Wind Power System - Master Thesis

# Operation and Control of Wind Power Plants with Electrolyzers


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**Aalborg University**

Department of Energy and Technology

AALBORG UNIVERSITY
DENMARK

**Department of Energy and Technology**
Aalborg University
http://www.aau.dk

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STUDENT REPORT

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**Participant(s):**
Asbjørn Benniche Skovgaard
Erik Emil Høgedal

**Supervisor(s):**
Florin Iov

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**Abstract:**

The political interest in P2X is growing significantly since this technology can be used as a springboard to decarbonize other high emitted sectors. Therefore, this project deals with integrating a large-scale Electrolyzer Plant in an existing onshore Wind Power Plant. Throughout the project, two main topics are studied: Investigating feasible collector system layout for large P2H2 installation and operational control strategies for Balance of Plant, and FCR. The studies are achieved through Model-Based Design, where representation models of collector system components, WTGs, and Electrolyzers have been developed in MATLAB/Simulink.
The project concludes that in order to obtain a feasible collector system layout, a set of evaluation criteria must be considered. It includes physical footprint, power losses, voltage levels, and nearby installations. However, for this particular research, a 6kV DC-configuration with separate Electrolyzer module division was the most feasible solution. Moreover, it can be concluded that the developed operational strategies for Balance of Plant, Wind Curtailment, and FCR-service, enable more revenue streams for the Plant when PEM-Electrolyzers are integrated into the energy mix.
**Keywords:** Wind Turbine Generator, Hybrid Power Plant, P2X, Electrolyzer Plant, Balance of Plant, Wind Curtailment, Frequency Containment Reserve

# Summary


This master thesis covers the studies of the design and operation of a Hybrid Power Plant that consists of wind power generation and green hydrogen production. The focus is on the interaction between the two technologies and how the introduction of Electrolyzers can benefit the overall operation of a Wind Power Plant.

The political goals are to reduce carbon dioxide emissions across several sectors. Therefore, the interest in Power to X technologies is growing. This technology utilizes renewable energy production in decarbonizing other sectors, such as the road transportation sector, which accounts for a large part of the CO2 emissions. One of the most promising methods is to exploit Electrolyzers that enable conversion from renewable electricity to green hydrogen, which can be used for creating other mediums such as Ammonia and Methanol. Across Europe, many countries commit to incorporating Power2Hydrogen in their energy mix. Therefore, many projects, which investigate the use of renewable energy to produce green hydrogen, are being supported. Some projects are even investigating the usage of Electrolyzers in the power system stability reserves.

However, the main focus has been on the technological aspects of the Electrolyzer, and not on the interaction between the systems and their operational strategies. Moreover, the current Electrolyzer modules will need to be connected in clusters to obtain the desired capacity. Therefore, it is crucial to investigate the design of Electrolyzer Plants and how the operational control of such Hybrid Power Plants can be utilized in the current power systems. In this project, the system in scope is an already operating WPP consisting of eight 3.6MW turbines, where it is proposed to install 6 MW of Electrolyzer Capacity.

The initial parts of the studies focus on the Design of the Electrolyzer Plant Layout and how to obtain a desirable setup considering the physical footprint and the power losses. The Electrolyzer Plant is configured based on the plant voltage level and voltage type and is evaluated in power loss studies. As a result of this ascertained that an adequate layout configuration depends on the plant application and the specified system requirements. The two main consideration parameters are the geographical location and the acceptable system losses. Moreover, it showed that the main contributor to the losses is converters and transformers. The selected layout for this study is a DC configuration with a system voltage of 6kV.

As a feasible Electrolyzer Plant Layout is obtained, a representative model of the Hybrid AC & DC Power System was developed to determine the electrical quantities and power flow in all nodes and cables within the Plant. In this way, the Hybrid Power Plant could be monitored when the production and consumption of the WTGs and Electrolyzers change, respectively. The power flow changes due to frequent wind fluctuations and Power-Demands from TSO/DSO. Following the changes in power flow, several operation strategies are developed to account for different scenarios and schemes. The balancing of plant strategy is utilized either by a Wind Power Plant Following operation or a Wind Power Curtailment operation. The operational strategies are based on how the production of green hydrogen or power injection to the utility grid should be prioritized. Lastly, the system is required to have the capability to participate with ancillary services in the form of FCR Operations, where this strategy is developed by using the Electrolyzer Plant as a demand response.

The Hybrid Power Plant is tested through realistic scenarios to show the benefit of different operational strategies and outline the advantages of incorporating green hydrogen production in Wind Power Plants. The scenarios are based on actual events, such as a specific high wind day on which the Wind Power Plant may be curtailed. Thus, with green hydrogen production, the Wind Power Plant capacity can be better utilized. Another tested scenario is the FCR operation where fluctuating frequency measurements from the Danish national grid are applied, and thereby the demand response of the Electrolyzers is utilized. Common for all the test scenarios is that the green hydrogen production is computed, giving the foundation for various revenue improvements. The results obtained by performing the scenarios prove that incorporating an Electrolyzer Plant into the Wind Power Plant makes it possible to increase the exploitation of its capacity.

# Preface

This report is conducted by the group WPS4-1050 as a Master Thesis project from the Department of Energy and Technology at Aalborg University. The project is developed based on interest and curiosity about the transition towards carbon-neutral energy production and the utilization of renewable power production with other energy forms. It investigates the Design of an Electrolyzer Plant Layout consisting of numerous Electrolyzer modules to obtain an adequate configuration considering power losses and physical footprint. Moreover, the overall system modeling and accompanying operational control strategies are developed. The model is then utilized for various realistic test scenarios to indicate the usability of the Hybrid Power System and the benefit of introducing green hydrogen production into the power plant.

## Reading Guide

The knowledge in this project is extracted from literature, technical reports, and Web Pages. Throughout the report, the sources are cited and can be found in the bibliography using the IEEE standard citation style. Moreover, the developed figures and tables are numbered based on the corresponding chapter. All figures that the report writers develop are not referenced. All graphs are developed using MATLAB, and diagrams using $diagrams.net$. The report is alone submitted digitally in PDF format.

# Nomenclature

| Abbreviation | Definition |
|---|---|
| AFE | Active Front End |
| ACLF | AC Load Flow Algorithm |
| BoP | Balance of Plant |
| DCLF | DC-Load Flow Algorithm |
| DEA | Danish Energy Agency |
| DMI | Danish Meteorologic Institute |
| DSM | Demand Side Management |
| DSO | Distribution System Operator |
| HPP | Hybrid Power Plant |
| MBD | Model-Based Design |
| NRLFA | Newton Raphson Load Flow Algorithm |
| P2H2 | Power-to-Hydrogen |
| P2X | Power-to-X |
| PCC | Point of Common Coupling |
| PEM | Proton Exchange Membrane |
| PoC | Point of Connection |
| PPC | Power Plant Controller |
| REDDAP | Renewable Dynamic Distributed Ammonia Plant |
| RES | Renewable Energy Sources |
| SCR | Short-Circuit Ratio |
| SLD | Single Line Diagram |
| STP | Standard Temperature and Pressure |
| WPA | Wind Power Array |
| WPP | Wind Power Plant |
| WTG | Wind Turbine Generator |
| 12-TR | 12-Pulse Thyristor Rectifier |

# List of Symbols

| Symbol | Definition | Unit |
|---|---|---|
| $e_{rev}$ | Reversible Potential Voltage | V |
| $f_{Grid}$ | Measured Grid frequency | Hz |
| $f_{Ref}$ | Reference Frequency | Hz |
| $f_{Deadband}$ | Limit of interval where measured frequency are considered nominal | Hz |
| $P$ | Pressure | bar |
| $P_{EP.Cap}$ | Active Power capacity of Electrolyzer Plant | MW |
| $P_{EP}$ | Electrolyzer Plant Loading Reference | - |
| $P_{EP.Loading}$ | Electrolyzer Plant Loading | MW |
| $P_{Grid.Demand}$ | Active Power Demanded from Grid | MW |
| $P_{loss.Conv_{\eta 98\%}}$ | Active Power Losses in Converter at an Efficiency of 98% | MW |
| $P_{loss.trafo}$ | Active Power Losses in Transformer | MW |
| $P_{PCC}$ | Active Power in PCC | MW |
| $P_{WPP}$ | Active Power Production of WPP | MW |
| $P_{WPP.Ava}$ | Available Active Power Production from WPP | MW |
| $P_{WPP.Ref}$ | Active Power Reference to WPP | - |
| $Q_{WPP}$ | Reactive Power Production of WPP | MW |
| $Q_{WPP.Ref}$ | Reactive Power Reference to WPP | - |
| $R_{Grid}$ | Grid Resistance | Ω |
| $S_{SC}$ | Short-Circuit Power | VA |
| $T$ | Temperature | $°C$ |
| $W_{measured}$ | Measured Wind Speed | m/s |
| $W_{rated}$ | Rated Wind Speed | m/s |
| $X_{Grid}$ | Grid Reactance | Ω |
| $XR$ | Reactance to Resistance Ratio | - |
| $Z_{Grid}$ | Grid Impedance | Ω |
| $\eta_{conv}$ | Efficiency of Converter(s) | % |
| $\eta_{PEM}$ | Efficiency of PEM Electrolyzer(s) | % |
| $\tau_0$ | Natural Time Constant | s |
| $\tau_P$ | Active Response Time | s |
| $\tau_Q$ | Reactive Response Time | s |

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# Chapter 1

# Introduction

## 1.1 Background and Motivation

Many different initiatives have been made to decarbonize the electrical grid to transition toward a renewable power system. One of the most promising renewable energy sources (RES) is Wind Turbines. Large manufacturers compete in the Research and Development of Wind Turbines to take leading positions, so the size and technology become more advanced in turbine topologies and system components. As a result, the controllability of the turbines has improved, thus enabling them to contribute to the power system challenges. Increased implementation of RES in the power system will contribute significantly to achieving the political goal in the Paris Agreement of 40% reduction of carbon emissions [2].

However, a decentralized grid with significant RES penetration has some drawbacks. Due to the nature of these sources, a more fluctuating and uncertain supply to the power grid occurs, which complicates the control and management of these sources to meet the system requirements. Moreover, renewable sources do not have the same power quality contribution capabilities as centralized power plants, so additional storage solutions are essential to maintain high power quality. Among the wide range of storage possibilities, electricity-based hydrogen production has gained in popularity[3][4] [5] since it is a springboard to electrify other energy-intensive sectors and stabilize fluctuating power production. The green hydrogen technology will play an essential role in the balance of plants (BoP) in the wind power plant (WPP) or other renewable power plants in the future power system. The Electrolyzer can be used to balance fluctuations between the production and demand in the power plants by regulating the green hydrogen production according to any imbalances and ensuring high power quality. It, therefore, introduces some financial benefits, as the park operators can avoid negative electricity prices for surplus energy but instead profit from green hydrogen production. However, this solution may create challenges in the existing grid since green hydrogen plants are predicted to be scaled up to Gigawatt size and require expansions of the existing electrical infrastructure.

However, electrical production only accounts for a part of the total carbon dioxide emission, so a springboard to other sectors is needed to fulfill the political emission goal. In Figure 1.1 the distribution of the carbon dioxide emissions in the European Union based on various sectors and industries is indicated. Therefore, it is evident that a considerable CO2 reduction can be obtained by combining electrical energy with other energy forms.

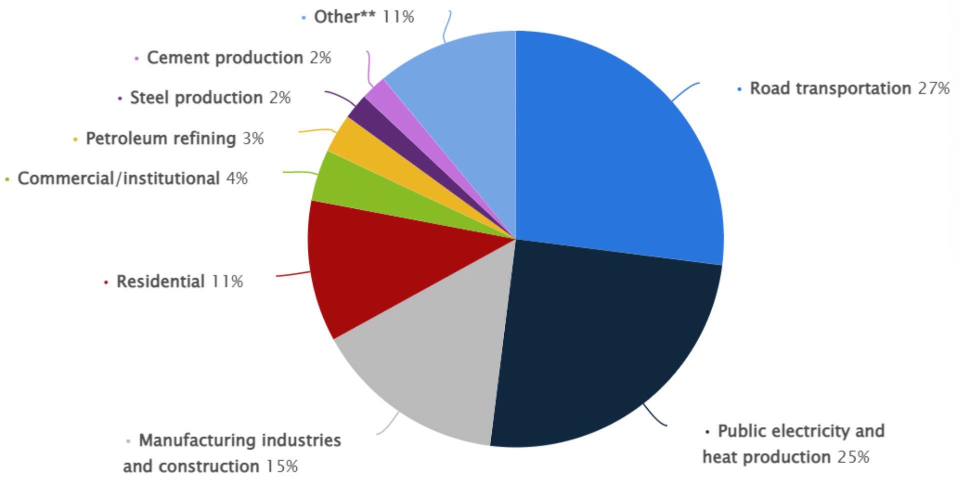


Figure 1.1: Distribution of Carbon Dioxide Emissions in the European Union in 2019[6]

The other sectors, such as manufacturing and transport, are significant emitters of carbon dioxide. Therefore, it is necessary to research solutions to replace traditional fossil fuels with more sustainable alternatives. A much-debated topic is the Power-to-X (P2X) technologies in which renewable electricity is converted to another medium, e.g., Hydrogen, Ammonia, and Methanol.

Hydrogen is expected to be one of the key drivers in the de-carbonization of the transportation, industrial, and electricity sectors. Therefore, various configurations and layouts have been discussed concerning this technology. The basic principle is that water electrolysis technology allows the exploitation of surplus power from RES to convert electricity to green hydrogen[7]. This increased popularity is because hydrogen as a medium possesses various favorable attributes in the current energy mix. Hydrogen is comparable with electricity because both are not energy sources but energy carriers. Both are versatile and can be used in various applications. No greenhouse gasses, particles, etc., are produced from the use of either. However, both mediums can have a significant intensity of CO2 produced from fossil fuels like coal, oil, or natural gas[3].

The Danish Energy Agency (DEA) evaluated that in order to comply with the 2030 and especially the 2050 goals, it is critical to incorporate Power-to-Hydrogen (P2H2) in the energy mix[8]. Therefore, DEA indicates in Figure 1.2 the expected use-cases of the green hydrogen and how to incorporate different sectors. Likewise, the Danish government has ambitions for 4-6 GW of Electrolyzers by 2030. In order to accommodate those ambitions, several projects are supported financially as a measure to promote technological development within the industry[9].

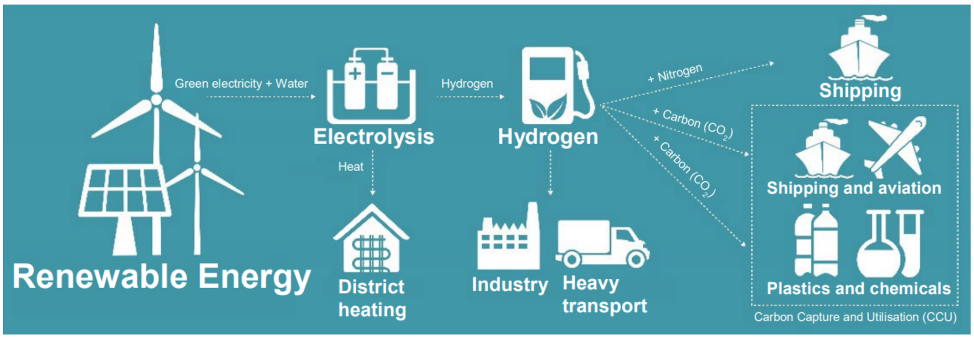


Figure 1.2: Expected Green Hydrogen Applications[9]

The green hydrogen market is characterized by two main topologies, the Proton Exchange Membrane (PEM) and the Alkaline Electrolyzers, respectively. Historically the Alkaline Electrolyzer has been the preferred topology in the production of green hydrogen because of its price advantage. However, the PEM-Electrolyzer is gaining popularity due to its superior current density and thus a reduced physical footprint. Therefore this topology is expected to become dominant in the coming years [10]. Common for both technologies is that the development has contributed to more compact and space-efficient solutions.

In the future energy mix, it is believed that both the technologies will coexist, and the application will play a significant role in the selection of topology. The production company, NEL Hydrogen, foresees that large Alkaline Electrolyzer plants will be most suitable for the industries that require a steady and significant hydrogen intake, such as the fertilizer industry or the steel industry. On the other hand, the PEM-Electrolyzers probably are more suitable for either decentralized production of small plants or system stability contribution due to dynamic procedure and faster response times [10].

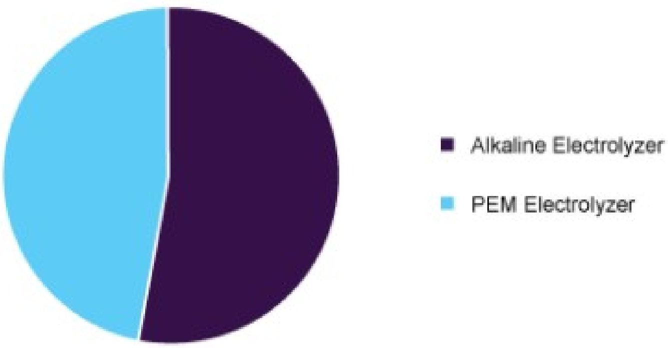


Figure 1.3: Share of Electrolyzer topology 2019 [11]

An example of a Danish Hybrid Power Plant(HPP) project including green hydrogen production is the Renewable Dynamic Distributed Ammonia Plant (REDDAP) project. It collaborates with the Danish Wind Turbine manufacturer Vestas Wind System and the catalysis company Haldor Topsøe. The project aims to use electricity produced by Wind Turbines and convert it into green hydrogen and further into ammonia. [12] [9]. Another danish example that will utilize renewable energy production with an on-site Electrolyzer is the Brande Hydrogen project. The renewable energy production is provided by Siemens Gamesa and the Alkaline Electrolyzer from Everfuel, which is planned to utilize the entire energy production from the turbine for hydrogen production to the Road Transportation sector, specifically to fuel Copenhagen Taxis [13]. Typical for many initial projects is that the Electrolyzers are retrofitted to existing Renewable Energy Systems. This means one of the main objectives in these hybrid projects is within the interconnection of technologies and significantly in the operation and control of the entire plants.

Integrating Electrolyzers into the energy mix of the power grid is expected to become economically feasible in the coming years [14]. Currently, the technical conditions and the support policies that are fundamental for the technological development of hydrogen technologies are limited [15]. A study investigating the economic impact of introducing a green hydrogen storage system into the Italian grid concluded that the current subsidies would not enable 20-year investment feasibility. However, it also concludes that with an expected increase in support subsidies and technological development, the investment economy improves [14] [16].

## 1.2 Problem Formulation

A decentralized power grid with significant penetration of RES often introduces a necessity to curtail production to meet the demand from the power grid. However, the process of curtailment leads to a loss in potential energy production[17] and hence affects the economical investment[18]. The integration of Electrolyzers in WPP can limit the need for curtailment by producing green hydrogen instead and thus maximize the total production of the plant.

When integrating a significant amount of RES with Electrolyzers in a renewable energy system, detailed analysis and understanding of unit interaction are vital. Most prominently are the ways to overcome the challenges regarding the interconnection of technologies leading to potential imbalances between production and demand that result in grid congestion and power quality issues. [4].

When establishing a decentralized power plant, stringent grid connection requirements are to be complied with [19] [20]. Namely, the requirements related to voltage stability are challenging due to the limitations caused by the relatively long distance between the plant and the Point of Common Coupling (PCC).

The current studies of green hydrogen production in combination with a renewable production focus on the technological aspect of the Electrolyzer. However, the influence of integrating Electrolyzers into HPP from the power system perspective and its combined operation has not been studied, meaning there is limited knowledge within the industry on these perspectives. Therefore, there are currently no clear control structures and dispatch algorithms for Hybrid plants consisting of Wind and Electrolyzers. Likewise, the assessment of grid integration and control of the hybrid combination through dynamic models is deficient.

### 1.2.1 Problem Statement

Electrolysis is widely discussed in the P2X technology field, and several studies have been conducted concerning this. However, in order to understand the requirements for implementation and connection of this technology, it is necessary to research auxiliary electrical load balancing for maximizing the WPP output and ensuring compliance with national/international standards[18]. Therefore, the project can be divided into the following tasks:

1. Investigate and propose feasible collector systems for large P2H2 installation
2. Develop operation and control strategies for combined wind and H2 hybrid plants geographically co-located

These control strategies aim to:

- Provide system services to Distribution System Operators (DSO).

- Enable power balancing capabilities for a mixed portfolio (Wind and Hydrogen plants) and thus participation in frequency reserve markets

The developed control system and equivalent system models will play a significant role in researching auxiliary electrical load balancing of wind and H2 hybrid plants. Therefore, this report aims to verify the functionalities of developed system models and control strategies with dedicated tools/or laboratory setups.

## 1.3 Methodology

Through the project, various methods are utilized to fulfill the tasks. Initially, an analytical approach is applied to study the State of the Art concepts within the field and the selection of models. Then, exploring the different Electrolyzer Plant Configurations is based on an analytical and mathematical approach, which combines known electrical theory and previous analysis in a new composition. Finally, the development of the Hybrid System Model and the control schemes is likewise based on an analytical approach to studying existing sub-system models while using them in new configurations. The primary tool used within the project is MATLAB/Simulink. Scripts are developed in MATLAB to improve the changeability in configurations and unit behavior while acting as initiators of the developed models. Initially, the scripts for determining the Electrolyzer Plant layout are characterized by focusing on the visual representation of the most adequate configuration. However, the functionality of the overall HPP model needs to be as fast as possible. Therefore, the functionality and calculation scripts are simplified and combined into single scripts to obtain a suitable simulation time. Moreover, the analytical method of the scripts is verified through simulation models designed in DIgSILENT PowerFactory.

