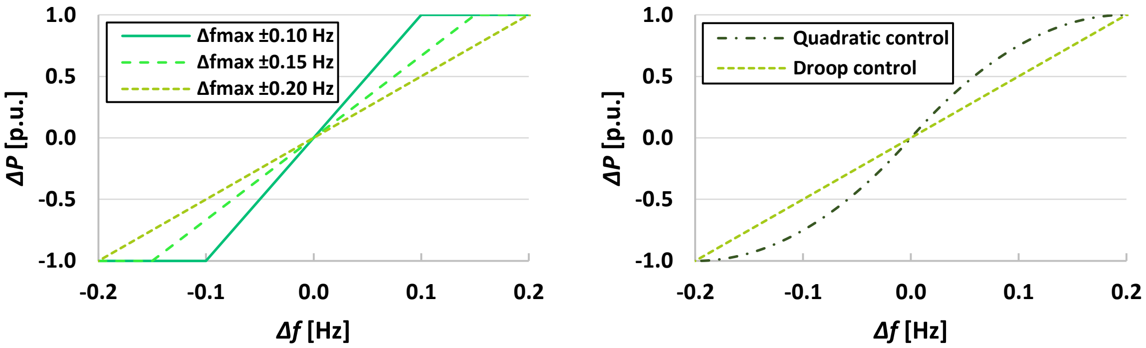


Fig. 4.5: Frequency response for the four described scenarios featuring different inertia values.

Up until this point, the case study has proven the usefulness of PEM electrolyzers to limit the frequency nadir after a sudden mismatch between generation and demand, even when rotational inertia is limited. Since electric loads are designed to perform certain tasks or applications (e.g. the goal of electrolyzers is to produce hydrogen), the potential solutions to improve the RoCoF should be mainly tackled by generating units (e.g. delivery of synthetic inertia with renewable energy sources) [37].

Nevertheless, the fast response capability of PEM electrolyzers could be exploited to further enhance the frequency behavior. For instance, the droop characteristic can be easily modified so that the delivered regulation capacity is larger for the same frequency deviations, while keeping the FCR bid size constant. This can be achieved by modifying the maximum frequency deviation value *(Δf_{max})* below ±0.2 Hz in the control system, which effectively increases the slope of the droop, as illustrated in Fig. 4.6 (a).



(a) Droop characteristic for different Δf_{max}. (b) Droop vs. quadratic characteristic (Δf_{max} = ±0.20 Hz).

Fig. 4.6: Alternative frequency-power characteristics for improved FCR support.

Another approach could be to keep the maximum frequency deviation constant but to modify the shape of the frequency-power characteristic. To name a few, the droop could be split into smaller sections with different slope values, or a quadratic characteristic could be implemented, as exemplified in Fig. 4.6 (b). The generic formula to calculate the quadratic equation is indicated in Eq. 4.1, in accordance to the control scheme explained in Fig 3.4.

$$\Delta P = -P_{bid} \cdot \left[\frac{1}{|\Delta f_{max}|}\right]^2 \cdot \Delta f^2 + 2 \cdot P_{bid} \cdot \frac{1}{|\Delta f_{max}|} \cdot \Delta f \quad \forall \quad \Delta f > 0$$
$$\Delta P = +P_{bid} \cdot \left[\frac{1}{|\Delta f_{max}|}\right]^2 \cdot \Delta f^2 + 2 \cdot P_{bid} \cdot \frac{1}{|\Delta f_{max}|} \cdot \Delta f \quad \forall \quad \Delta f < 0 \tag{4.1}$$

For the described alternative FCR characteristics, the low inertia scenario is recomputed. The results are condensed in Table 4.2 and the frequency responses are plotted in Fig. 4.7. As expected, a better steady state value and frequency nadir are accomplished with steeper slopes. Also, the time it takes to reach the nadir is lowered, which indirectly improves the RoCoF, but not significantly (still 7 times faster than the base case). From the results, it is concluded that the ramping requirements of the frequency-power characteristic should be intensified to optimally exploit the capabilities of PEM electrolyzers for FCR and to counteract the unfavorable effects of low inertia.

Table 4.2: Results for different FCR characteristics in the low inertia scenario.

Scenario	Nadir [Hz]	Nadir time [ms]	RoCoF [mHz/s]
Droop | Δf_{max} ±0.20 Hz	49.914	222	552.539
Droop | Δf_{max} ±0.15 Hz	49.929	192	526.471
Droop | Δf_{max} ±0.10 Hz	49.947	152	472.591
Quadratic | Δf_{max} ±0.20 Hz	49.941	162	488.387

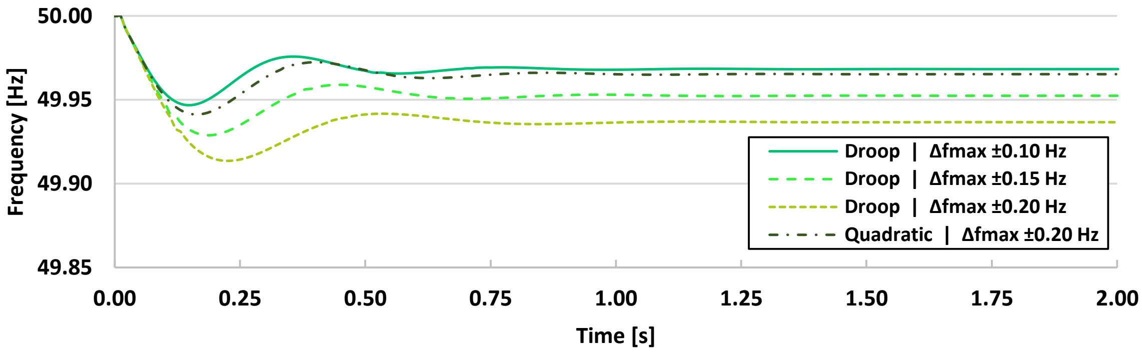


Fig. 4.7: Frequency response for different FCR control characteristics in the low inertia scenario.

4.5. Mitigating the Variability of Renewable Energy Sources

Besides the provision of the traditional range of electrical ancillary services, PEM electrolyzers could offer other functionalities for the short-term balancing of renewable energy sources. Specifically, the stochastic variability of these sources could be controlled by adapting the consumption of nearby electrolyzers to the variations of wind speed and solar irradiance [31].

A theoretical example of the coordinated operation between a wind park and a large power-to-gas plant is proposed in Fig. 4.8. Assuming that both facilities are connected to the same bus in the grid, the speed of PEM electrolyzers would facilitate the absorption of the power fluctuations, allowing to forecast a constant active power injection to the remainder of the grid, in similar fashion to classic dispatchable generators. The electrolyzers could still be scheduled to achieve the planned hydrogen production without compromising working at the highest capacity during periods of inexpensive electricity. When the price of electricity is not competitive (e.g. peak hours), the system can completely shut down or it can operate at partial loading level. If shutdown, the control system of the renewable energy power plant and/or other technologies should take care of the mitigation of its instantaneous variability. However, the PEM electrolyzers could be ordered to quickly increase their consumption or to come back online at any moment to avoid the curtailment of surplus renewable power.