## 1.4 Assumption and Limitations

The proposed representation models and control systems are based on phasor representations, so some assumptions and limitations are considered. Furthermore, simplified equivalent models for representing power system components/units will be utilized, as the development of overall operational strategies for the Hybrid Plant and their verification, are the main objective of this project. Therefore, the following assumption and limitations are considered:

- High-Frequency transients and oscillations are not considered in the modeling.
- RMS positive sequence modeling approach is considered for the AC part of the collector system and external grid
- Modeling of Wind Turbine Generators (WTG) is not considered in this project, and a validated model developed prior in other research projects is used [21].
- The modeling of Wind Turbines is simplified to a representation model of one turbine, the power of which corresponds to all 8 turbines. the production of each turbine is therefore equal.
- The modeling of Electrolyzer Modules is simplified to a representation model of one Module, the capacity of which correspond to all Electrolyzer Modules. The distribution of power consumption is therefore balanced equally between them.
- Internal control loops and physical limitations related to chemical processes in the Electrolyzer module are not considered. Thus it is assumed that Electrolyzer module is always operating optimally and the technical constraints are not exceeded.

## 1.5 Project Outline

**Chapter 2:** This chapter evaluates the State of the Art for Electrolyzer Modules. It provides insight into the development within the field of Electrolyzer systems and what development has already been done. Furthermore, the gaps in the studies are defined.

**Chapter 3:** In this chapter, the system specification for the project is defined, including the WPP as well as the other systems that will complete the HPP in scope. Moreover, the system requirements and the investigated scenarios are defined based on the desired capabilities and foreseen applications of the system.

**Chapter 4:** This particular chapter contains the Design of the Electrolyzer Plant Layout, including an investigation of the physical footprint of the Electrolyzer Plant. Moreover, it contains the development and study of the most feasible layout for the collector system of the Electrolyzer Plant. The assessment is done based on extensive testing of the different configurations. Lastly, it summarizes the general considerations to consider when designing an Electrolyzer Plant.

**Chapter 5:** The chapter contains a description of the System Modelling and Operational Control of the HPP. It describes the Collector System in scope and analyzes the components that have to be utilized in the HPP Model. Moreover, it introduces the proposed Operational Strategies for the Plant through descriptive flow charts. This includes different modes of operation that can be utilized to obtain the desired functionality.

**Chapter 6:** This chapter presents the Results and Tests of the System Model. Initially, the Logic and Functionality of the operational strategies are verified to ensure the desired functionality. Ultimately the developed model and control strategies are utilized to perform tests on the defined scenarios, where the different operational modes are combined to obtain a satisfactory operation.

**Chapter 7:** In this chapter, the conclusion of the project concerning the stated objectives is evaluated. Furthermore, future improvements and further developments are discussed.

# Chapter 2

# State of the Art

## 2.1 Collector Systems for Large Electrolyzers Plants

When integrating a large Electrolyzer in WPP for the production of green hydrogen, it is crucial to consider the layout of the plant. The infrastructural layout will play a significant role in project investment. As the location of the Electrolyzer becomes a trade-off between gas pipes and wires hence electrical losses due to transmission. For example, in reference [22] they mention that *"In a scenario constrained by transmission networks, hydrogen facilities are more likely to be connected to single groups of energy plants situated in an area of high power density, thus limiting electricity exports."*.

The existing projects and studies focus primarily on optimizing production/demand response, ancillary services, and energy arbitrage; however, they are not covering the performance and optimization of the electrical layout and design of the collector grid. For example, in reference [23] regarding Operational Experience, Performance Testing, and Systems Integration of a Wind-to-Hydrogen Project, the developed model for the plant is not considered a representation of electrical cables and tests of various voltage-levels and types for streamlining the power flow. Similarly, in reference [24] regarding power quality control in Electrolyzer Hybrid Systems, the proposed simulation model in this paper represent only the production units and connection points in the system, which is why the research of the collector grid is neglected.

Although there is a lack of attention related to optimal collector grid designs, some key components to be included in the system are covered in the state-of-the-art research, which can be helpful for the overall design. An example of this is the converter topologies. In reference, [25] an overview of power electronic converter topologies enabling large-scale hydrogen production via water electrolysis, is discussed. All configurations include a DC/DC converter to control the current injection to the Electrolyzer. However, the system consists of two main rectifying topologies, 12-pulse Thyristor Rectifier (12-TR) and the Active Front End (AFE). An illustration of the 12-TR topology can be seen in Figure 2.1.

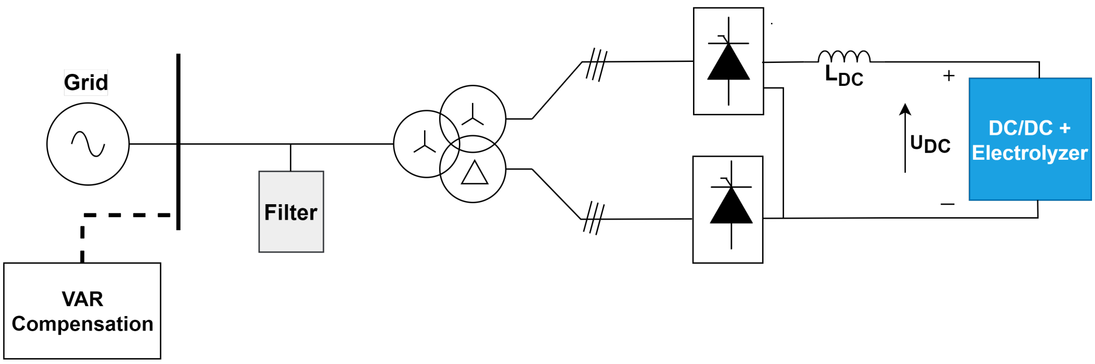


Figure 2.1: Circuit diagram of a 12-TR.

The Electrolyzer current can be regulated by adjusting the firing angle. However, a large firing angle can, for the low-power operating condition, lead to an increase in harmonics and a decrease in power factor [26]. Therefore, it may be necessary to compensate for these harmonics through filters and install VAR compensation to maintain a satisfactory power factor in the connection point. Compared to the 12-TR, the AFE does not require any VAR compensation. The AFE-converter consists of three IGBT half-bridges stacked in parallel to achieve a higher power rating. In the AFE rectifier system, the AC-current can be controlled sinusoidal by shaping the duty cycle, which results in lower harmonic emissions. Furthermore, a higher power factor can be achieved as the phase shift between the AC-current, and the grid voltage can be manipulated by adjusting the modulation signal. An illustration of the AFE circuit diagram can be seen in Figure 2.2.

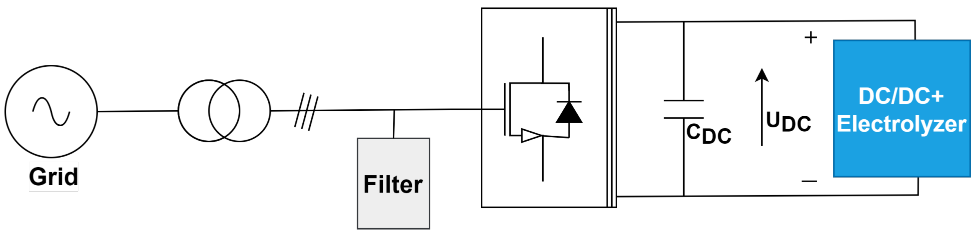


Figure 2.2: Circuit diagram of an AFE rectifier.

The 12-TR- and AFE-converter topology have advantages and disadvantages related to cost, power quality, reliability, and control complexity. The 12-TR is considered very resilient and cost-effective in comparison to the AFE-converter. However, it requires filters and VAR compensation for the large firing angle to improve power quality, which is relatively costly. On the other hand, the AFE-converter has a more complex control strategy but a very high power quality, so filters and VAR compensation are not required in most cases.

The State of the Art research covers studies of critical components within the collector system. However, a complete design has been neglected, which leaves a gap in the research. Therefore, it is essential to consider the specification and layout of the Electrolyzer Plant and hence the collector system, including geographical location, voltage type and levels, production and demand, existing installation, and connection points to the utility grid to get the most efficient plant.

## 2.2 Power Control Strategies for Electrolyzers Plants

Integration of large-scale renewable power production introduces challenges due to the nature of such sources. For example, weather-dependent production leads to fluctuations and uncertainty, complicating operational management and grid balance. In addition, wind power production also poses the challenge of not having rotational inertia directly coupled to the grid. As a result, it requires a faster response and longer duration ramps for balancing the grid. A promising solution to this challenge is utilizing Electrolyzers to overcome power imbalances by varying the loads due to their fast-response, and ramping capabilities [27] [16]. In Figure 2.3 the control structure of an HPP utilizing Electrolyzers is shown.

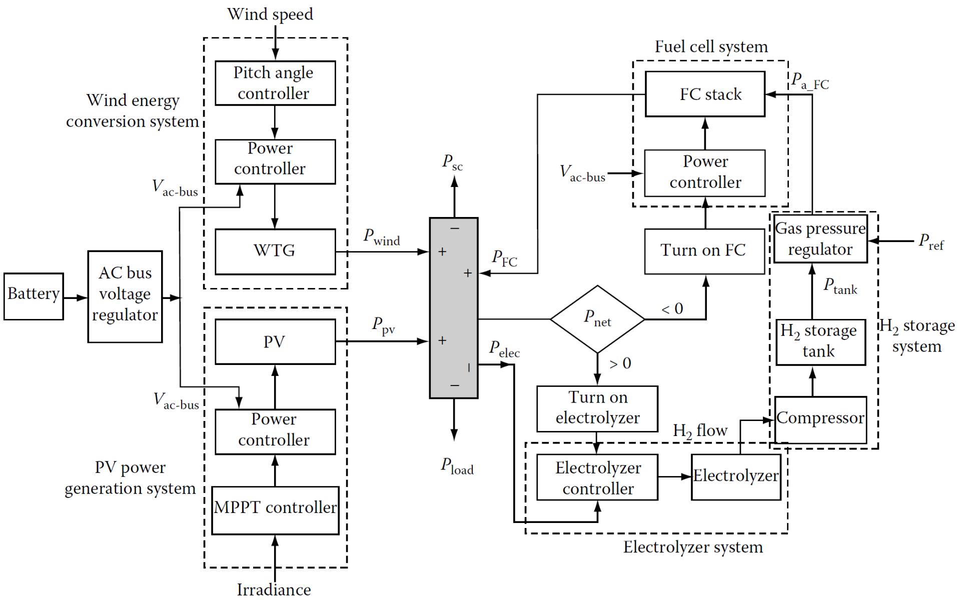


Figure 2.3: Block Diagram of an overall control scheme for HPP with Electrolyzers [28]

The capabilities of Electrolyzers concerning frequency stabilization and control have been investigated successfully within the industry. In reference, [29] it was demonstrated that by utilizing Alkaline Electrolyzers, the overall system frequency is kept within its acceptable limits. Moreover, it showed that the frequency fluctuations are reduced significantly when the system undergoes a significant change in system loading. The studies suggest that up to five times fewer spinning reserves are required to maintain the frequency within the acceptable range when Electrolyzers act as demand-side management(DSM).

Another reference [30] utilized green hydrogen as a balancing service. It indicated that in a pilot project with Independent Electricity System Operator Ontario, a PEM-Electrolyzer has the capabilities to stabilize the system frequency after a sudden change in loading. However, the project only utilized a 2 MW Electrolyzer unit, while it is expected that larger units will be added in the future, and thus a more extensive Electrolyzer penetration. A more considerable penetration will have a more significant impact on the frequency balancing, so there is a need for further analysis of the control strategies of hybrid systems consisting of wind power production and Electrolyzers.

## 2.3 Operational Strategies for Combined Wind and Electrolyzers Plants

Integration of Electrolyzers into the energy mix of a renewable power plant enables further flexibility to the revenue streams while increasing the demand for operational strategies. Currently, the revenue streams when combining wind and Electrolyzers are limited to point-to-point and project-based infrastructure and to bidding in the electricity spot market, as a hydrogen spot market is expected to be decades away [31].

The electric spot market is characterized by fluctuating prices based on the electricity demand. When the power production to the electric grid is high, it is reflected in the electricity prices, which decrease or even become negative [32]. Therefore two operational strategies are applicable, increase in self-consumption or energy arbitrage. The increase of self-consumption is obtained by, at times of low or negative electricity prices, renewable production is prioritized to the Electrolyzer, and thus hydrogen production is obtained. Thereby need for curtailment of wind production is reduced, which improves the total energy production of the plant. A typical layout for a Hybrid Wind Electrolyzer System that combines the electricity and hydrogen loads is given by Figure 2.4.

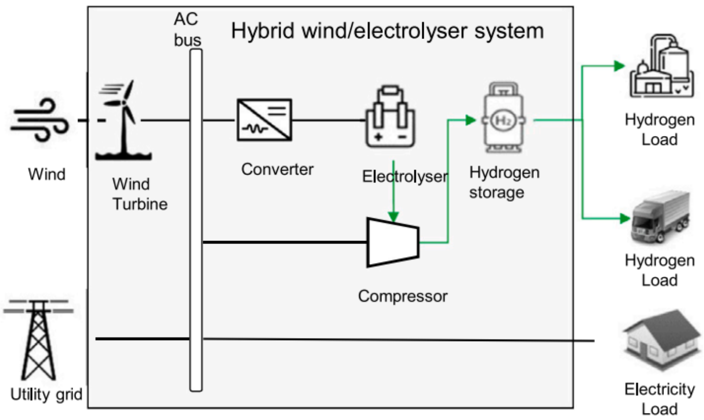


Figure 2.4: Typical Layout of HPP with Green Hydrogen Production [33]

As various units are connected, operational control schemes must be obtained to ensure the high performance of the plant. In Figure 2.5 a typical control structure of a HPP utilizing Electrolyzers is given. Each of the assets has a designated controller that defines its behavior. The overall HPP controller defines the dispatch functions and power distribution.

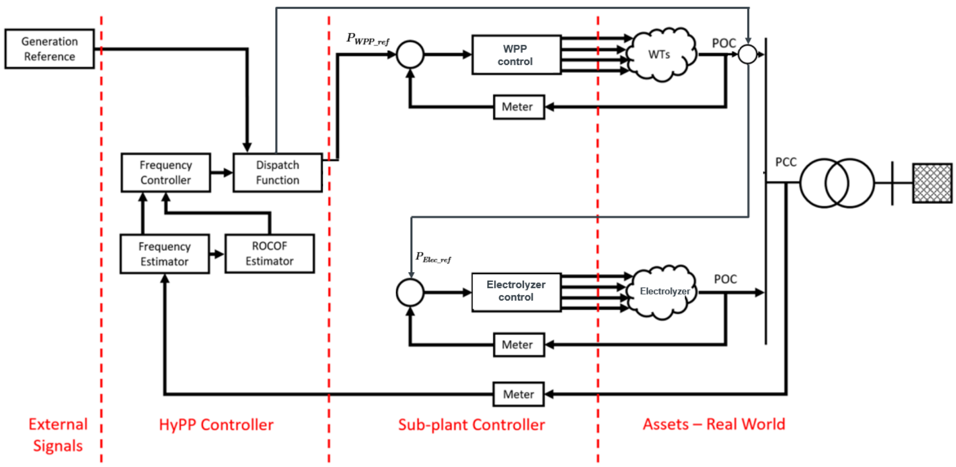


Figure 2.5: Typical Control Structure of HPP with Green Hydrogen Production [33]

The operational principle of the control structure is that a production set-point to the hybrid plant is defined externally, which gives the operational strategy to be followed. Then the dispatch function defines the share to be transferred to the Electrolyzer and the utility grid. Thus it divides based on the operational priorities (i.e., producing Hydrogen through the Electrolyzer instead of producing electricity). Subsequently, each sub-plant controller will again perform a reference distribution among the individual assets (i.e., individual turbines, Electrolyzer Modules).

Hydrogen storage and fuel cells need to be implemented to obtain energy arbitrage capabilities and enroll in the electricity spot market. Thereby, it introduces the possibility of selling electricity when the demand is high, thus increasing revenue. Currently, this approach introduces additional energy losses due to the added conversion in energy and thus lowers the energy efficiency, making it less competitive. As a result, the value of producing and selling Hydrogen to the specific industries and off-takers surpasses the business case of storage and energy arbitrage [34] [27].

## 2.4 Participation in Ancillary Service Markets

Ancillary services are a mechanism that provides additional generation, transmission, and consumption in order to ensure high power quality [35]. There are several different ancillary services the Operators can be paid for, which depend on response time, power reserves, and generation/demand control. Demand response is a technique where the consumption is up or down-regulated when the frequency deviates from the reference value.

Therefore, the essential question is whether this can be adapted to Electrolyzers? In reference, [36] the Ancillary services from Hydrogen-based technologies for supporting Power system frequency stability were studied through offline simulations. It concludes that a PEM Electrolyzer can provide frequency support by participating in the Frequency Containment Reserves (FCR) markets, which require that the reserve can be activated within 15-30 seconds and stay active for up to 15 minutes[37]. Furthermore, the studies indicated that this arrangement improved the frequency nadir and reduced oscillations compared to conventional frequency support utilizing synchronous generators.

In addition to frequency regulation, an increasing incentive of demand response for grid services is globally demanded. Distribution grids are sized for peak demands, but new power lines must be installed when the electrical demand grows. It can be very costly or challenging to build and can be partly avoided by storage units. Therefore, the requirement of these services is limited to a time scale operation of minutes to hours in response times[38]. In reference, [27] several Electrolyzer applications and technologies were tested concerning their response times and ramp rates during both ramping up and ramping down. The testing was done experimentally on both Alkaline and PEM stacks from Teledyne Technologies [39]. Since the studies alone focused on the behavior of the Electrolyzer stacks, further investigation is needed to assess the capabilities in interconnection with Wind Turbines.

## 2.5 Summary of Gaps in State of the Art

The existing projects regarding large Electrolyzer Plants primarily focus on optimizing production/demand response, ancillary services, and individual components. However, the performance and optimization of the electrical collector grid in an HPP are not covered. Therefore, it is essential to study relevant topics related to this, including geographical location, voltage levels, voltage type, connection point, etc., in order to obtain an efficient collector system layout.

Since the indicative analysis showed that Electrolyzer utilization could reduce frequency deviations compared to wind turbines alone, it was also evident that it demands faster response and duration of ramps for grid balancing. Therefore, these power control attributes must be investigated further on a larger scale and with even more significant interaction between technologies due to the higher foreseen impact on power balancing.

The revenue streams of introducing Electrolyzers into the energy mix are broadened due to the possibility of further utilizing renewable production. However, it is achieved by increasing self-consumption during low or negative electricity prices instead of producing green hydrogen. Moreover, using it for energy arbitrage is considered non-feasible due to the lowering of energy efficiency, thus making it less competitive in the current market. However, the studies are not covering future scenarios where the market and efficiency of Electrolyzers are different.

Studies on ancillary services to the power grid using an HPP of wind power and green hydrogen production show that Electrolyzers can participate in FCR markets, thus improving the frequency nadir and oscillations. Moreover, the incentives for demand response of Electrolyzers are successful in an experimental setup where the response rates and ramps are assessed. However, the current studies investigate Electrolyzers from an overall viewpoint without considering the challenges in interaction with connected Wind Turbines and a larger-scale setup.

# Chapter 3

# System Specification

## 3.1 System Definition

The system in scope is an existing WPP called Tagmark Wind Park placed in Northern Jutland. This site is opted for since it is representative for Danish onshore wind power plants in terms of size and layout. Therefore, it is applicable as a starting point for the studies. Onshore WPPs generally consist of an interconnection of several Wind Turbines that are connected to the national power grid. The particular park includes eight V117-Vestas Turbines with a rating of 3.6 MW each and a collecting substation, WPP Substation, that accumulates the produced power from the assets. An overview of the geographical site and the WPP layout can be seen in Figure 3.1. The voltage level from the turbines to the WPP Substation is medium voltage, 10kV [40].


Figure 3.1: Geographical location of Tagmark WPP

It is proposed to integrate a 6MW Electrolyzer Plant consisting of 12 PEM-Electrolyzer Modules of 500 kW each to balance the system through green hydrogen production. However, the WPP is not located near any existing gas pipelines or direct consumers, so Hydrogen needs to be transported by vehicles. Therefore, when the Electrolyzer Plant has to be implemented in the original power plant, its placement must be determined. It is a trade-off, as the losses of the wind power plant will increase with distance, so from an efficiency point of view, it is more favorable to locate the Electrolyzer Plant closer to the Wind Turbines. Furthermore, the system in scope is illustrated in the single line diagram (SLD) in Figure 3.2.

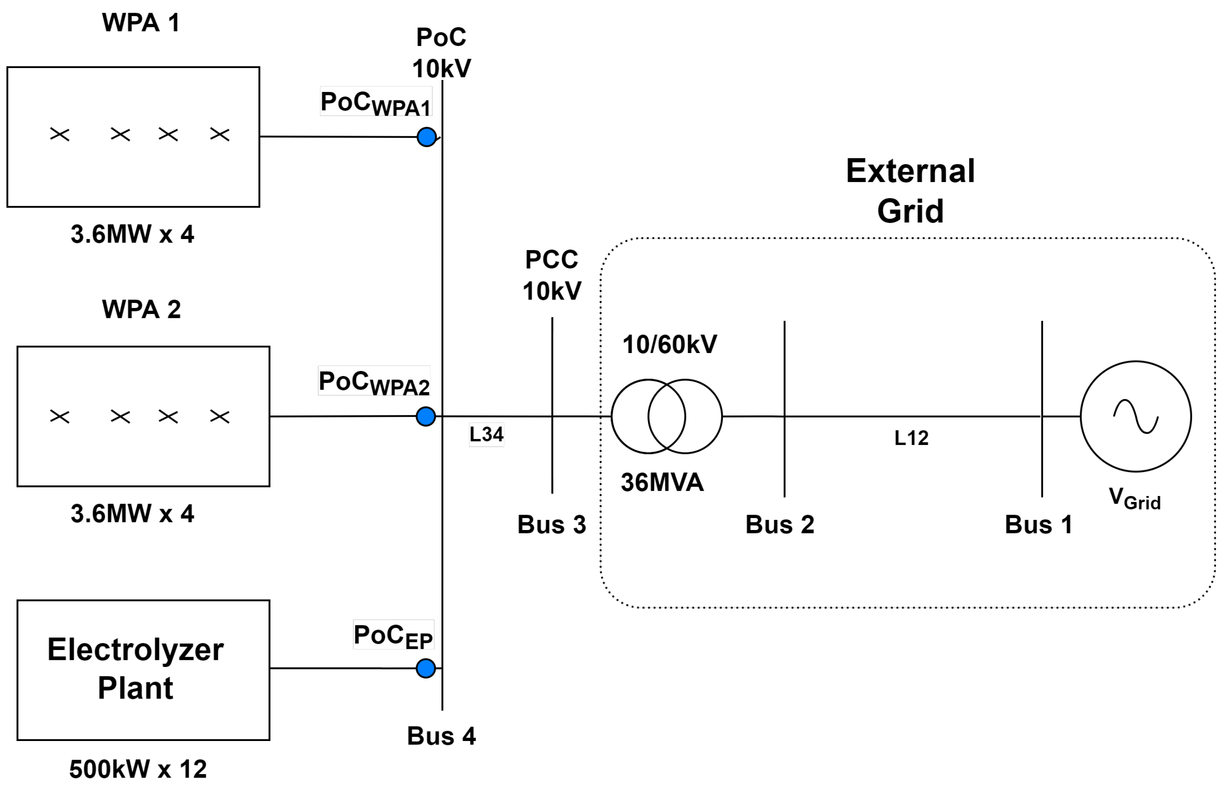


Figure 3.2: SLD of the WPP with Electrolyzers

The SLD in the Figure shows the reconfigured system. It consists of two similar Wind Power Arrays (WPA1 & WPA2) as the physical system, injecting power into the Point of Connection (PoC) on Bus 4. The power is either transferred to the Electrolyzer Plant to produce green Hydrogen or into the External Grid through the PCC. The PCC is located at the WPP Substation, and The External Grid represents the High Voltage Substation, Nors. Since one of the objectives of this project is to investigate a feasible collector system for a large P2H2 installation, the design of the Electrolyzer Plant will be explained further in the later chapters. However, the characterization of the WPA will be explained in the following subsection.