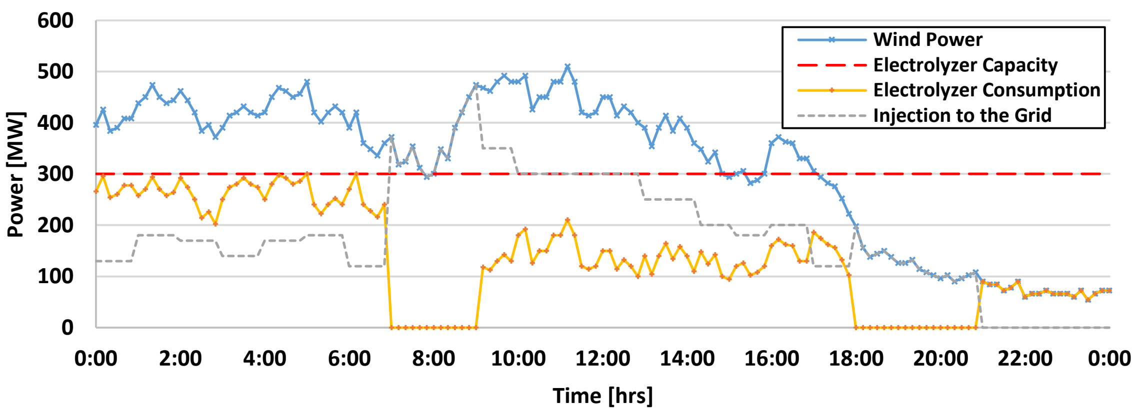


Fig. 4.8: Coordinated operation between a wind park and a large-scale power-to-gas facility.

5

Research Conclusions

The progressive decarbonization of society is leading to important structural changes in several sectors. In the electrical power system, the replacement of fossil fuel power plants with variable renewable energy sources is creating a more uncertain and challenging operational scenario for TSOs. Accordingly, achieving a smarter, more robust and more reliable electrical grid will depend on the successful integration of innovative flexibility solutions. In particular, the multi-energy sector coupling between electricity and gas may become a valuable asset for power systems, due to the potential positive contributions of energy conversion and hydrogen storage. In line with this topic, the presented thesis has thoroughly investigated the adequacy of power-to-gas conversion with PEM electrolyzers for the exploitation of future ancillary services markets. This final chapter serves as a summary of the main conclusions drawn during the development of the thesis.

5.1. Future Framework of Ancillary Services Markets

Which are the fundamental mechanisms of ancillary services markets? What modifications can be expected for the future?

While voltage profiles and congestions in transmission lines are inherently local issues relieved by local measures, frequency variations affect every control area in the grid. As a consequence, the implementation of a unified frequency balancing market (for all FCR, aFRR and mFRR) in the interconnected synchronous area of Continental Europe is being planned for the early 2020s [10]. The envisioned market has two clear objectives. First, assisting on the integration of renewable energy sources. Second, improving the operational flexibility of suppliers and facilitating the inclusion of new technologies in the market. These goals are addressed in the new regulatory framework by shortening the duration of the products and by shifting the auction procedure as close as possible to the procurement period. To give an example, the cited measures can foster the participation of renewable energy in frequency regulation, as it would be easier to estimate the offered regulating capacity when relying on accurate, close to real-time weather forecasts.

5.2. PEM Electrolyzers as Ancillary Services Providers

Do PEM electrolyzers comply with the technical requirements of ancillary services markets? If so, which services should be favored according to the business model of power-to-gas conversion?

The technical characteristics of PEM electrolyzers widely fulfill the minimum prequalification requirements of ancillary services for frequency balancing, voltage control and congestion management. Especially, their capability to quickly ramp-up or ramp-down to change the consumption setpoint is remarkably valuable for frequency support. The future business model of power-to-gas conversion and its annual capacity factor will determine the strategy for the integration in the ancillary services markets. Participating in upward regulation aFRR is already viable through voluntary bidding in the energy market, while the FCR market will become attractive when the 4-hour capacity product is implemented with the new framework. The provision of voltage control is limited by the active power consumption of the electrolysis stack, which implies that only the remainder apparent capacity of the electronic converter can be used for reactive power support. Last, congestion management with PEM electrolyzers could be a very promising option for TSOs, due to the possibility to automate their control to react to sudden disturbances that may induce congestions in the grid.

It is expected that PEM electrolyzers will have to compete with other upcoming technologies than can offer similar performance for the procurement of ancillary services. In Table 5.1, a small comparison is made between battery storage [15], PEM electrolyzers and PEM fuel cells [38]. Although each of the technologies is in different state of their life cycle, partaking in ancillary services is appealing for all of them. The PEM fuel cell technology shows the most complete capabilities overall, but at the moment it is still in a very early stage. The response for frequency services can be achieved within 1 second in any case. As experienced in the United Kingdom, battery storage is dominating the EFR market. Also, in the Netherlands there is 10 MW of installed battery storage procuring FCR (i.e. 9% share of the total national market) [11]. On the other hand, the energy supply of batteries is limited by their capacity, while PEM electrolyzers and also fuel cells (as long as there is enough hydrogen) have an unlimited energy supply. For voltage control, PEM fuel cell and batteries are more effective than electrolyzers, due to the presence of a DC-AC inverter that allows complete control over the output power factor.

Table 5.1: Comparison of the technical capabilities of different technologies for the procurement of ancillary services.

	Battery storage	PEM electrolyzers	PEM fuel cells
Type of technology	Generator / Load	Load	Generator
Setpoint change response	< 1s	< 1s	< 1s
Energy supply capacity	Limited (e^-)	Unlimited (e^-)	Unlimited (H_2)
Voltage control	Full	Partial	Full
Congestion management	Redispatch / Curtailment	Curtailment	Redispatch

5.3. Impact of PEM Electrolyzers on Frequency Stability

How does the participation of PEM electrolyzers in frequency balancing markets influence the dynamic performance of the power system?

The proposed case study showed how the involvement of PEM electrolyzers in the FCR market can enhance the dynamic frequency stability of the power system. For the same active power disturbance and FCR bid size, the frequency response when PEM electrolyzers procure the service produces a better frequency nadir, a smaller time to reach steady state and a lower oscillating behavior than classic synchronous generators. The improvements are associated to the dominant role of the dynamics of the electrolysis process, which are much faster than governor-turbine controls. Moreover, the beneficial effects are not linearly related to the share of PEM electrolyzers, as even a reduced amount of integrated capacity already produces a noticeable positive impact on the dynamic performance of the network.

Limited levels of rotational inertia in the system were also tested to identify the contributions of PEM electrolyzers in such scenario. The reduction of inertia will inevitably deteriorate the initial rate at which the frequency deviates after the disturbance. However, in a hypothetical case where the entire FCR capacity in the grid corresponded to fast acting technologies such as PEM electrolyzers, it was found that the frequency nadir could still be limited effectively, but the rate of change of frequency would remain very high. To further limit the maximum deviations and to quickly stabilize the frequency response, it was suggested to increase the support of quick ramping technologies by making the power-frequency characteristic of FCR stricter. In this context, it is also advisable to check how to incorporate HVDC interconnectors in the frequency control loop. This technology is technically feasible to do so, as it has been established in the current grid codes [39]. Anyhow, given that the HVDC links are owned by the TSOs, this may require the modification of the FCR market framework.

It is worth noting again that the test network featured a reduced amount of the total ±3000 MW of FCR capacity distributed throughout the European power system. Since frequency is a global variable in the grid, the dynamics of the distinct technologies participating in FCR in neighboring countries will influence the overall performance of the frequency response. As a result, the impact of fast technologies such as PEM electrolyzers or battery storage will depend on the ratio of integrated capacity. In any case, performance improvements shall be noticed with respect to the support with synchronous generators.

5.4. Outlook for Future Work

In the next stage of this research, the preliminary simulations presented in this thesis will be repeated with RTDS, to improve the accuracy of the results. The modeling of the northern Dutch transmission grid will be improved significantly, as it will include detailed dynamic models for the PEM electrolyzers [33], the HVDC interconnectors and the offshore wind park. To further evaluate the participation of PEM electrolyzers in accordance to the framework of future ancillary services markets, more complex scenarios will be proposed for frequency balancing, as well as for voltage control and congestion management. Concurrently, potential innovative methods to enhance the overall frequency response of the system will be explored (e.g. to attenuate the large RoCoF values caused by low rotational inertia in the grid). For such purpose, the interaction and coordination between the different control schemes of the PEM electrolyzers, the wind parks and COBRAcable will be analyzed in depth.