### 3.1.1 Wind Power Arrays

From the geographical site in Figure 3.1 and the SLD in Figure 3.2, it is indicated that the Wind Turbines Generator (WTG) is placed in two feeder arrays of four turbines in each (WTG 1...WTG 4 and WTG 5...WTG 8). These feeders supply the accumulated power through underground cables to the PoC, Bus 4. Each feeder is built up as a radial daisy chain array. Consequently, there are different distances and thus cable lengths between the turbines and the WPP substation. The specified cable distances and thus cable lengths are given by Table 8.4 in Appendix C. In Figure 3.3 the SLD of the radially connected WTGs of each feeder is shown.

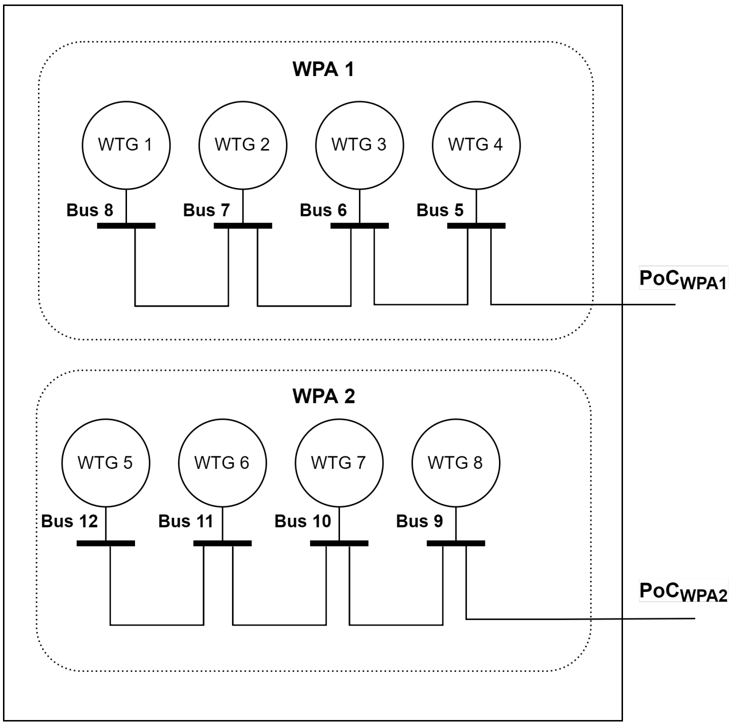


Figure 3.3: Internal Block Diagram of WPP

## 3.2 System Requirements Specifications

The system consists of various sub-systems, so it is crucial to ensure accuracy and agreements between them. Therefore, several system requirements need to be specified. The following section captures the requirement specification and evaluation of the various sub-systems and overall system behavior concerning its performance and accuracy.

1. The Electrolyzer Plant layout must be designed appropriately, accurately, and effectively.
    (a) Model shall be accurate with respect to the outputs in voltage magnitude and phase angle, with a maximum allowable error of ±1% compared to a load flow calculation performed in a dedicated power system tool.
    (b) Power Plant must be designed to maintain the accumulated power losses below 6% (360kW).
    (c) Power plant must be designed to maintain the voltage in the system within ±10% of the nominal system voltage.
2. The Consumption of the Electrolyzer Plant must be designed to comply with the technical requirements for medium voltage connections.
    (a) The Power Factor (PF) in the PoC must be between 0.95 and 1, calculated as an average value measured over 15min[19].
    (b) The Electrolyzer Plant must be designed so that it can maintain normal operation in the voltage range ± 10% of normal voltage and in the frequency range of 49 Hz to 51 Hz in the PoC [19].

3. The system must be able to curtail the power to the utility grid based on injunctions from the TSO/DSO.
   (a) Control must start no later than 2 seconds after an injunction is demanded and must be completed within 15 seconds [20]
4. The system must contribute ancillary services for frequency support (FCR).
   (a) Control must start no later than 2 seconds after a frequency change is detected and must be completed within 15 seconds [41]
   (b) Frequency support must remain active for a minimum of 15 minutes [42].
   (c) The system must provide FCR at a frequency deviation up to ± 200mHz in relation to the reference frequency of 50Hz, with an allowable ± 20mHz deadband[42].
   (d) The control must provide a symmetrical product of at least ± 1MW [42]. It must be able to supply both up-and down-regulation in the interval from 0-100% of rated capacity.

The requirement specified in this section will be studied and tested with different scenarios specified in the following section.

## 3.3 Scenarios

In order to assess the capabilities of the system against the requirements stated in Section 3.2 and the gaps in the State of Art of Section 2.5, a set of test scenarios is established. The scenarios can be divided into three overall scenarios that individually contribute to an assessment of the specified goals of the project. These three scenarios are stated in Table 3.1, while a more detailed description of each scenario is given below.

Table 3.1: List of Scenarios

| No. | Name |
|---|---|
| 1 | Electrolyzer Plant Module Layout |
| 2 | Energy Balancing |
| 3 | Ancillary Services |

### 3.3.1 Electrolyzer Plant Module Layout

As mentioned in the State of Art in Chapter 2, the utilization and integration of Electrolyzers in HPP are in the novel stages, with exclusively pilot and demonstration projects with a small Electrolyzer penetration. However, since this project considers a more significant penetration consisting of numerous base modules, the original Electrolyzer layouts may be unsatisfactory in terms of the electrical power flow. Therefore, scenarios that investigate alterations of the below aspects are to be performed to assess a good layout.

1. Voltage Levels and Voltage Types may be altered to reduce the power losses within the system associated with operating large Electrolyzers in a traditional layout.
2. An investigation of Feeder Configuration for modularity and flexibility in the system must be adapted to reduce the power losses and physical footprint.

Thus the aim is to clarify how the collector system for an Electrolyzer Plant can be designed to minimize the losses concerning the specified requirements in Section 3.2 through adequate system specifications and structuring.

### 3.3.2 Balance of Plant

As an Electrolyzer is added to an existing WPP, the demand for internal energy balancing increases, and thus a change in the control structures is needed. The energy balancing demand can be divided into two operational scenarios.

#### 3.3.2.1 WPP Following

The role of this scenario is to obtain an assessment of the balancing capabilities of the HPP when the green hydrogen production is prioritized over injection into the electrical utility grid. In order to ensure this prioritization is feasible, the system must obtain balance quickly. This mode of operation is desirable because the electricity prices can be low, and thereby it can be more feasible to produce green hydrogen than to sell it to the power to the grid. Thus the scenario aims to obtain Electrolyzer capabilities to off-take as much as possible and only inject the surplus power from the wind production to the main utility grid.

> ***An increase in wind speed and, thus, wind power production must increase green hydrogen production to avoid low prices in exchange with the main utility grid.***

#### 3.3.2.2 Wind Curtailment Restraint

The role of this scenario is to attain further an assessment of the balancing capabilities of the hybrid power system, where the aim is to reduce the curtailment of Wind Turbines. Wind curtailment reduces power production, resulting in significant economic losses for the operators. Due to the high penetration of renewables, the Danish TSO, Energinet, claimed a continuous growth in the need for special regulation. For example, in 2020, the German TSO, TenneT, paid the danish Wind Turbine owners 172kr/MWh for curtailing 1.463GWh of wind power[43]. The statistic from Energinet for the special regulation for the last couple of years can be obtained from Table 3.2.

Table 3.2: Annual Report for special regulation from 2017-2020 - Energinet [43].

| | **2020** | **2019** | **2018** | **2017** |
|---|---|---|---|---|
| Received From TenneT(GWh) | 3.901 | 1.914 | 1.598 | 1.210 |
| Down-regulated among Danish Operators(GWh) | 3.048 | 1.312 | 1.114 | 781 |
| Stop/Reduction of production of Thermal plant | 35% | 46% | 53% | 64% |
| Start of Electric Boilers | 17% | 22% | 21% | 22% |
| Stop/Curtailment of Wind Turbines | 48% | 32% | 26% | 14% |
| Avg. Price for all domestic down-regulation (kr/MWh) | -172 | -92 | -69 | -57 |

Since the curtailment of Wind Turbines accounts for 48% of the total special regulation in Denmark in 2020, a need for an alternative solution has to be considered. Therefore, instead of curtailing the turbines, the excess produced energy can be fed into the Electrolyzer modules and thus contribute to hydrogen production. Therefore, it is highly relevant to test a scenario where the energy is redistributed when curtailment is needed to maximize production. Therefore, the following scenario will be tested:

> ***A command to down-regulate the power production of the plant provided by the TSO/DSO must result in up-regulating of green hydrogen production in order to reduce curtailment of wind power and thus increase economic revenue for plant operators due to the additional revenue stream.***

Curtailment of Wind Turbines can, in addition to down-regulation, also be used for controlling the HPP in order to avoid negative electricity prices. It often occurs due to extreme daily wind conditions, which leads to overproduction in the grid. The Park-Operators will have to pay for the power injected into the grid, which is undesirable. Therefore, it is relevant to test the following scenario:

> ***Negative prices in the electricity spot market must lead to maximum production of green hydrogen while no wind power production is delivered to the utility grid.***

### 3.3.3 Ancillary Service

This scenario is designed to assess the capabilities of contributing ancillary services to the connected utility grid. The scenario is divided into two sub-scenarios. The power system shall reevaluate the power flow to the utility grid, and Electrolyzer module as either a positive or a negative frequency change is detected on the utility grid. Thus the aim is to contribute to demand response as a measure of ancillary service. In order to define a realistic scenario, the expected frequency deviations must be investigated. In Figure 3.4 the frequency for the Western Danish Electrical Grid, DK1 in 2019, is plotted to see normal frequency fluctuations.

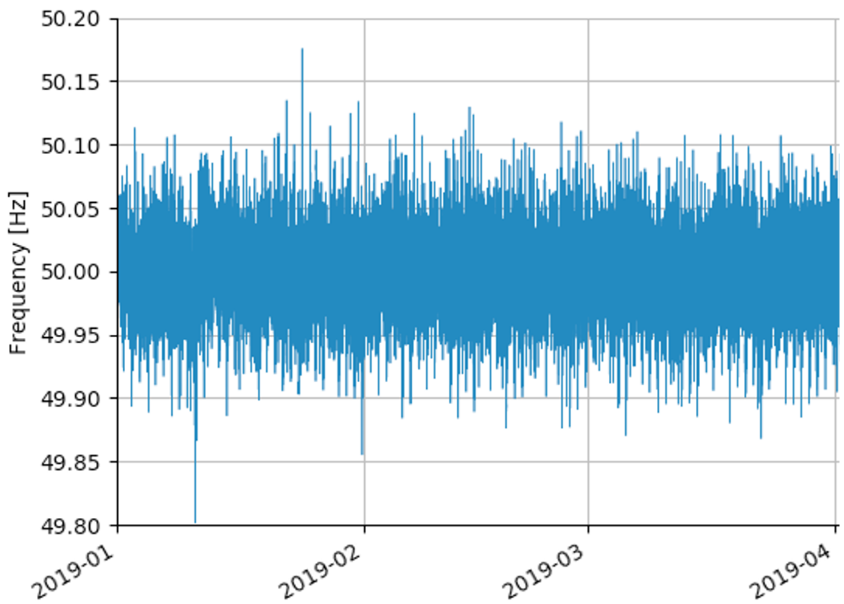


Figure 3.4: Frequency Measurement in Western Danish Grid, DK1, Jan - Apr 2019 [44].

As obtained from the Figure, the frequency fluctuates continuously, so the FCR needs to regulate the changes, to stabilize the frequency at 50Hz. In order to observe the expected frequency of ancillary services, the data is represented as a Boxplot in Figure 3.5.

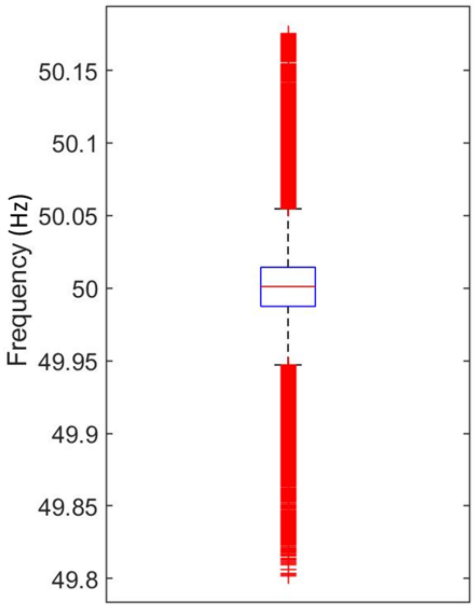


Figure 3.5: Boxplot of the data from Frequency Measurement in Western Danish Grid, DK1 - 2019

Therefore, the following scenarios related to Ancillary services should be tested.

> ***As a result of an imbalance in power demand and production, frequency fluctuation occurs. The Electrolyzer Plant must regulate the production of green hydrogen in order to provide FCR. The FCR service must operate in relation to specified requirements in Section 3.2.***

## 3.4 Summary

In this Chapter, the system specification is defined. The proposed system is an existing onshore WPP consisting of eight V117-Vestas turbines with a rating of 3.6MW each, connected to a distribution grid. It is proposed to integrate a 6MW Electrolyzer Plant into the energy mix, to balance the HPP through hydrogen production. As the HPP consists of various sub-systems, it is crucial to ensure accuracy and agreements between them. Therefore, several system requirements have been specified.

To assess the capabilities of the system against the requirements, some scenarios have been established. As the development of Electrolyzer integration in HPP is in the novel stages, the first scenario aims to find a feasible layout for the Electrolyzer collector system. The role of the second scenario is to obtain an assessment of the balancing capabilities when integrating an Electrolyzer in the HPP. Finally, in the third scenario the capability of the Electrolyzer to participate in FCR-market is studied, to introduce more potential revenue streams for the Park Operator.

In the following Chapter, the Electrolyzer Plant layout will be studied to find a feasible design, which can be utilized in further system development.

# Chapter 4

# Design of Electrolyzer Plant Layout

## 4.1 Footprint of Electrolyzer Plant

As mentioned in the Background section in Chapter 1, the Electrolyzer technology has been optimized and physically compressed during the last few decades. A complete single 500kW module has a footprint of a 20ft container, and two can be fitted in a 40ft container as shown in Figure 4.1 [45]. Moreover, the technology is modular and scalable, meaning that coupling for higher capacity is possible, and thus, more containerized modules can be connected in clusters [45].

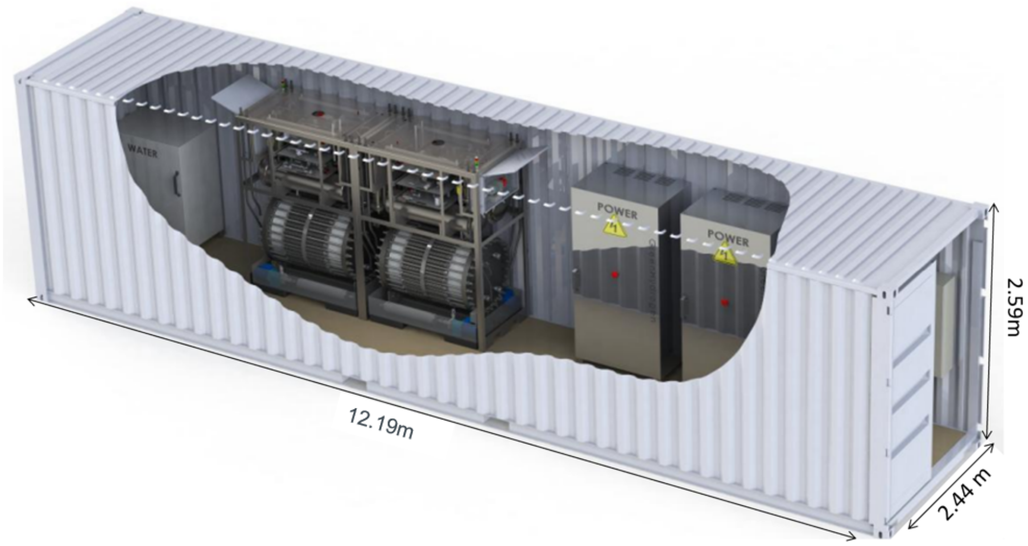


Figure 4.1: Containerized Electrolyzer Module of 2 X 500kW[45]

A module consists of a 500 kW Electrolyzer stack that measures 2.1m X 1.3m X 2.4m and a power converter module that likewise occupies space within the container. Conventionally, the power module consists of a step-down transformer as the Electrolyzer require a relatively high current [45], an AC/DC converter, which rectifies the current into a controlled DC/DC converter. However, this particular plant layout may be revised based on the applications, capacity, and electrical infrastructure.

## Converters

The Electrolyzer converters are essential units for controlling and rectifying the current in the Electrolyzer. It consists of an AC/DC rectifier and a DC/DC converter. The role of the DC/DC converter is to provide control of the current through the Electrolyzer stack by varying the voltage across the system. It typically has an efficiency of 98% [46]. AC/DC converters can have different topologies described in Chapter 2 - State of Art. The common type used for rectifying is the 12-TR or AFE. Both topologies have, as previously mentioned, some advantages and disadvantages related to control complexity, power quality, cost, and reliability. However, evaluation of their physical footprint is also important. The 12-TR topology may need reactive power compensation, e.g., Static Synchronous Compensator (STATCOM) and filters that increase the physical footprint compared to the AFE topology. However, both topologies fit into standard power converter cabinets [47].

## Transformers

Two-winding or three-winding transformers are typical approaches to step down the AC voltage in Electrolyzer Plants. When opting for the thyristor-based rectifier, a method of mitigating the current harmonics of the diode bridge rectifiers is by incorporating a three-winding transformer connected in wye-delta-wye configuration [25]. Alternatively, a two-winding transformer can be utilized, but designated harmonic filtering may be added. The two-winding transformer is also utilizable for the AFE topology because the harmonic contributions are less than its counterpart, and thus the filtering capabilities may be unnecessary. The physical footprint of the transformers is expected to be similar to a pad-mounted transformer. Thus, approximately $2m^3$ space should be allocated [48]. Besides stepping down the voltage, the role of the transformer is also to provide Galvanic isolation, which is often used to enhance system safety. In addition, it protects the maintenance personnel by preventing ground potential differences or ground loops.

## Cables

Several modules are to be combined to obtain the desired Electrolyzer capacity. The modules must be interconnected using power cables, affecting the plant footprint.

When selecting power cables, the main limitations lie within the physical sizing of the cables due to the demand for their current-carrying capability. Moreover, the bending radius of cables may become the limiting factor as the cross-section increases. The cable manufacturers ScanKab and NKT agree on a bending radius of up to 10 times the cable diameter [49] [50]. For low voltage applications below 1kV, the largest commercially available cable is $500mm^2$ from ScanKab [49] and thus, for applications that require bigger cables, specially manufactured cables are necessary. Alternatively, more parallel cables or system voltage increases can mitigate these challenges.

## Electrolyzer Plant Footprint

In designing an overall Electrolyzer plant, some considerations must be considered. Firstly, the substation layout must not introduce safety concerns to maintenance-personnel. In addition, the layout has to provide adequate accessibility both to the hydrogen off-taking trucks and ensure that maintenance and reparations on subsystems do not force a total shutdown of the station[51]. Moreover, it is vital to consider the existing system to which the Electrolyzer substation is connected. This includes its location and surrounding infrastructure, since extensive cabling connections may influence the optimal placement. Thus the following criteria should be considered when designing the Electrolyzer Plant layout.

- Safety
- Maintenance
- Geographical location of Connection Point

In consideration of the module footprints and the transformers associated with them, an estimate of the footprint of the Electrolyzer Plant for this project is presented in Figure 4.2. To obtain an overall rating of 6MW capacity, the plant consists of separate Electrolyzer Modules grouped in clusters. Moreover, the distances between the neighboring modules and transformers are presented to comply with the mentioned accessibility considerations, while the layout also indicates the expected distance to the WPP Substation.

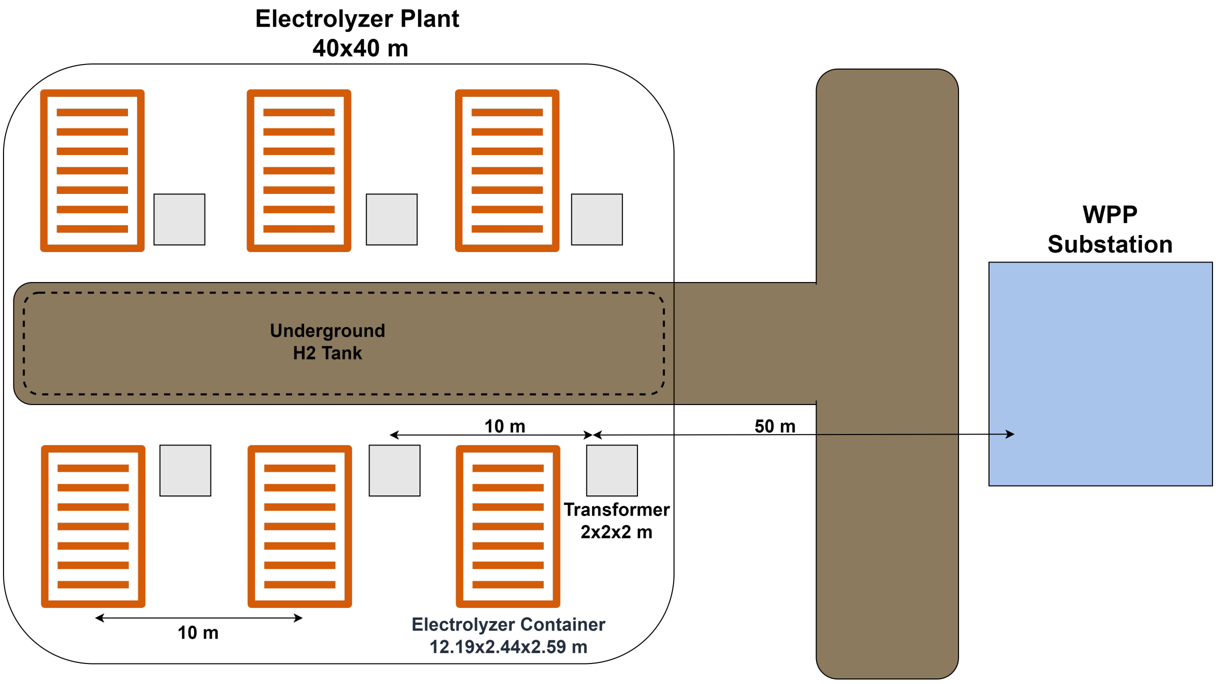


Figure 4.2: Electrolyzer Plant Layout

In order to get an indication of a potential physical layout, an illustration of the Electrolyzer plant is presented in Figure 4.3, where it is also shown how an operation Truck can pick up the produced green hydrogen.

Figure 4.3: Illustration of Electrolyzer Plant Layout

## 4.2 Electrolyzer Plant Configurations

One of the main objectives is, as mentioned in Chapter 1, to investigate a feasible collector system layout for large P2H2 installation. However, this can be a comprehensive task as many design considerations must be taken into account. Therefore, it is highly relevant to test various configurations to find a suitable design solution for the Electrolyzer plant layout. Common for the configurations is that they are developed to obtain desirable modularity and flexibility as described in the Scenarios in Section 3.3. The following section captures a description of various configurations based on physical limitations and opportunities covered in Section 4.1 *Footprint of Electrolyzer Plant*. The configurations are based on different cases with varying voltage- types and levels. An overview and identification of the various configurations can be seen in Table 4.1.

Table 4.1: Design Cases for Electrolyzer Collector System

| **Case No. / Voltage ID** | **A** | **B** | **C** |
|---|---|---|---|
| Case 1 (AC) | 1kV | 3.3kV | 6kV |
| Case 2 (AC) | 1kV | 3.3kV | 6kV |
| Case 3 (DC) | 1kV | 3.3kV | 6kV |
| Case 4 (DC) | 1kV | 3.3kV | 6kV |

### 4.2.1 AC Configurations

This subsection covers the AC configurations of the Electrolyzer collector system. It consist of two main cases, which can be seen in Figure 4.4 and 4.5, respectively. The purpose of the cases is to study the behavior of the plant, when evaluating power system losses and physical footprint. In the first case, Case 1, two Electrolyzer Modules are combined to fit in a 40ft container. The voltage level is transformed from 10kV in PoC to 1/3.3/6kV in the Electrolyzer plant. Then it is further stepped down to 400V at each group of modules. The cables listed in Table 4.2 are sized to carry the load current equivalent to two modules with respect to the voltage levels, A,B,C explained in Table 4.1.

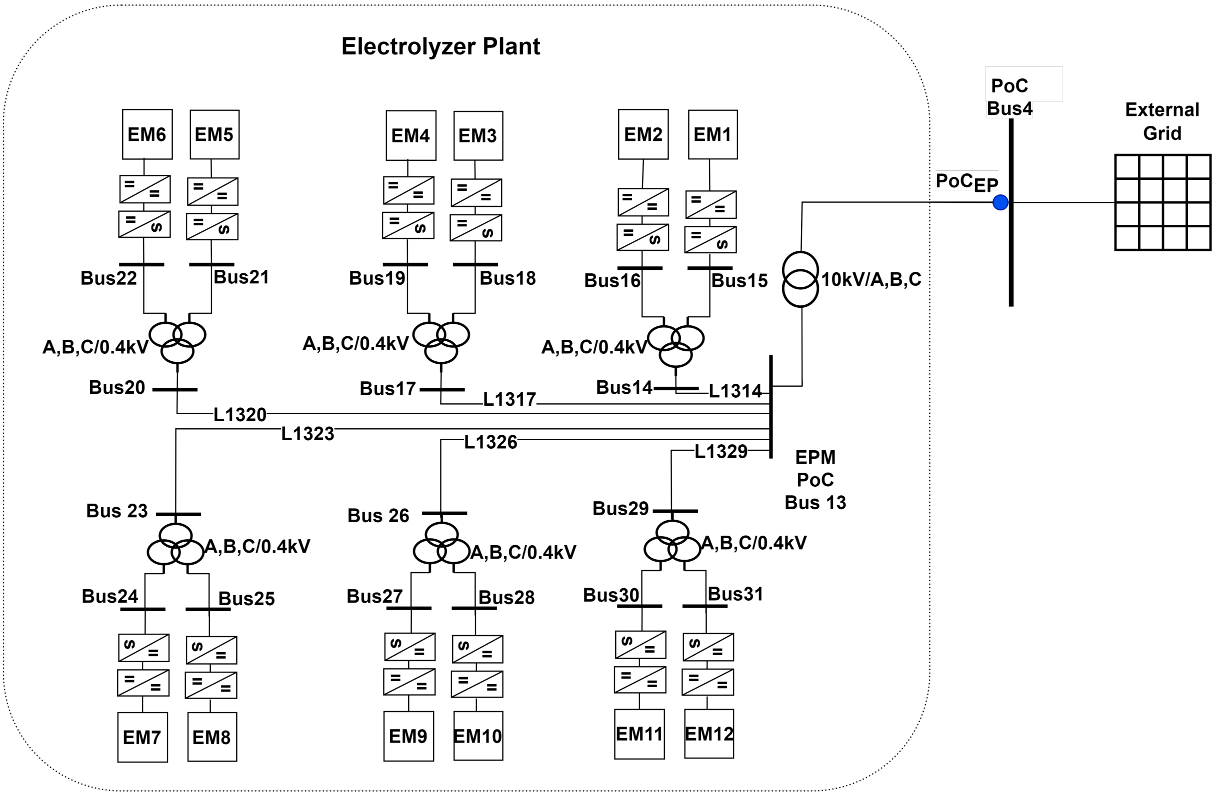


Figure 4.4: Electrolyzer Plant Layout for AC-configuration Case 1.

Table 4.2: List of Cables for AC-configuration Case 1

| Cable Name | Length[m] | Cross Section[mm$^2$]/Ampacity[A] | | |
|---|---|---|---|---|
| | | A | B | C |
| L1314 | 50 | 240/679 | 95/240 | 50/170 |
| L1317 | 60 | 240/679 | 95/240 | 50/170 |
| L1320 | 70 | 240/679 | 95/240 | 50/170 |
| L1323 | 70 | 240/679 | 95/240 | 50/170 |
| L1326 | 60 | 240/679 | 95/240 | 50/170 |
| L1329 | 50 | 240/679 | 95/240 | 50/170 |

In the second AC configuration, Case 2, the Electrolyzers are singularly connected to the Electrolyzer Plant Module (EPM) Bus through cables, sized to carry current equivalent to one Electrolyzer module. The modules are located in 12 containers distributed into two rows with 10 meters between them. It contains a two-winding transformer, transforming the voltage from 1/3.3/6kV to the desired 400V. Compared to Case 1, the cross-section of the cable size is smaller. However, more assets are needed. The SLD of the layout can be seen in Figure 4.5 and values can be obtained by Table 4.3.

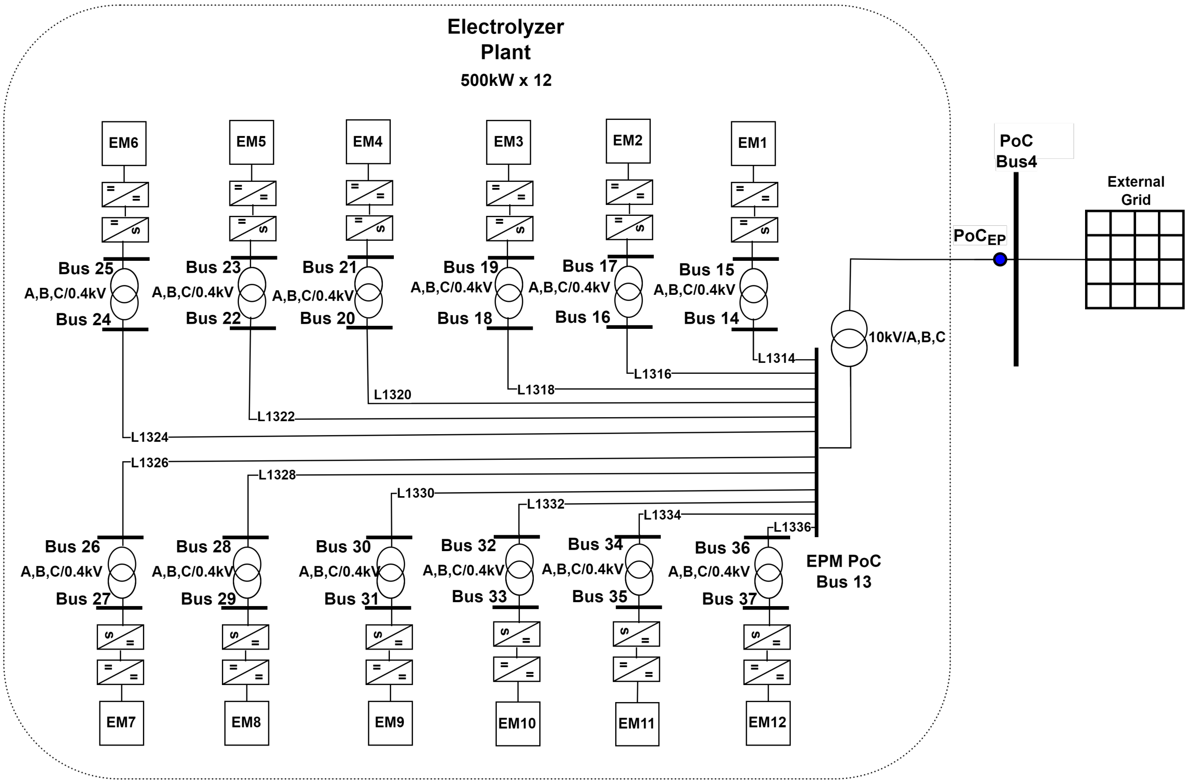

Figure 4.5: Electrolyzer Plant Layout for AC-configuration Case 2.

Table 4.3: List of Cables for AC-configuration Case 2

| Cable Name | Length[m] | Cross Section [mm$^2$]/Ampacity[A] | | |
|---|---|---|---|---|
| | | A | B | C |
| L1314 | 50 | 120/346 | 25/115 | 25/115 |
| L1316 | 60 | 120/346 | 25/115 | 25/115 |
| L1318 | 70 | 120/346 | 25/115 | 25/115 |
| L1320 | 80 | 120/346 | 25/115 | 25/115 |
| L1322 | 90 | 120/346 | 25/115 | 25/115 |
| L1324 | 100 | 120/346 | 25/115 | 25/115 |
| L1326 | 100 | 120/346 | 25/115 | 25/115 |
| L1328 | 90 | 120/346 | 25/115 | 25/115 |
| L1330 | 80 | 120/346 | 25/115 | 25/115 |
| L1332 | 70 | 120/346 | 25/115 | 25/115 |
| L1334 | 60 | 120/346 | 25/115 | 25/115 |
| L1336 | 50 | 120/346 | 25/115 | 25/115 |

### 4.2.2 DC Configurations

This subsection covers the DC configurations of the Electrolyzer Collector System. Similar to the AC configurations, it contains two cases where the purpose is to investigate a feasible design solution concerning losses and footprint for future P2H2 installations. The physical configuration of the third case (Case 3) is almost identical to the AC Configuration in Case 2. However, in this case, a large AC/DC converter is connected to the EPM Bus providing direct current to the collector system. The footprint of the AC/DC converter is significant as it has to carry the whole load current of the Electrolyzer Plant. However, the advantage of the DC configuration is that the module transformers and AC/DC converters can be removed from each Electrolyzer Module. An illustration of the SLD can be seen in Figure 4.6 and the length and size of cables can be obtained by 4.4.

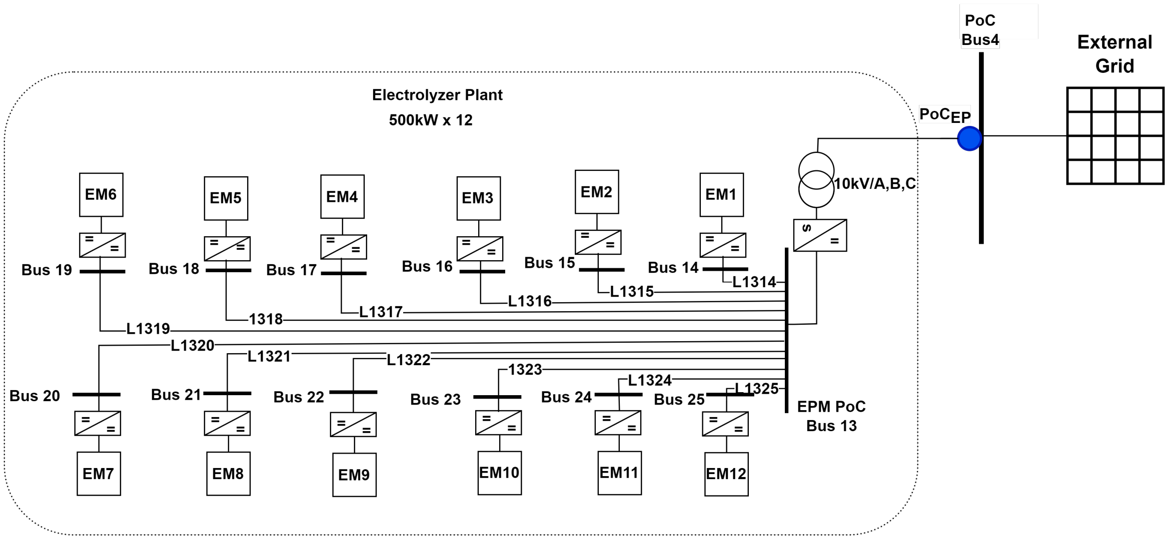


Figure 4.6: Electrolyzer Plant Layout for DC-configuration Case 3

Table 4.4: List of Cables for DC-configuration Case 3

| Cable Name | Length[m] | Cross Section [mm$^2$]/ Ampacity [A] | | |
|---|---|---|---|---|
| | | A | B | C |
| L1314 | 50 | 185/504 | 25/115 | 25/115 |
| L1315 | 60 | 185/504 | 25/115 | 25/115 |
| L1316 | 70 | 185/504 | 25/115 | 25/115 |
| L1317 | 80 | 185/504 | 25/115 | 25/115 |
| L1318 | 90 | 185/504 | 25/115 | 25/115 |
| L1319 | 100 | 185/504 | 25/115 | 25/115 |
| L1320 | 100 | 185/504 | 25/115 | 25/115 |
| L1321 | 90 | 185/504 | 25/115 | 25/115 |
| L1322 | 80 | 185/504 | 25/115 | 25/115 |
| L1323 | 70 | 185/504 | 25/115 | 25/115 |
| L1324 | 60 | 185/504 | 25/115 | 25/115 |
| L1325 | 50 | 185/504 | 25/115 | 25/115 |

In the fourth DC-configuration, Case 4, the Electrolyzer modules are similar to Case 1, connected in groups of two located in one large 40ft. container. Six main cables connect each module group to the EPM Bus 13, which carries a load current equivalent to two modules. The power is then transferred to each of the DC/DC modules through 12 smaller cables. Compared to the AC configuration, a larger AC/DC converter is required, which should be sized to carry full load current for the entire Electrolyzer Plant. However, transformers and rectifiers for each module can be neglected in this configuration. An illustration of the proposed plant layout for Case 4 can be seen in Figure 4.7 and the length and size of cables can be obtained by Table 4.5.

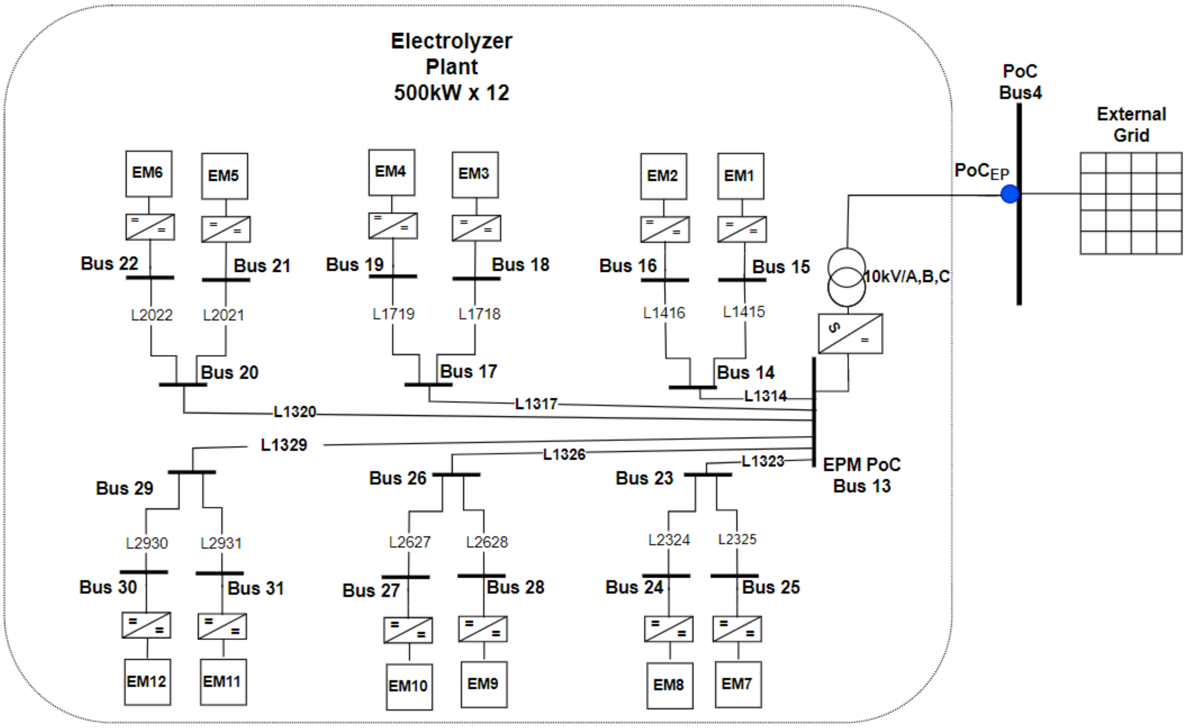


Figure 4.7: Electrolyzer Plant Layout for DC-configuration Case 4.

Table 4.5: List of Cables for DC-configuration Case 4

| Cable Name | Length[m] | Cross Section [$mm^2$]/Ampacity[A] | | |
|---|---|---|---|---|
| | | A | B | C |
| L1314 | 50 | 185x2/575x2 | 95/240 | 35/190 |
| L1415 | 10 | 185/575 | 25/115 | 25/115 |
| L1416 | 10 | 185/575 | 25/115 | 25/115 |
| L1317 | 60 | 185x2/575x2 | 95/240 | 35/190 |
| L1718 | 10 | 185/575 | 25/115 | 25/115 |
| L1719 | 10 | 185/575 | 25/115 | 25/115 |
| L1320 | 70 | 185x2/575x2 | 95/240 | 35/190 |
| L2021 | 10 | 185/575 | 25/115 | 25/115 |
| L2022 | 10 | 185/575 | 25/115 | 25/115 |
| L1323 | 50 | 185x2/575x2 | 95/240 | 35/190 |
| L2324 | 10 | 185/575 | 25/115 | 25/115 |
| L2325 | 10 | 185/575 | 25/115 | 25/115 |
| L1326 | 60 | 185x2/575x2 | 95/240 | 35/190 |
| L2627 | 10 | 185/575 | 25/115 | 25/115 |
| L2628 | 10 | 185/575 | 25/115 | 25/115 |
| L1329 | 70 | 185x2/575x2 | 95/240 | 35/190 |
| L2930 | 10 | 185/575 | 25/115 | 25/115 |
| L2931 | 10 | 185/575 | 25/115 | 25/115 |

## 4.3 Collector System Components

The following section describes the collector system components in the proposed system. It explains how the cables and transformers are captured through representation/equivalent models. Furthermore, it describes how a Thevenin Equivalent represents the External Grid. Equivalent models of the network components are further studied in the Model-Based Design (MBD).

### 4.3.1 Cables

The different assets in the HPP are connected through underground cables of varying lengths. Cables with lengths below 60 km can be represented as equivalent pi-terms with lumped parameters as seen in Figure 4.8 [52] [53]. Thus the cables can be represented and modeled by their equivalent series resistance R, series reactance X, and shunt admittance Y.

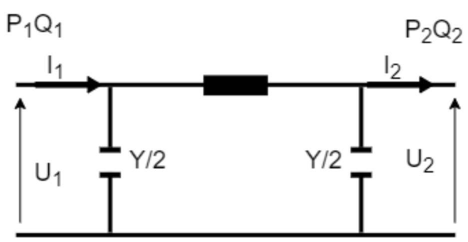


Figure 4.8: $\pi$-Equivalent of the Cables

### 4.3.2 External Grid

As the parameters that constitute the external grid in the system are unknown, an approach to model it is needed. Commonly the grid can be described through a Thévenin Equivalent representation which consists of a voltage source, $V_{Grid}$ and an equivalent impedance, $Z_{Grid}$.