A

Author's Thesis Related Publications

- **Title:** Integration of Power-to-Gas Conversion into Dutch Electrical Ancillary Services Markets
- **Authors:** V. García, J.L. Rueda, B. Tuinema, A. Perilla and M.A.M.M van der Meijden
- **Conference:** ENERDAY 2018 – 12th Conference on Energy Economics and Technology
- **Venue and Date:** Dresden, Germany, April 27th, 2018

Abstract – This paper investigates the viability of the integration of demand side response of large scale electrolyzer facilities into electrical ancillary services markets. A review of the current structure and mechanisms of balancing markets, voltage control and congestion management in the Netherlands is presented, taking into consideration future market harmonization measures proposed by transmission system operators of central Europe. The conducted research includes the assessment of the technical adequacy of electrolyzers with respect to existing prequalification requirements, as well as basic notions on the expected revenue from participation in these markets. Furthermore, to illustrate the value of electrolyzer support for electrical networks, a case study derived from the predicted Groningen-Drenthe-Overijssel area for the year 2030 is developed. This section of the northern Dutch transmission grid includes the upcoming HVDC interconnection with Denmark (COBRAcable) and one of the largest offshore wind parks located in the North Sea (Gemini). Computer based simulations are performed with DIgSILENT PowerFactory. The obtained results highlight the potential benefits of electrolyzer utilization for power system operation, particularly for frequency control.

- **Title:** Demand Side Response in Multi-Energy Sustainable Systems to Support Power System Stability
- **Authors:** V. García, P. Ayivor, J.L. Rueda and M.A.M.M van der Meijden
- **Conference:** 16th Wind Integration Workshop
- **Venue and Date:** Berlin, Germany, October 27th, 2017

Abstract – This paper provides a review on emerging developments and challenges for provision of ancillary services by means of distributed generation, electrical and non-electrical demand side response and storage in the context of multi-energy conversion systems. To illustrate the value of demand side response as part of multi-energy sector coupling, a case study is built upon a three-area system, which includes conventional and renewable power plants as well as power to gas conversion system with electrolyzers. Computer based simulations are performed by using PowerFactory platform to investigate the impact of the response of the electrolyzers on power system operation. The results show that positive impacts on steady state and dynamic performances can be achieved by contributing to reduce the system stress. The extent of the contribution depends on the location, activation time, rating, and size of demand side associated to the electrolyzer.

- **Title:** Provision of Ancillary Services with PEM Hydrogen Technologies in Future Multi-Energy Sustainable Power Systems
- **Authors:** F. Alshehri, V. García and J.L. Rueda
- **Journal:** International Journal of Electrical Power & Energy Systems
- **Status:** Under review

Abstract – This paper examines the prospect of PEM (Proton Exchange Membrane) electrolyzers and fuel cells to partake in European electrical ancillary services markets. First, the current framework of ancillary services is reviewed and discussed, emphasizing the ongoing European harmonization plans for future frequency balancing markets. Next, the technical characteristics of PEM hydrogen technologies and their potential uses within the electrical power system are discussed to evaluate their adequacy to the requirements of ancillary services markets. Last, a case study based on a realistic representation of the transmission grid in the north of the Netherlands for the year 2030 is presented. The main goal of this case study is to ascertain the effectiveness of PEM electrolyzers and fuel cells for the provision of primary frequency reserves. Dynamic generic models suitable for grid simulations are developed for both technologies, including the required controllers to enable the participation in the ancillary services markets. The obtained results show that PEM hydrogen technologies can improve the frequency response when compared to the procurement with synchronous generators of the same reserve value. Moreover, the fast dynamics of PEM electrolyzers and fuel cells can help mitigate the negative effects attributed to the reduction of inertia in the system.

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