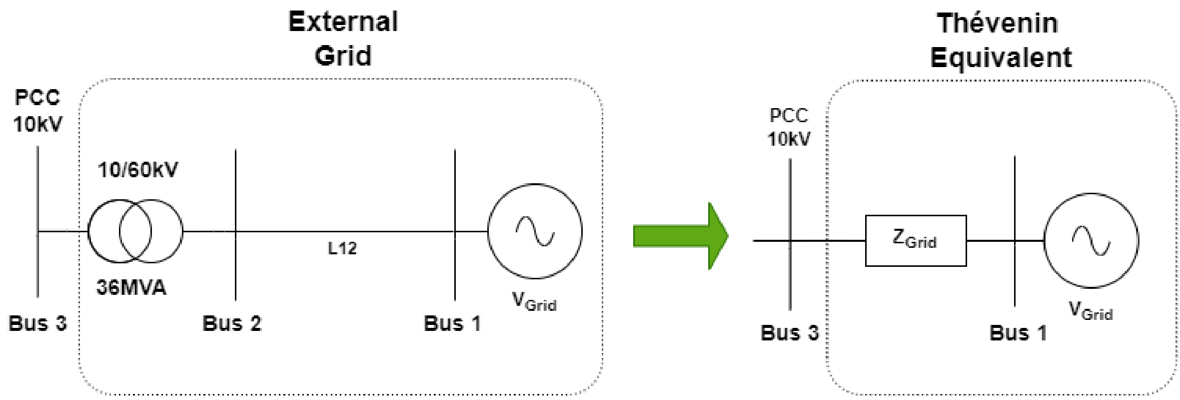


Figure 4.9: Thévenin Equivalent representation of External Grid

The grid impedance $Z_{Grid}$ is characterized by a resistive and reactive part, $R_{Grid}$ and $X_{Grid}$. The magnitude of these can be calculated through the short-circuit ratio (SCR) of the utility grid. The SCR is defined based on the short-circuit power ($S_{SC}$) that occurs in case of a system fault, and the rated power in PCC ($P_{rated}$).

If the SCR is large, the grid impedance is small, meaning that the voltage variations in $V_{Grid}$ have a negligible influence, indicating a stiff grid. Likewise, a low SCR causes a higher grid impedance and thus a more significant influence on the voltage variations.

$$SCR = \frac{S_{SC}}{P_{rated}} \tag{4.1}$$

The grid resistance and reactance magnitudes are given by the following equations using the XR-ratio of the grid.

$$Z_{Grid} = \frac{V_{Grid}^2}{S_{SC}} \tag{4.2}$$

$$R_{Grid} = \sqrt{Z_{Grid}^2 - X_{Grid}^2} = \frac{Z_{Grid}}{\sqrt{1 + XR^2}} \tag{4.3}$$

$$X_{Grid} = R_{grid} XR \tag{4.4}$$

The typical XR ratio for a stiff grid is $\geq 10$ and will be utilized in the further work to represent the stiffness of the External Grid.

### 4.3.3 Transformers

Transformers play a significant role in the power system, enabling various voltage levels. Multiple transformer configurations are available. However, only two-winding transformers will be presented in the proposed system. In order to capture the behavior of the transformer, an equivalent circuit model can be used, which enables a simplified calculation method. The two-winding transformer can be simplified by referring the impedance to either the primary or secondary side of the transformer. The simplified two-winding transformer model can be seen in Figure 4.10.

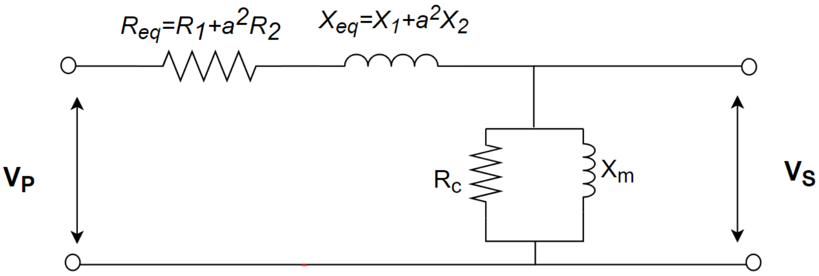


Figure 4.10: Equivalent Circuit Model of Two-winding Transformer Referring to Primary Side

In the Figure, the shunt branch represents the transformer core losses, $R_c$ and magnetization reactance, $X_m$, which are significantly high for large transformers. As a result, losses are low due to the minimal excitation current, and therefore, the shunt branch can be neglected. The Transformer model can therefore be simplifies to a equivalent resistance, $R_{eq}$ and reactance, $X_{eq}$, where the turns ratio $a = \frac{V_P}{V_S}$.

### 4.3.4 Verification of Components for Collector System

This section contains the verification of the collector system designed for the Electrolyzer Plant Layout. The equivalent models of the components have been implemented in a Newton Raphson Load Flow Algorithm (NRLFA) to indicate the system losses and voltage magnitudes in both AC and DC configurations. Therefore, it is crucial to verify the algorithm to ensure the reliability of the calculation results. The verification is based on a simplified system representation of the Electrolyzer Plant Layouts.

#### AC Load Flow Algorithm Verification

For the AC-system verification, the voltage of the PoC, Bus 4, is assumed to be $1\angle 0$ according to the specification of a stiff grid. Furthermore, two Electrolyzer modules of 500kW each are connected similarly to Case 1A with an intermediate voltage of 1kV. An SLD of the system can be seen in Figure 4.11.

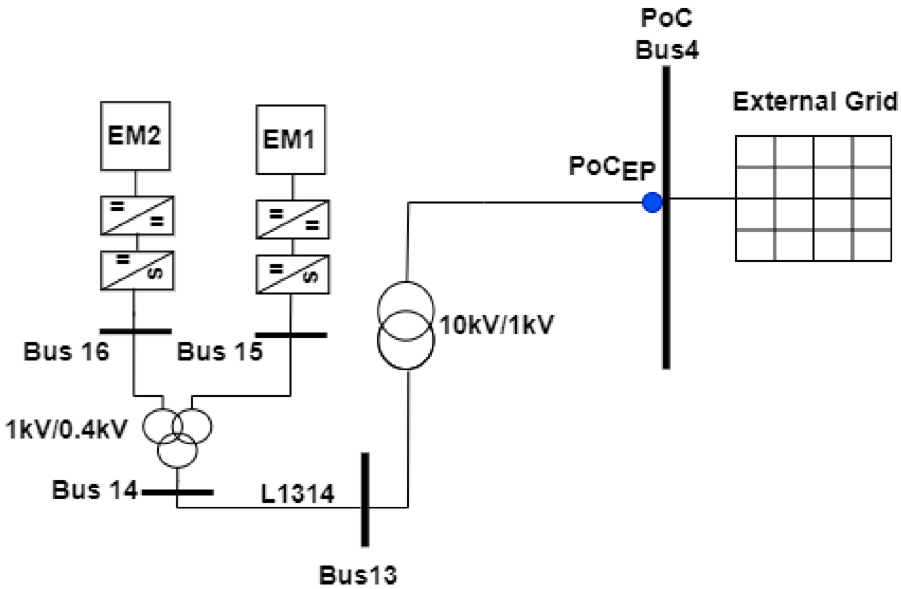


Figure 4.11: Proposed Simplified Model for Verification of AC Load Flow Algorithm (ACLF)

The proposed MATLAB model of the simplified system has been verified through a DIgSILENT PowerFactory model, where an identical layout has been developed. The deviation between voltage magnitude and angles for the NRLFA of the two models (MATLAB-model and DIgSILENT PowerFactory-model) is calculated through the Equations in 4.5 and 4.6.

$$V_{MagDev} = \frac{V_{MagPF} - V_{MagMATLAB}}{V_{MagPF}} * 100\% \tag{4.5}$$

$$V_{AngDev} = (V_{AngPF} - V_{AngMATLAB}) \tag{4.6}$$

The results of the calculated deviations can be seen in Figure 4.12 and 4.13, respectively. The simulation results and obtained data can be found in Appendix A.

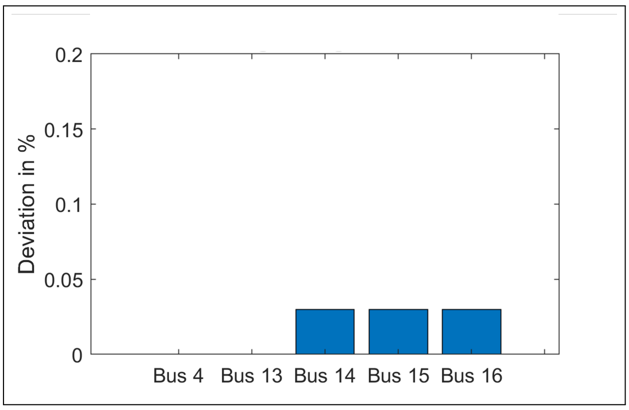


Figure 4.12: Voltage Magnitude deviation in % for the Test-Case, calculated based on NRLFA

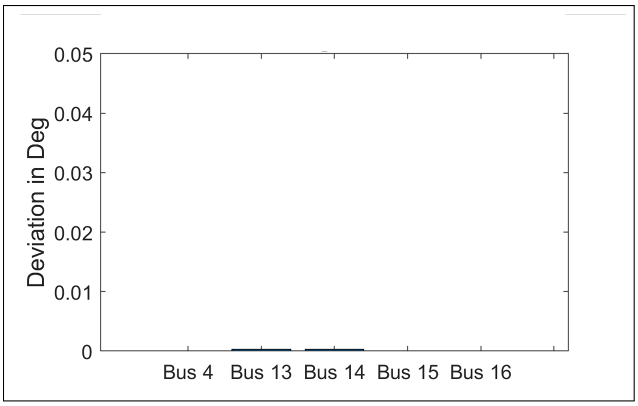


Figure 4.13: Angle deviation in Degrees for the Test-Case, calculated based on NRLFA

The figures show that the maximum deviation between the MATLAB-model and PowerFactory-Model is 0.003% for Voltage Magnitude and 0.009 degrees for voltage phase angle. Therefore, it is considered acceptable, as the converge settings for the NRLFA may be slightly different compared to built-in settings in Power Factory.

#### 4.3.4.1 DC Load Flow Algorithm Verification

The DC load flow has to be verified, similar to the AC system. The proposed simplified model for verification reflects Case 4A. The main AC/DC converter and transformer, connected between Bus 4 and Bus 13, are represented as an equivalent impedance in series with a DC source. An illustration of the system can be seen in Figure 4.14.

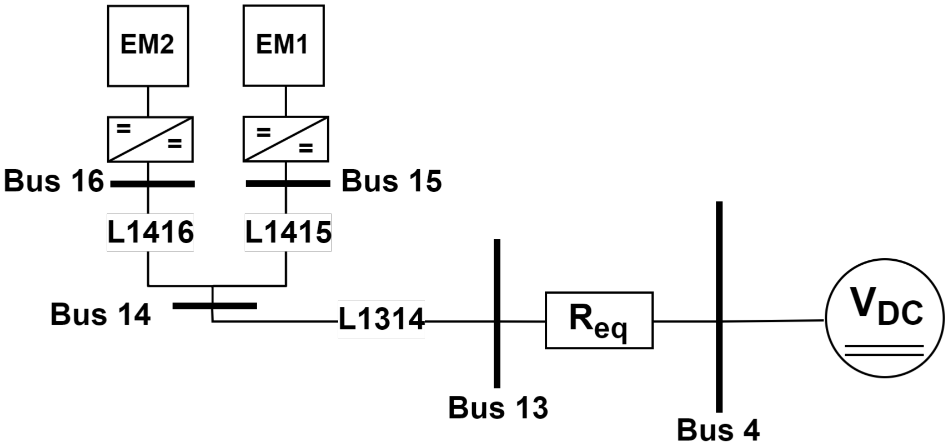


Figure 4.14: Proposed Simplified Model for Verification DC Load Flow Algorithm (DCLF)

The equivalent impedance reflects the losses in the transformer and converter. It is calculated based on equations 4.7, whereas the $P_{loss.trafo}$ reflects the total $I^2R$ losses caused by active and reactive current flow in the transformer and $P_{loss.Conv_{\eta 98\%}}$ reflects the converter losses at an efficiency of 98%. The $I_{EP}$ is the Current when assuming 1pu voltage at Bus4.

$$R_{eq} = \frac{P_{loss.trafo} + P_{loss.Conv_{\eta 98\%}}}{I_{EP}^2} \tag{4.7}$$

The proposed model has been verified through an identical model built in DIgSILENT PowerFactory. The deviation in Voltage magnitude between the MATLAB calculation and PowerFactory can be seen in Figure 4.15 and simulation results and obtained data can be seen in Appendix A.

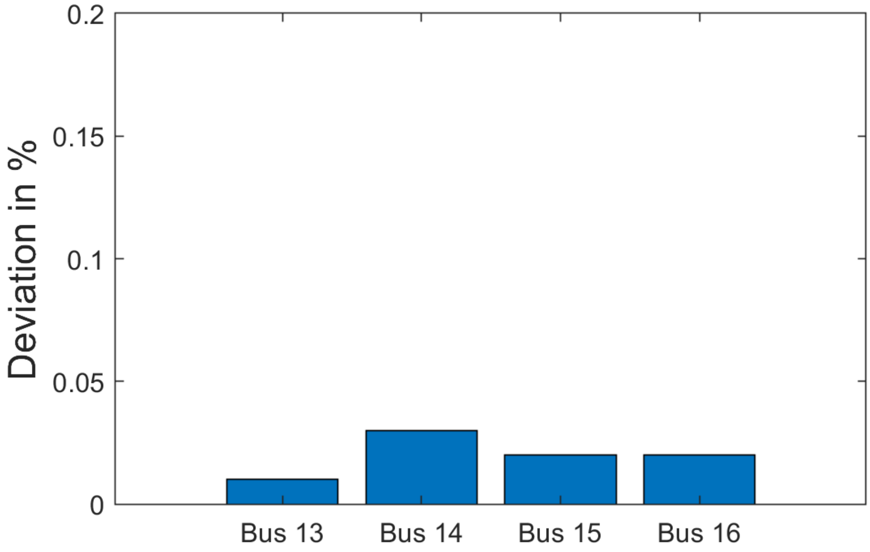


Figure 4.15: Voltage Magnitude deviation in percentage for the Test-Case, calculated based on DC Load Flow Algorithm

As obtained from the plot, the deviation in voltage magnitude between the two models is a maximum of 0.03%, which is considered acceptable.

## 4.4 Electrolyzer Plant Test

The load flow verification for both the AC and DC configurations showed satisfactory and reliable results. Therefore, the tests for selecting Electrolyzer Plant configuration can be conducted. This section contains the evaluation and results of the base cases, which consist of the four test cases described in Section 4.2. All cases are evaluated based on the accumulated power losses, the Bus-voltage profiles, the power factor at the PoC of the Plant, the physical layout, and sensitivity when all Electrolyzers are fully loaded (6MW).

In order to evaluate all the proposed plant layouts, the verified power flow analysis is considered. The different converters introduced in the configurations are represented as AFE-converter topologies with a static gain corresponding to their efficiency of $\eta_{conv} = 98\%$, which is applicable for both AC/DC and DC/DC converters. All cable sizes and thus impedances have been selected based on datasheets from acknowledged companies to get a realistic evaluation of the layouts. Similarly to the verification process of DC configurations in Section 4.3.4, Figure 4.14 an Equivalent impedance of the 10kV/A, B, C transformer + Main AC/DC converter has been calculated for Case 3 and 4, and for each Sub-case in order to represent the losses.

The assessment of the accumulated power loss is obtained by $I^2R$ losses of the DC configurations and by $I^2R$ and $I^2X$ losses for the AC configurations. It is determined by comparing the power transferred between the busses, where the loss account for the power dissipated in the different elements connecting the busses. In Figure 4.16 the accumulated power losses for each test-case is shown. It illustrates the power loss contribution of cables, transformers, and converters within the Electrolyzer Plant. The specific losses of the test cases can be found in Appendix B in Section 8.2.

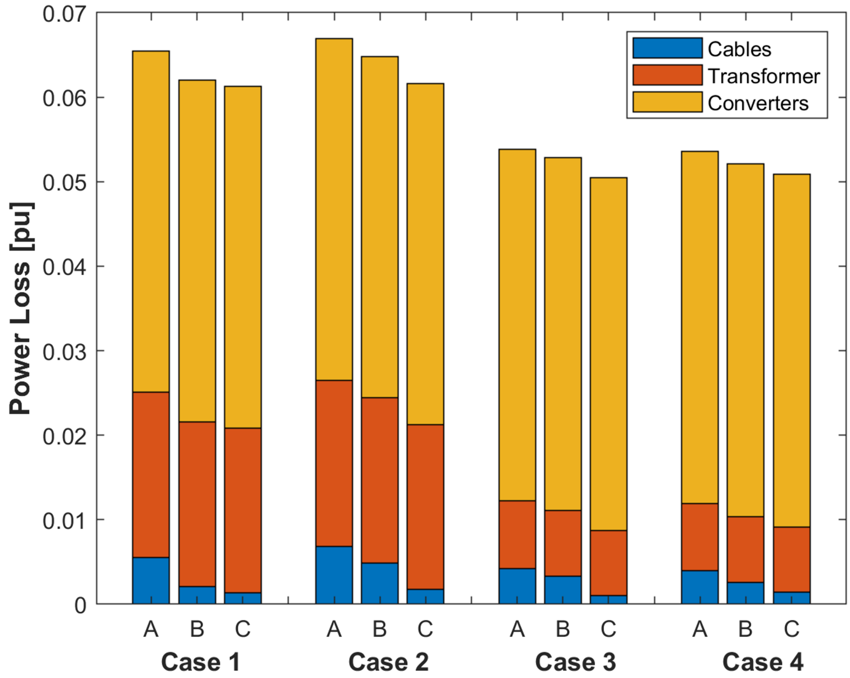


Figure 4.16: Accumulated Power Loss for Electrolyzer Plant with contribution of Cables, Transformers and Converters at a 6MW base

As obtained from the results of test cases, the power losses are reduced as expected when the voltage level is increased. It is also clear that the power losses for the AC-cases 1 and 2 are significantly higher than the DC-cases 3 and 4. The reason is the introduction of additional transformers to obtain the intermediate voltage level before connecting to the Electrolyzer modules. A solution to decrease the power losses could be utilizing the system at a voltage of 10kV because this would make the main transformer redundant and thus decrease the losses.

Besides the power losses, the bus voltages of each configuration are also assessed. The complete voltage profiles of each case are shown in Appendix B in Section 8.2. It indicates that the difference in magnitude at each module is influenced by the variation in cable length, which is why the modules connected to the longest cable experience the most significant voltage drop. In Figure 4.17 the voltage magnitudes of busses located farthest away for the four test cases are shown. Bus numbers for the four cases refer to the SLD in Section 4.2.

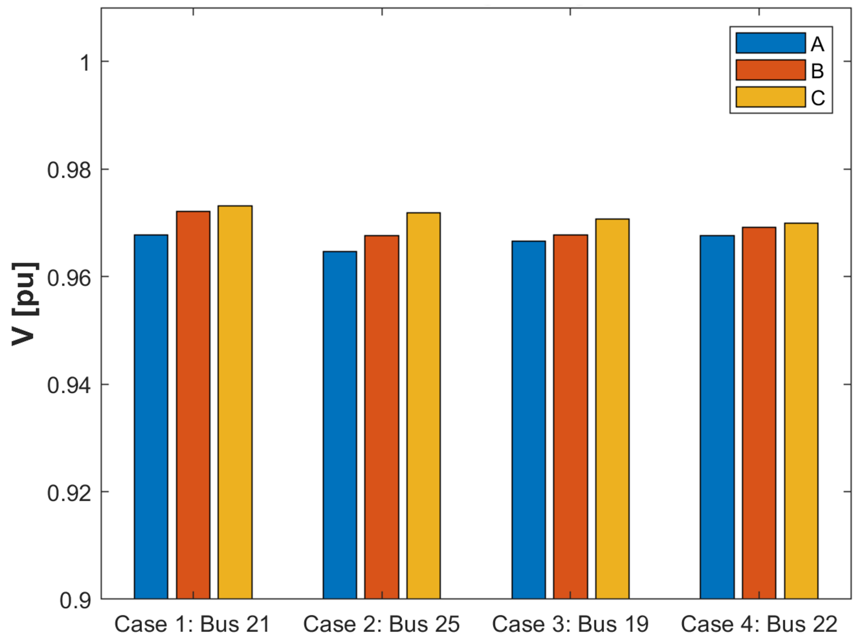


Figure 4.17: Minimum Recorded Voltage for Electrolyzer Plant Cases

All test cases have been evaluated in compliance with the voltage drop requirement of ±10% stated in Section 3.2, where it is clear that all the cases comply with the requirement.

As mentioned in Section 3.2 regarding the system requirements when connecting an Electrolyzer Plant to the utility grid, the power factor in the connection point has to be $\geq 0.95$. Therefore, the test cases are evaluated against these criteria by assessing the active and reactive power demand at PoC for each configuration. The result of these is shown in Table 4.6. As a result, it is clear that the power factor in the $PoC_{EP}$, according to the SLD in Figure 3.2, is all within the required limit for these base cases when considering AFE-converter for the DC-configurations. However, the power factor is affected by the inductive behavior of the transformers.

Table 4.6: Power Factor Analysis

| | **A** | **B** | **C** |
|---|---|---|---|
| **Case 1** | | | |
| Power Factor | 0.9919 | 0.9925 | 0.9926 |
| **Case 2** | | | |
| Power Factor | 0.9921 | 0.9924 | 0.9926 |
| **Case 3** | | | |
| Power Factor | 0.9980 | 0.9980 | 0.9980 |
| **Case 4** | | | |
| Power Factor | 0.9980 | 0.9980 | 0.9980 |

### 4.4.1 Sensitivity Analysis

The Electrolyzer Plant- configuration, layout, and location can vary from site to site depending on accessibility, existing installation, political and financial interest, etc. It is, therefore, relevant to assess the influence of changing sets of parameters such as distance to the connection point. Moreover, the primary substation to which the overall plant is connected utilizes tap-changers that enable altering the system voltage based on the connected loads. Therefore investigations of the effect of Tap-Changes in the Grid Voltage are to be accounted for.

#### 4.4.1.1 Voltage Drop over Distance

In order to analyze whether the AC and DC configurations exceed the specified requirements for permissible voltage deviation of ± 10% of nominal voltage, the voltage drop in relation to the distance for Case 1C and 4C is plotted in Figure 4.18. For this test, equal cable resistances are used to see the impact of the $I^2X$ losses. The busses under test, for the two cases, are illustrated in the SLD's in Figure 4.4 and 4.7, respectively.

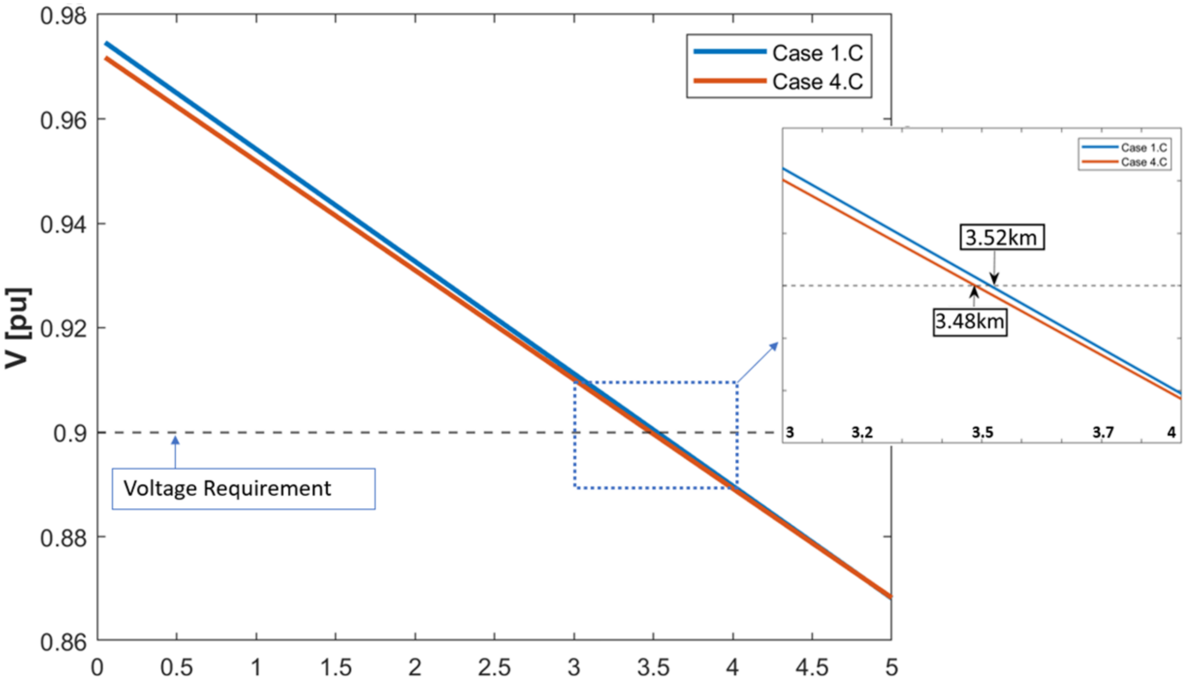


Figure 4.18: Minimum Voltage obtained for Bus 21 - Case 1C and Bus 22 - Case 4C, when distance between Substation and Electrolyzer Plant increases.

As obtained from the Figure, the distance will play a role in selecting the Electrolyzer Plant layout and location. In this test, the voltage requirements are exceeded at 3.48km for the DC configuration and 3.52km for the AC configuration.

#### 4.4.1.2 Influence of Tap-Changer Settings

The effects of the grid voltage changes in the Electrolyzer Plant are crucial to investigating and assessing the robustness of the configurations. The tap-changer consists of five steps of 2.5% change in PCC Voltage from 0.95pu to 1.05pu and the impact on the minimum voltage of Case 2C is investigated. The results are as seen in Figure 4.19 where it is evident that with a grid voltage of 0.95pu, the voltage at Bus 25 approaches the voltage requirement limit.

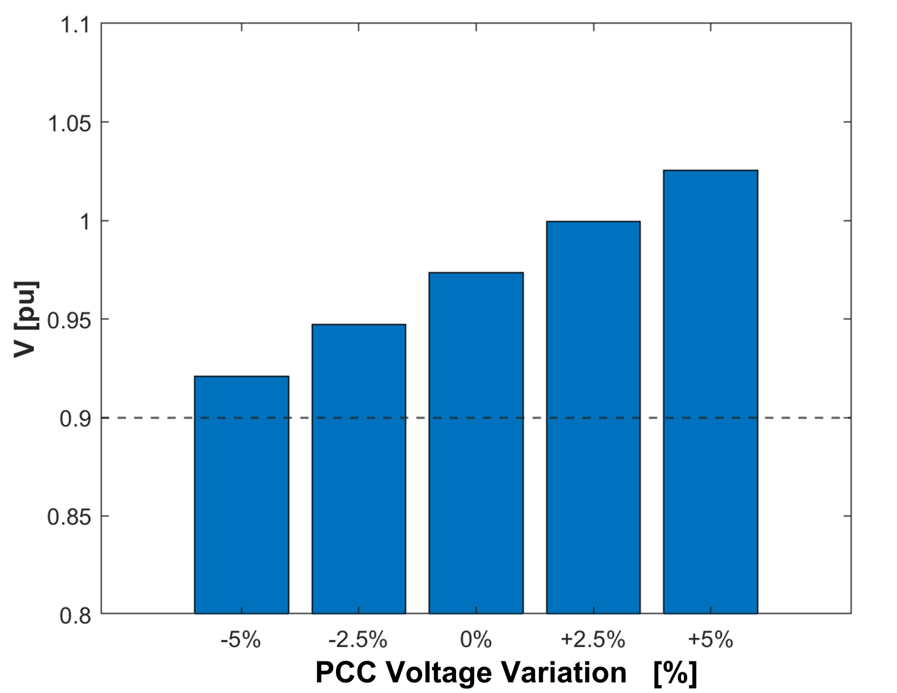


Figure 4.19: Minimum Voltage on Bus 25, Case 1C during voltage Tap-Changing in Grid

The results showed no reactive power compensation was needed to maintain the voltage within the required limits. However, more considerable fluctuation in the Grid voltage may require the installation of reactive power compensation, tab-changers, or reactive power control of Wind Turbines.

## 4.5 System Considerations of Collector System

As a result of the previous study, it is clear that in order to obtain the most optimal collector system layout, a set of evaluation criteria are to be considered. It includes physical footprint, power losses, voltage levels, etc. However, a suitable design is also greatly dependent on the specific application and requirements of the particular system. The following section captures some criteria that should be considered when designing a collector system for an Electrolyzer Plant.

1. **Consideration of Geographical Location and Physical Footprint**
   (a) Green hydrogen production may be located near populated - and urban areas or other space-restricted locations. Therefore, it is important to consider how the space can be optimally utilized, e.g., modularity, underground Hydrogen tanks, etc.
   (b) When selecting a location for the Electrolyzer Plant, analysis of the existing connection point must be investigated. It includes an investigation of existing gas pipes, accessibility for hydrogen collecting trucks, electrical connection points, the strength of the grid, etc.

(c) The voltage drop is significantly influenced by the distance from the modules to PoC. Therefore, the placement of the Electrolyzer Plant must be considered in relation to this.

2. **Consideration of System Losses**

   (a) An increase of the voltage level will lower the accumulated power loss and voltage drop regardless of voltage type. Therefore, it is highly relevant to consider suitable voltage levels for the specific application.

   (b) The accumulated power losses in the system are greatly dependent on the losses in the system converters and transformers. Therefore high, efficiency components are preferred to minimize losses.

   (c) The transformer losses are significantly more prominent in the AC cases due to the additional transformers present on each module and the additional contribution from $I^2X$-losses.

#### 4.5.0.1 Removal of Electrolyzer Plant Transformer

From the different results, it was evident that power losses reduce as the voltage increases. Therefore, it is eminent to increase the voltage of Electrolyzer collector grid to 10kV, thus making the primary role of the Plant transformer obsolete. The benefit is the accumulated power losses will decrease by approximately 50kW for all configurations. The voltage drop to the Electrolyzer modules will likewise decrease while the power factor will improve. An illustration of the proposed AC collector system layout corresponding to Case1 is given by Figure 4.20, where the transformer between Bus 4 and Bus 13 is removed.

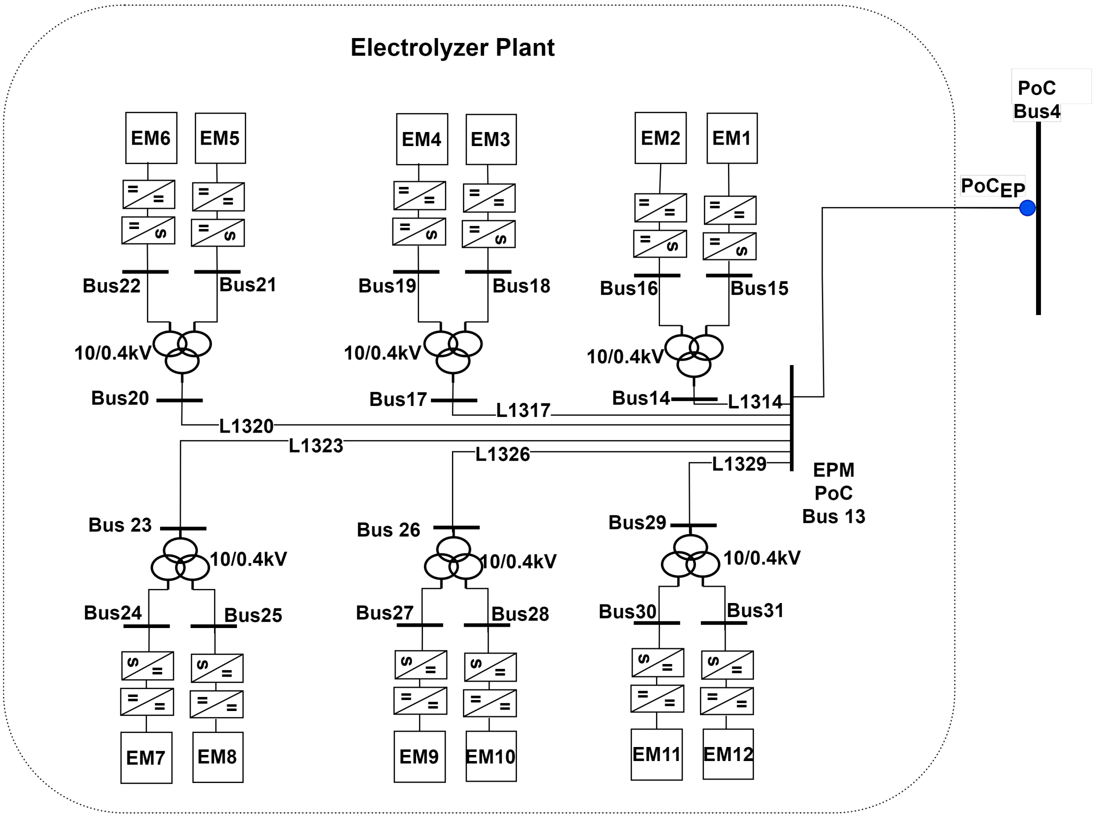


Figure 4.20: Electrolyzer Plant layout for AC-configuration 10 kV, Case 1D.

In order to assess the influence of removing the Electrolyzer Plant transformer and thereby increasing the Plant voltage to 10kV, the configuration is tested. In Figure 4.21 and 4.22 the accumulated power loss and the minimum voltage is shown. Case 1D represents the 10 kV configuration, where the transformer has been removed.

From the analysis, it is clear that as the voltage level is increased and the Plant Transformer is removed, the power losses decrease to approximately 5%. Furthermore, the minimum voltage at Bus 22 is 0.988pu compared to 0.973pu in Case 1C.

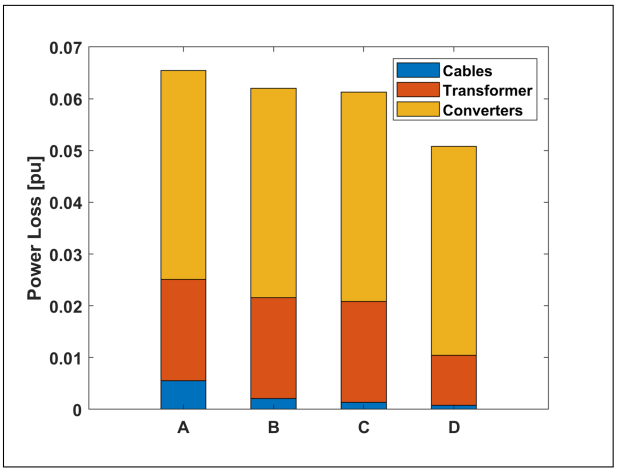


Figure 4.21: Accumulated Power Loss Case 1 A,B,C,D with a 6MW-base

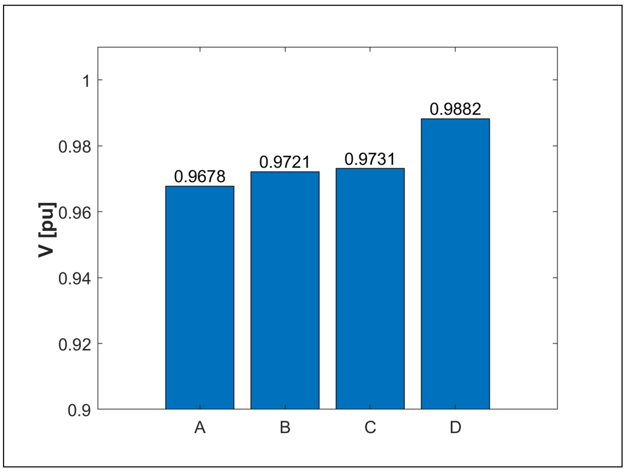


Figure 4.22: Minimum Voltage Case 1 A,B,C,D

Throughout the test, it is evident that the voltage drop and power losses can be reduced by removing Electrolyzer Plant Transformer. However, some drawbacks are associated with this.

The transformer provides galvanic isolation between the Electrolyzer Plant and the remaining system. In some countries, this is a prerequisite for grid connection [54] to maintain safety, as it provides isolation between the electrical system and thus breaks ground loops by preventing current from flowing between them. Furthermore, converters generate harmonic voltage and current, which causes additional power losses and reduce the power quality. Therefore, it is desired to mitigate this harmonic distortion. The Electrolyzer Plant Transformer will play a significant role in the reduction of harmonic distortion as the connection-type will have a cancellation effect [52].

It can be concluded that removing the Electrolyzer Plant Transformer will reduce the accumulated power losses. However, some additional system challenges will be introduced. It will require more comprehensive studies to assess whether it is a durable solution and is therefore out of scope in this project.

## 4.6 Summary

When designing an Electrolyzer Plant, multiple factors have to be taken into account to achieve the most suitable solution. An important factor is the footprint of the plant. It can play a significant role since the Hydrogen production may be located in populated- and urban areas, where space is a constraint. Furthermore, the geographical location of the Electrolyzer Plant also depends on existing/new connection points and accessibility concerning maintenance, construction, and safety.

Investigating feasible solutions for collector systems for large P2H2 installation is also an essential factor. Several cases were tested for different voltage levels, voltage types, and configurations throughout the chapter. All test-cases were investigated through verified load flow studies, where equivalent models for the collector system components were considered. The accumulated power losses, the voltage drop at the farthest Electrolyzer module, and power factor were investigated for all the base cases, when considering a full load of 6MW. The result showed as expected that the power losses and voltage drop increase with a lower voltage level. A summary of the cases can be seen in Table 4.7. The minimum voltage measured for all cases complies with the voltage requirement specified in Chapter 3.2 of ± 10%. However, the power losses for Case 1 and Case 2 exceed the Power Loss requirement of 6% or 360kW. The power factor in PoC for the Electrolyzer Plant is close to unity for all cases.

Table 4.7: Summary of Cases

| | | **A** | **B** | **C** |
|---|---|---|---|---|
| **Case 1** | | | | |
| | Power Factor in $PoC_{EP}$ | 0.9919 | 0.9925 | 0.9926 |
| | Power Loss [%] | 6.55 | 6.19 | 6.12 |
| | Minimum Voltage [pu] | 0.9678 | 0.9721 | 0.9731 |
| **Case 2** | | | | |
| | Power Factor in $PoC_{EP}$ | 0.9921 | 0.9924 | 0.9926 |
| | Power Loss [%] | 6.68 | 6.49 | 6.16 |
| | Minimum Voltage [pu] | 0.9646 | 0.9675 | 0.9719 |
| **Case 3** | | | | |
| | Power Factor in $PoC_{EP}$ | 0.9980 | 0.9980 | 0.9980 |
| | Power Loss [%] | 5.38 | 5.28 | 5.05 |
| | Minimum Voltage [pu] | 0.9665 | 0.9678 | 0.9707 |
| **Case 4** | | | | |
| | Power Factor in $PoC_{EP}$ | 0.9980 | 0.9980 | 0.9980 |
| | Power Loss [%] | 5.36 | 5.21 | 5.09 |
| | Minimum Voltage [pu] | 0.9676 | 0.9692 | 0.9699 |

The sensitivity analysis made it clear that the voltage requirement was challenged when the distance from the Electrolyzer Plant to the WPP-Substation/Connection point was increased. An increase of more than approximately 3.5km for Case 1C and Case 4C will result in the plant failing the voltage requirement. Furthermore, variance in the voltage at $PoC_{EP}$ will also challenge the fulfillment of the requirement.

As a result of the various configuration layouts, it was clear that several criteria must be considered when designing the collector system of an Electrolyzer plant. An example of the criteria is the accumulated power losses, which increase with a lower voltage. Therefore, removing the Electrolyzer Plant Transformer may be considered as it accounted for approximately 14% of the accumulated power losses. However, some challenges related to safety, electrical separation, and power quality may be affected by removing this transformer. This requires more comprehensive studies to assess whether it is a durable solution and is therefore out of scope in this project.

Through the test of the four primary cases, it can be concluded that Case 3C is the most suitable solution, evaluated based on voltage drop, accumulated power losses, and power factor in $PoC_{EP}$. Therefore, Case 3C will be utilized in the following chapters to develop the operational and control strategies of the Hybrid AC & DC Power systems.

# Chapter 5

# Operational Control Strategies

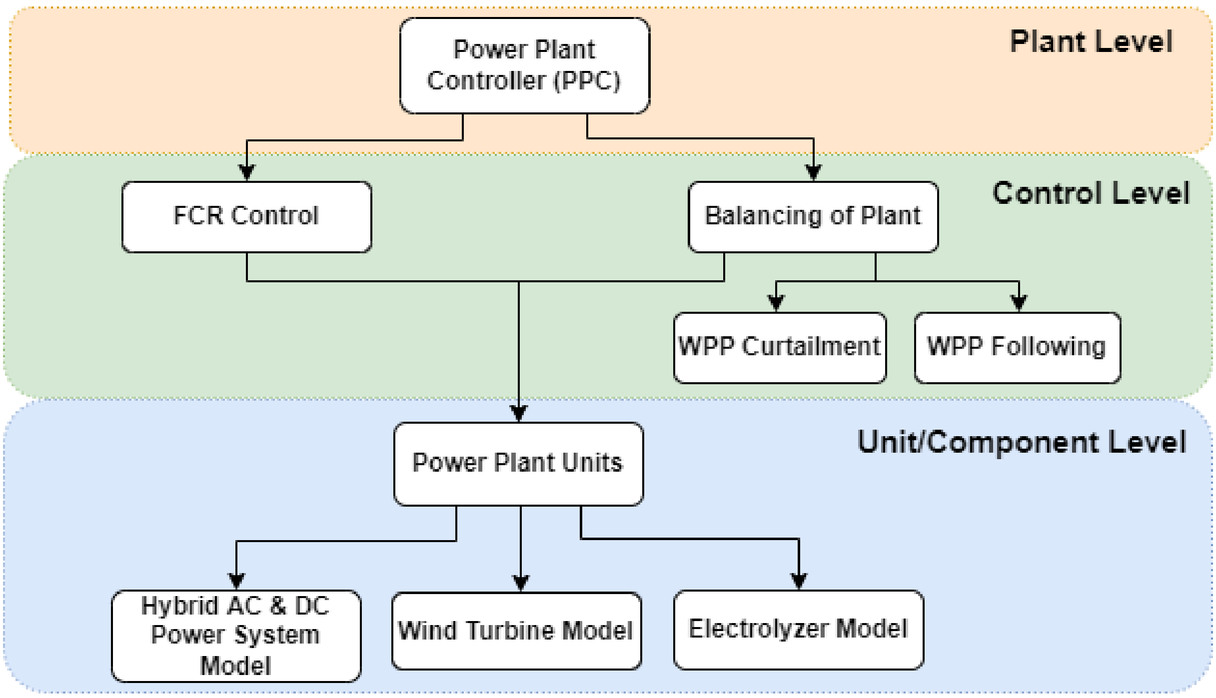


Figure 5.1: Hierarchy Diagram Structure for HPP

## 5.1 Collector System

Based on the analysis in Chapter 4, the most feasible Electrolyzer Plant layout proved to be the DC-configuration, Case 3C. As a result, it can be integrated into the overall Collector system of the P2H2 Power Plant presented in the system specification in Chapter 3. Thus the complete collector system includes the two WPAs and the proposed Electrolyzer Plant layout. The system is as shown in Figure 5.2. As mentioned in the system definition, each WPA connects four turbines in a radial configuration (WPA1 & WPA2). The role of the arrays is to transfer the produced power to either the electrical grid or the Electrolyzer Plant, depending on the mode of operation. Moreover, the connection to the utility grid occurs at PCC, where the requirements stated in Section 3.2 are to be met.

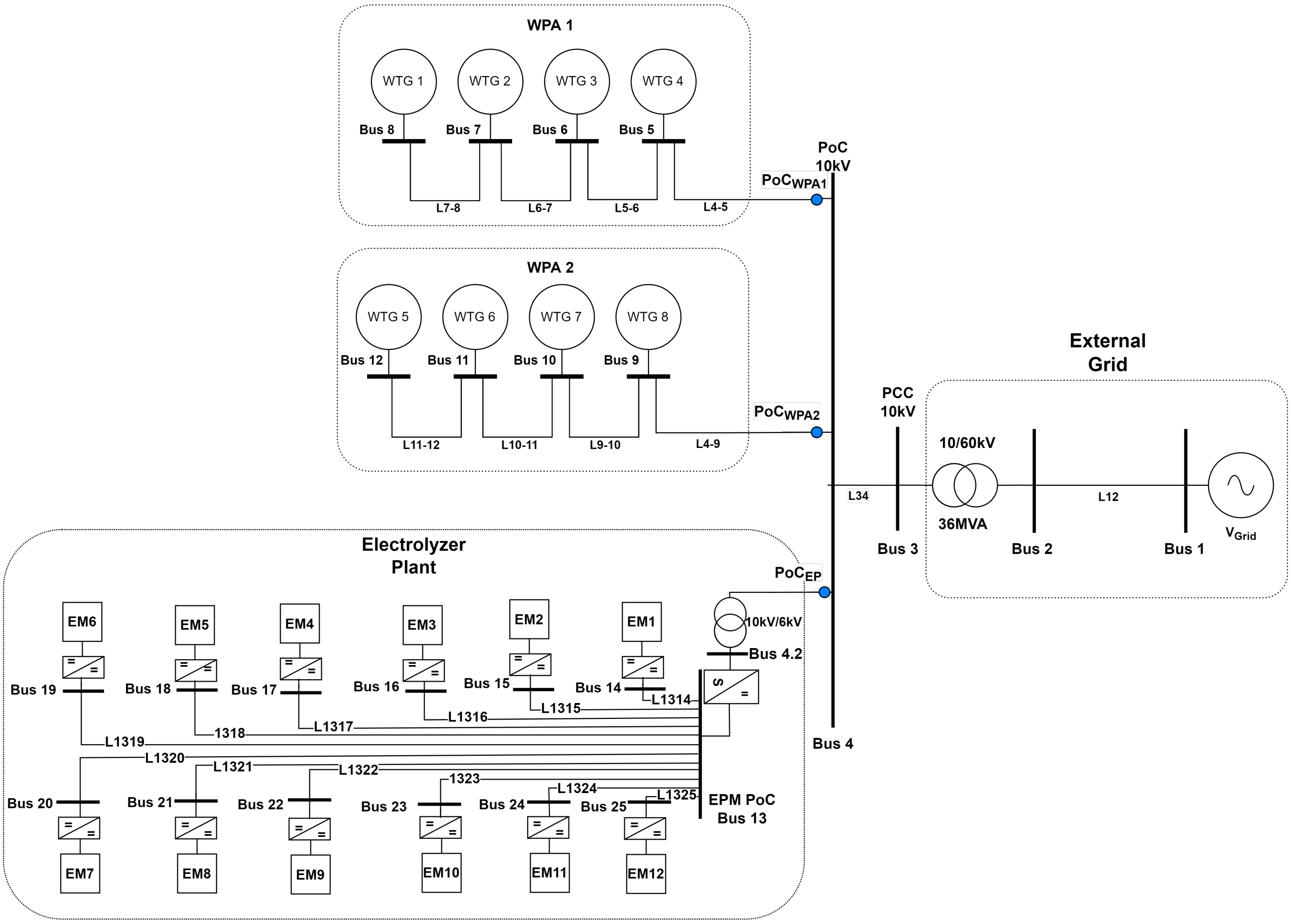


Figure 5.2: Overall Collector Grid Layout of the HPP

From the figure, it is clear that the Collector system can be divided into two main components. There is an AC system in the WPP collector system described in Chapter 3 and a DC system consisting of the Electrolyzer Plant collector grid from the previous Chapter 4. Therefore, the main challenge is the interconnection of both systems into a combined system. Thus, an additional bus, Bus 4.2, is added to cater to this interconnection of an AC and a DC system.

## 5.2 Asset Models

The following section describes the asset models in the proposed P2H2 Power Plant. It explains how the WPP, the Electrolyzer module, and the converters will be captured through representation/equivalent models and thus be utilized in the HPP model.

### 5.2.1 Wind Power Plant

As mentioned in the System Specification in Chapter 3.1 the WPP consists of eight existing Vestas V117-3.6MW turbines with a cut-in wind speed, 3m/s, and cut-out wind speed, of 25 m/s. In this system, a model of a single Wind Turbine will be developed, representing the power corresponding to the whole WPP.

A very detailed model that captures the rapid variations in wind speed, converter dynamics, and other specific components is unnecessary for use in this context because it would demand small simulation time steps. Which, as mentioned in the Limitations in Section 1.4 is out of scope.

A simplified approach is opted for where the active power output can describe the overall behavior of the turbine, $P_{WPP}$, corresponding to the power curve at a given wind speed, $W_{WPP}$ Moreover, a reactive power output, $Q_{WPP}$ corresponding to the PQ-capability chart [55]. In addition, the turbines can be controlled by adjusting the active- and reactive- power reference, $P_{WPP.Ref}$, $Q_{WPP.Ref}$, which characterize them as a PQ power source [56]. Lastly, the available WPP production, $P_{WPP.Ava}$ is also presented. The particular power curve and PQ-chart for the turbine can be found in Appendix D, and an illustration of the model can be seen in Figure 5.3 and 5.4. The WPP model is validated in a previous project, so it can be utilized without further validation [21].

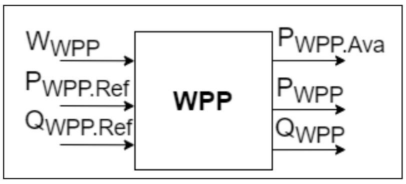


Figure 5.3: Simplified Diagram of WPP

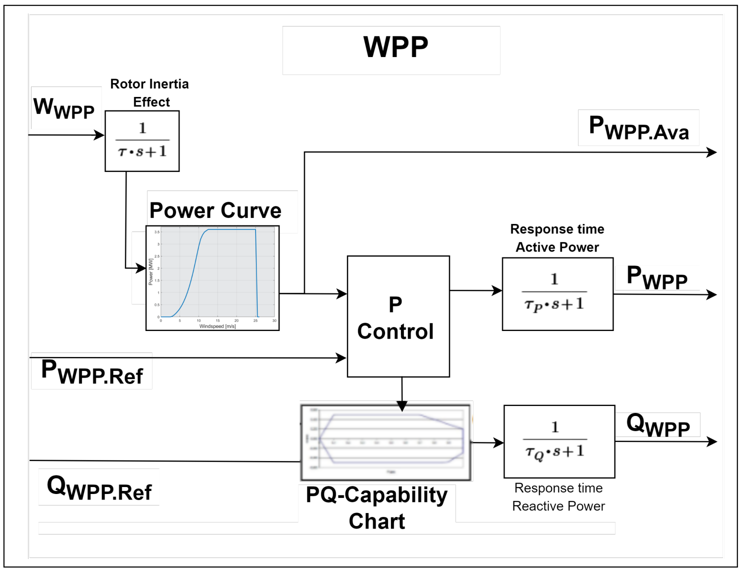


Figure 5.4: Detailed Diagram of WPP modeling

As illustrated in the Figure, a Rotor Inertia Effect block is added to smooth out the rapid wind speed variations. This term is described as a first-order filter containing a time constant which can be described as Equation 5.1 [57].

$$\tau = \tau_0 \frac{W_{rated}}{W_{measured}} \quad (5.1)$$

The natural time constant $\tau_0$ defines the time to reach the rated speed from a standstill, and $W_{rated}$ is the rated speed of the turbine. Likewise, the active and reactive power output of the Wind Turbine is not instantaneous, so a first-order filter containing time constants for both the active and reactive power response times is added. Typical values for these are $\tau_P = 1s$ and $\tau_Q = 100ms$ [58].

### 5.2.2 Electrolyzer Modules

The PEM Electrolyzer consists of multiple connected series and parallel to reach specific power levels. The operational principle of a PEM-based electrolytic hydrogen production and its corresponding electrical equivalent model for a single cell can be seen in Figure 5.5.

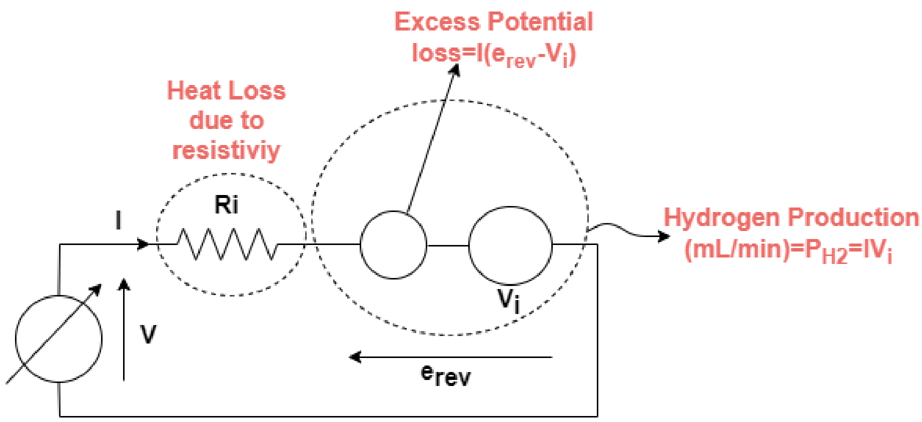


Figure 5.5: Single cell Equivalent Electrical Model for a PEM-Electrolyzer

The PEM-Electrolyzer cells introduced some Heat Loss due to resistivity and Excess Potential losses obtained from the equivalent model. The efficiency of the PEM-Electrolyzer can, therefore, typically reach up to 82-83% [59] however, optimization of this technology is still being studied. Therefore, future PEM configurations are expected to reach higher efficiency.

Based on the equivalent model, the I-V characteristic of the PEM Electrolyzer cell can be obtained. The characteristic is slightly non-linear. However, when the current reaches 0.02A, it can be described as a linear function. Therefore, the steady-state operation can be simplified to define the I-V characteristic of the PEM-Electrolyzer cell as a function of pressure and temperature.

$$V(T,P) = IR_i(T,P) + e_{rev}(T,P) \quad (5.2)$$

.

Where the reversible potential voltage $e_{rev}$ in equation 5.2 is the minimum required voltage to drive the chemical reaction. The I-V characteristic of the model is illustrated in Appendix E.

The PEM-Electrolyzer system has been modelled mathematically in order to capture the electro-chemical reactions accurately. It consist of a current transformation block, a PEM-equivalent circuit and a hydrogen storage tank. The block diagram can be seen in Figure 5.6

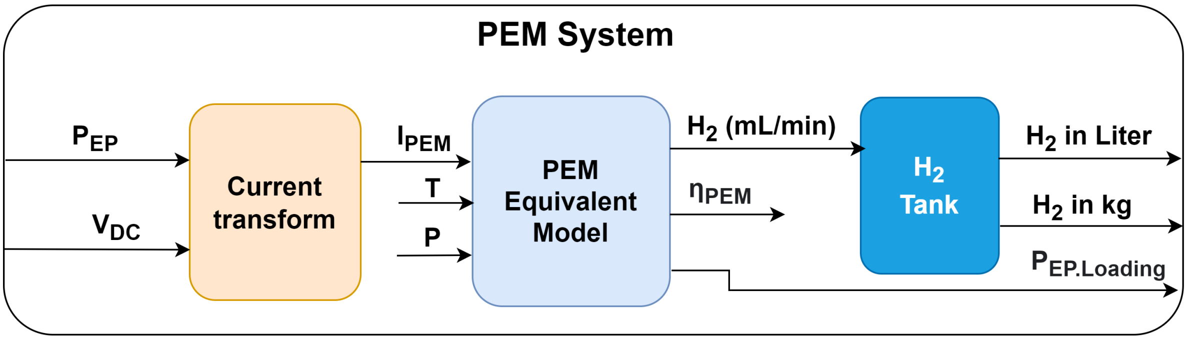


Figure 5.6: Block Diagram for the PEM Electrolyzer System

As obtained from the Figure, the current injection to the Electrolyzer is initially determined, which depends on the voltage input from the DC/DC converter $V_{DC}$ and the active power reference $P_{EP}$ from the Power Plant Controller (PPC). Then, based on current injection, temperature, and pressure, the efficiency and the green hydrogen flow rate can be calculated using the electrochemical equations covered in Appendix E. Lastly, the $H_2$-flow rate can be integrated to determine the total volume and mass of the hydrogen, which is stored in the Hydrogen storage Tank.

Like the other models, the mathematical model has been built in the MATLAB/Simulink environment, where it has been verified according to comparable published work. Moreover, the theoretical models show similar efficiency and production characteristics as in the published IEEE reference papers [59], and [60]. It can therefore be considered reliable.

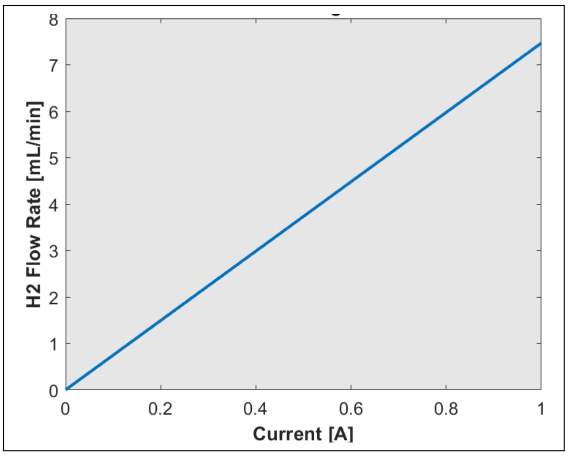


Figure 5.7: Flow-rate characteristic of a single cell PEM-Electrolyzer at an operating temperature of $20^oC$ and a pressure of 1 atm. - Simulation results

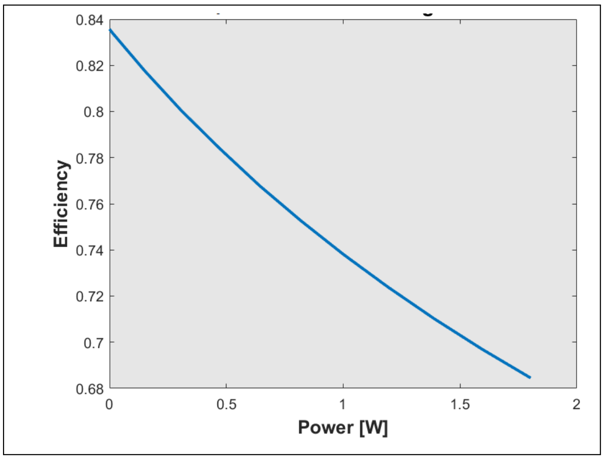


Figure 5.8: Efficiency characteristic of a single cell PEM-Electrolyzer at an operating temperature of $20^oC$ and a pressure of 1 atm. - Simulation results

### 5.2.3 Converter Characteristics

The converters in the Electrolyzer collector system have to be adequately represented to capture their non-linear efficiency. State-of-Art converters have significantly increased efficiency by optimizing control strategies, components, and materials. However, some losses are unavoidable. The converter efficiency will vary relative to the load profile and is typically non-linear during low-loading, and linear during high-loading profiles [61].

In order to account for the non-linearity, the converters will be presented as look-up tables based on their efficiency curve. An illustration of the DC/DC converter model can be seen in Figure 5.9 and a similar method for the AC/DC converter will be applied in the development of the model.

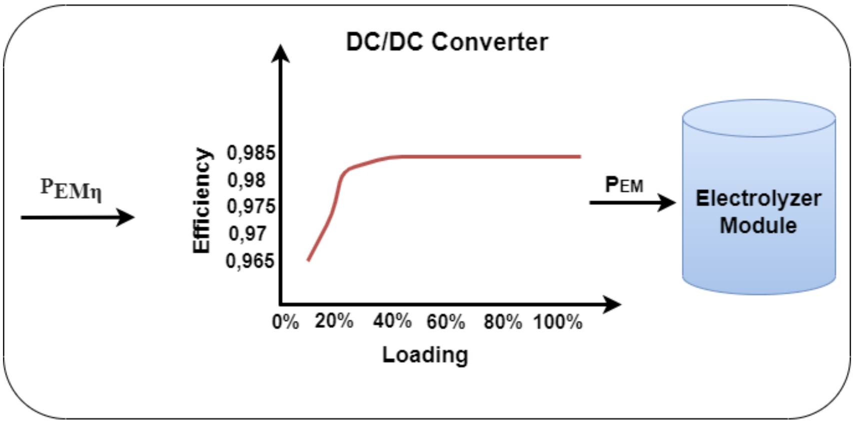


Figure 5.9: Representation of Converter Module

## 5.3 Design of Power System Model and Control

This section describes the Hybrid Power System Model and the operational control schemes, including the BoP and the FCR strategies corresponding to the Scenarios described in Section 3.3. In order to understand the interface between the system components and the underlying control strategies, a high-level control scheme for the plant has been made. It illustrates the main signal interfaces between the sub-systems and their corresponding feedback and can be seen in Figure 5.10.

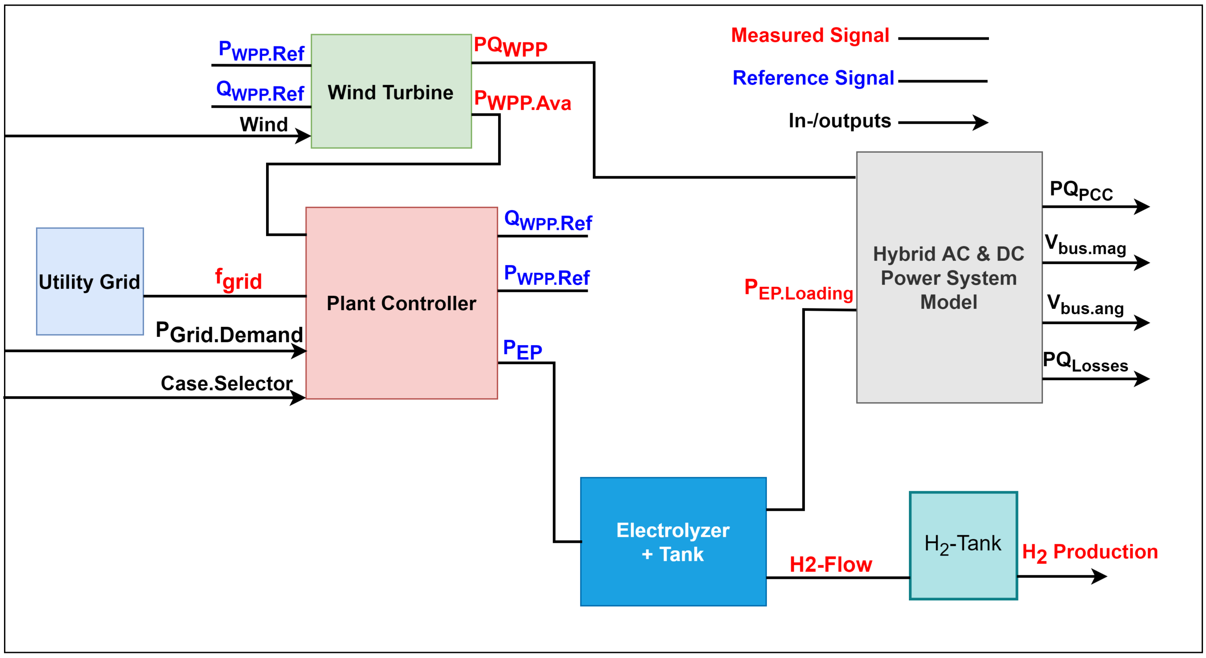


Figure 5.10: High-Level Control Scheme and Signal Interfaces between the sub-systems

### 5.3.1 Hybrid AC & DC Power System Model

In order to assess the capabilities of the entire P2H2 Plant, a Hybrid Power System Model is developed. The role of the model is to continuously calculate the AC- and DC power flow of the Plant in every time step.

The model operates based on designated active and reactive power inputs from the WPP model, $P_{WPP}$ and $Q_{WPP}$, and through the specified loading of the Electrolyzers, $P_{EP.Loading}$. In Figure 5.11, the proposed design for the Hybrid Power System Model is shown.

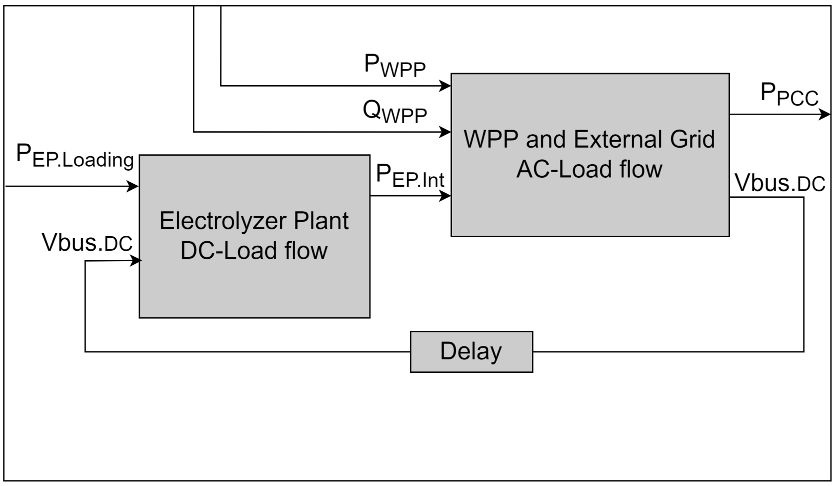


Figure 5.11: Hybrid AC & DC Power System Model for WPP with Electrolyzer Plant

The AC-load flow initializes the Hybrid Power System Model, and thus the voltage at the interfacing bus (Bus 4.2 Figure 5.2 is computed, $V_{bus.DC}$. This voltage is fed back to the DC-load flow through a unit delay to avoid an algebraic loop. Hereafter the DC-load flow can be executed, and the model will run continuously regardless of changes in the production and loading.

### 5.3.2 Operational Strategies for Hybrid Power Plant

As mentioned in the Scenarios in Section 3.3, the demand for energy balancing of the plant increases as Electrolyzer modules are introduced. The overall system goes from being a producing WPP to a Hybrid Plant with self-consumption that must be controlled. The system must operate based on different production priorities and contribute to system stability by providing FCR-ancillary services.

#### 5.3.2.1 WPP Following

In this mode of operation, the loading of the Electrolyzer Plant and thus green hydrogen production is prioritized over injection to the utility grid.

The operational principles and procedures can be explained through the flow-chart in Figure 5.12. Initially, the WPP Following operation has been selected. The control loop is entered hereafter, and the wind power production from the WPP model is measured.

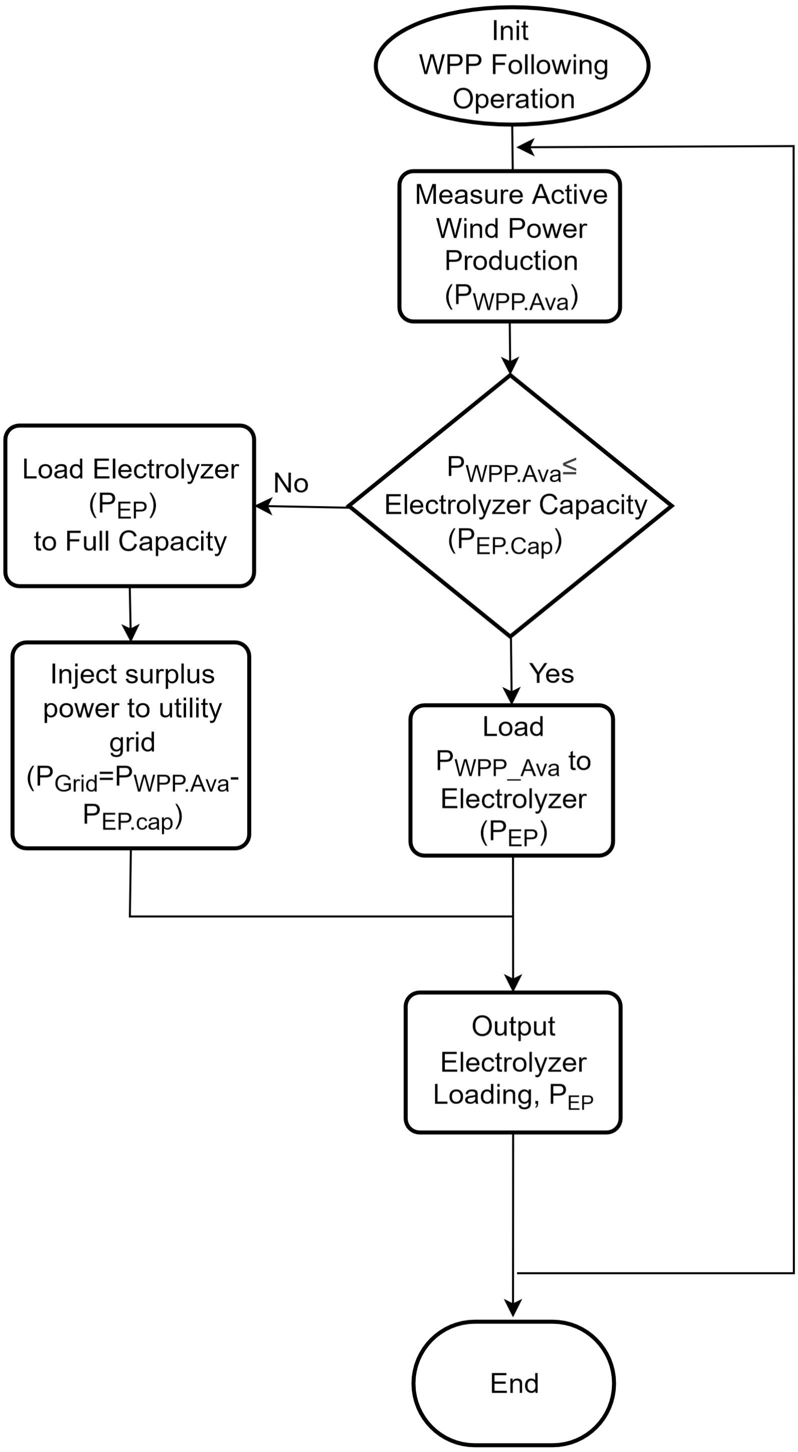


Figure 5.12: Operational Strategy for WPP Following

The algorithm has two operational branches decided by the WPP production. In the case where the available power production, $P_{WPP.Ava}$ is below the Electrolyzer capacity, $P_{EP.cap}$, the entirety of the production is loaded into the Electrolyzer Plant, corresponding to the Electrolyzer reference, $P_{EP}$, and thus no injection to the utility grid occurs. The other branch is executed when the production exceeds the Electrolyzer capacity. Thus, the Electrolyzers are loaded to their full capacity, and the surplus power production is injected into the utility grid, $P_{Grid}$. Lastly, the procedure is looped back in order to account for the changes in input wind speed and thus the available power production from the turbines.

#### 5.3.2.2 WPP Curtailment

In this case of operation, the loading of the Electrolyzer Plant and thus green hydrogen production is prioritized under injection to the utility grid. Furthermore, when a power command is provided by the TSO/DSO, the HPP must regulate the power injection in the PCC according to it. As described by the requirements in Section 3.2 the algorithm must start curtailment no later than 2 seconds after a command is demanded and must complete within 15 seconds. The operational principle to obtain the desired functionality can be explained through the flow-chart in Figure 5.12. The case-selector initializes the control loop and is thus prepared for continuous operation before measuring the available wind power production.

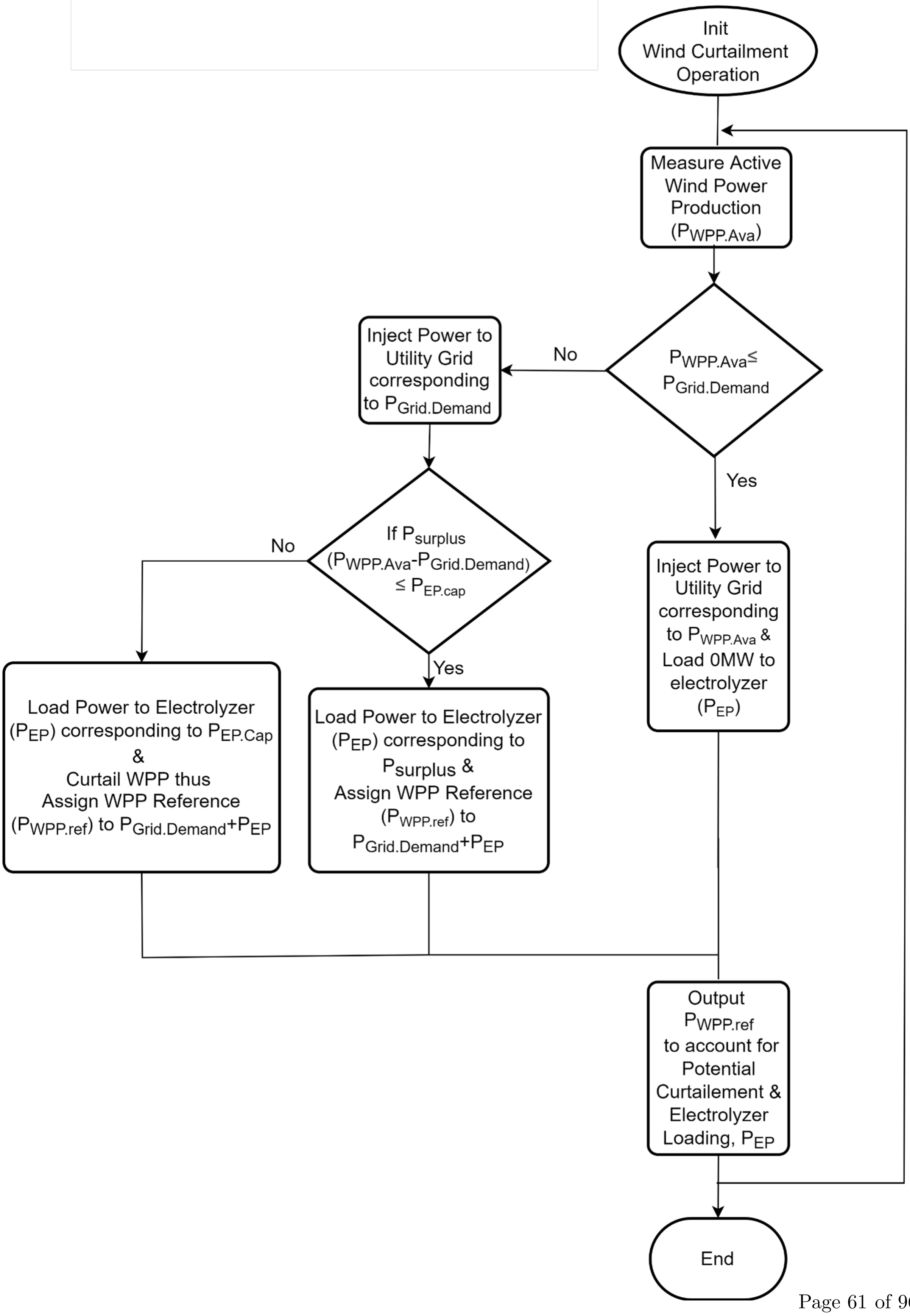




Figure 5.13: Operational Strategy for WPP Curtailment

The decision-making is initialized by comparing the command from the TSO/DSO, $P_{Grid.Demand}$ and the available products from the WPP, $P_{WPP.Ava}$. If it is below the command limit, the entirety of power is injected into the utility grid. Otherwise, the Electrolyzer Plant off-takes the surplus production up to its capacity limit. Moreover, in this case, a new reference is provided to the Wind Turbines, $P_{WPP.Ref}$, which specifies the power to be produced and ensures the grid injection does not exceed the command.

Ultimately, suppose the available production exceeds the capacity of the Electrolyzers, $P_{EP.cap}$. Initially, the Electrolyzer is fully loaded, and a new power reference for the turbines is calculated. The reference must correspond to the specified grid demand and the Electrolyzer capacity. Thus the remaining power must be curtailed by the Wind Turbines. Ultimately, the control scheme is looped-back to account for changes in the input wind speed and thus power production from the turbines.

#### 5.3.2.3 FCR Control Strategy

The role of this scenario is to introduce ancillary service capabilities. It enables detecting frequency changes in the utility grid and using the Electrolyzer Plant as a demand response. The operational principle is that a detected imbalance will lead to a change in the Electrolyzer loading to either increase or decrease the self-consumption in the system.

In Chapter 2 and 3, it was stated that the FCR operation is determined based on a bidding process where the bid size has to be at least 1 MW and a symmetrical product. As a result of an accepted bid, the frequency must be regulated according to the droop characteristic shown in Figure 5.14. The deadband and the minimum and maximum frequencies encapsulating the FCR domain are indicated by the dotted purple and blue lines. Moreover, the vertical axis represents the percentage loading increase or decrease of the Electrolyzer Plant according to the symmetrical bid size (e.g., $\pm 1MW$).

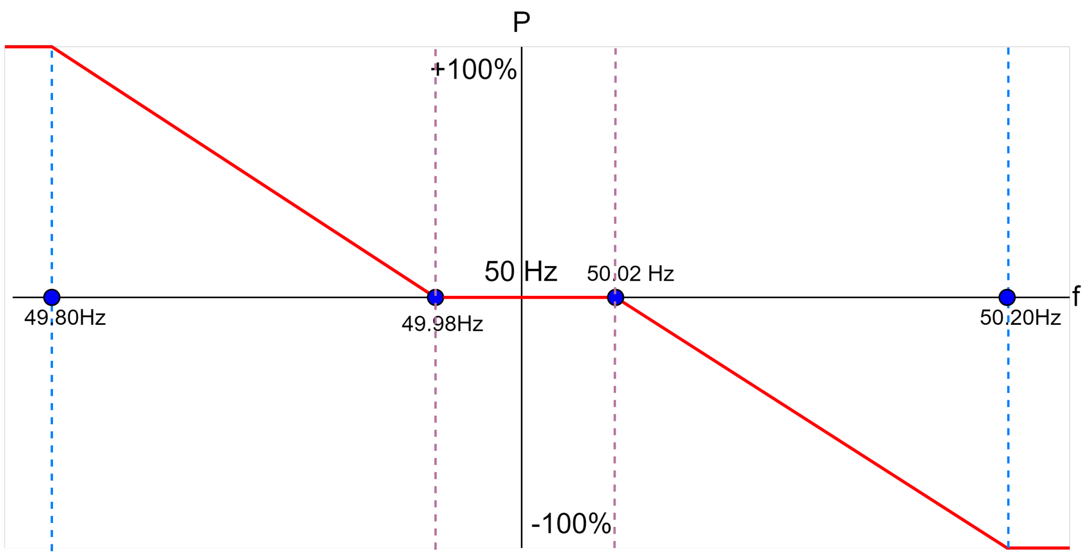


Figure 5.14: Droop Characteristic of FCR [42]

As mentioned in Requirements in Section 3.2 the decision-making must start 2 seconds after the frequency change is detected, and it must remain active for at least 15 minutes. The operational principles of the FCR control strategy are shown in Figure 5.15.

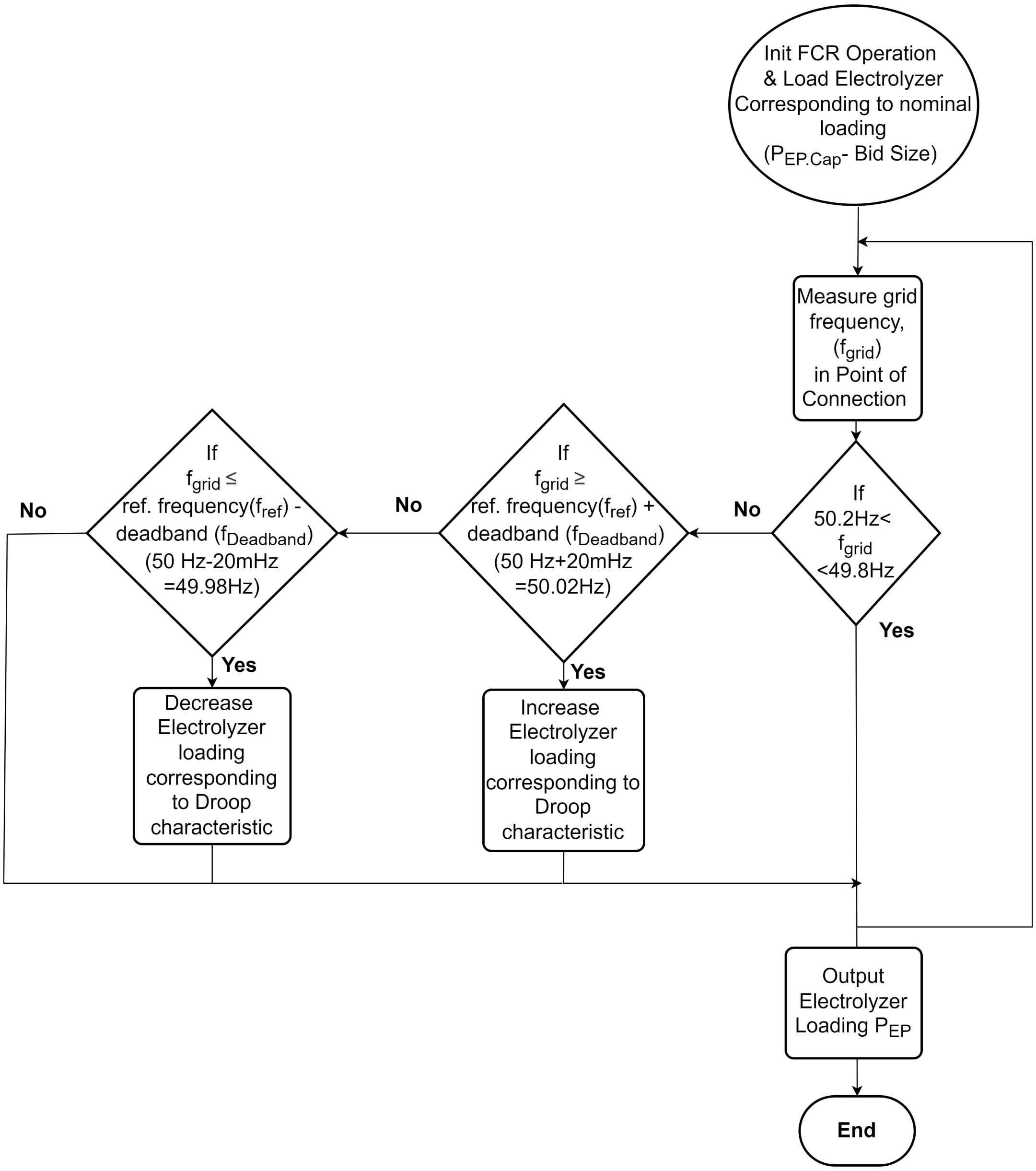


Figure 5.15: Flowchart of FCR Control Strategy

The operational scenario is initialized based on the accepted symmetrical bid size, and the corresponding nominal loading of the Electrolyzer is determined. The control system continuously monitors the grid frequency and observes whether it goes beyond the frequency deadband, $f_{Deadband}$ of $\pm 20mHz$. The Electrolyzer loading increases or decreases, corresponding to the droop characteristic when the measured grid frequency deviation is larger than the deadband limits.

## 5.4 Summary

Within this chapter, the operational control strategies were designed and specified. Initially, the Collector System in scope consisting of the WPP and the proposed Electrolyzer Plant layout was presented.

The applicable assets of the HPP were designed as representation models, including the WPP, Electrolyzer modules, and Converters. Furthermore a representative model of the Hybrid AC & DC Power System was developed to determine the electrical quantities and power flow in all nodes and cables within the Plant. It was evident that the AC load flow of the WPP is initialized to determine the voltage in PoC in order to run the dynamic model continuously.

Ultimately, the operational strategies for the HPP were developed to reflect the Scenarios proposed in the System Specification. It includes the WPP Following, WPP Curtailment, and FCR operation. All the control methods are presented in flowcharts to indicate the different operational branches and the associated selectors.

The functionality and logic must be verified based on the HPP models and Operational Strategies. The HPP performance in realistic scenarios must be tested, which is obtained in the following chapter.

# Chapter 6

# Results and Tests

## 6.1 Verification of Logic and Functionality

As a result of the developed operational strategies from Chapter 5, it is necessary to ensure that the control algorithms match the design. Therefore, the logic and functionality have to be verified to ensure the capabilities. It is obtained by establishing distinctive test scenarios that consist of single input testing. This means that the rest of the changeable parameters are kept constant to maintain decision-making control.

### 6.1.1 Hybrid AC & DC Power System Model

Reliability of the Hybrid Power System Model is essential, as it determines the electrical quantities and power flow in the system. Therefore, the designed and implemented dynamic model has to be verified according to the results of the Electrolyzer Plant layout design in Chapter 4. The dynamic model has been tested under a full load condition of the Electrolyzer (6MW). Thereby the power consumed in the PoC for the Electrolyzer Plant has been determined. The test result is shown in Figure 6.1.

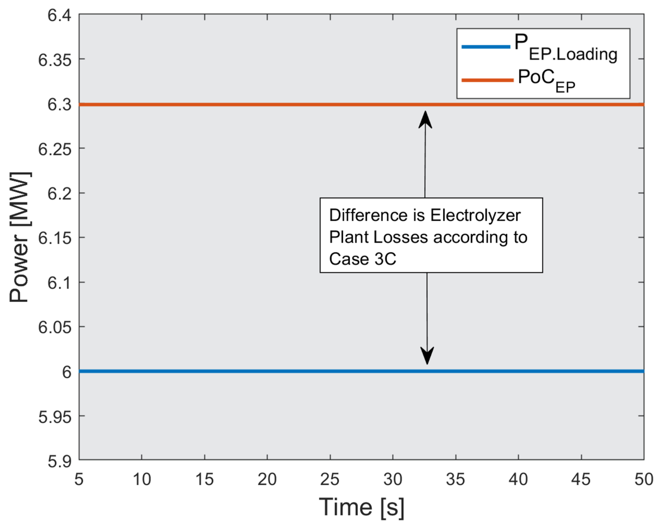


Figure 6.1: Verification of Hybrid AC & DC Power System Model

As obtained from the Figure, the Electrolyzer Plant consumes 6.3MW in the PoC, which gives a total loss of 300kW for the entire Electrolyzer Plant under full load conditions. This match the results obtained for Case 3C in Chapter 4, where an accumulated power loss of 303kW was determined with equivalent impedance approximation. The Hybrid Power System Model can therefore be considered reliable.

### 6.1.2 Balance of Plant Cases

In this section, verification of the operational strategies related to the BoP is conducted. It will ensure that the control algorithms operate satisfactorily according to the flowcharts and prove them reliable for testing of further realistic scenarios.

#### 6.1.2.1 WPP Following

The WPP Following operational strategy is utilized during low electricity prices in the spot market. Its operation is characterized by prioritizing loading to the Electrolyzer rather than injection to the utility grid. Therefore, it has two operational branches. One where the available production from the WPP is above the capacity of the Electrolyzer plant and one where it is below its capacity. The operations are verified by utilizing a step-change in the wind speed, which directly alters WPP production, thus testing both branches. The test is conducted with a change in wind speed from 10 m/s to 5.5 m/s after 25s. The test-result is shown in Figure 6.3 and 6.2.

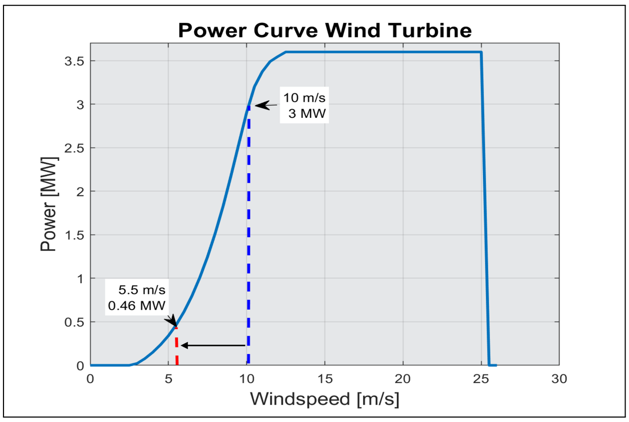


Figure 6.2: Tested Windspeeds on the Turbine Power Curve, Blue:10m/s & Red: 5ms/s

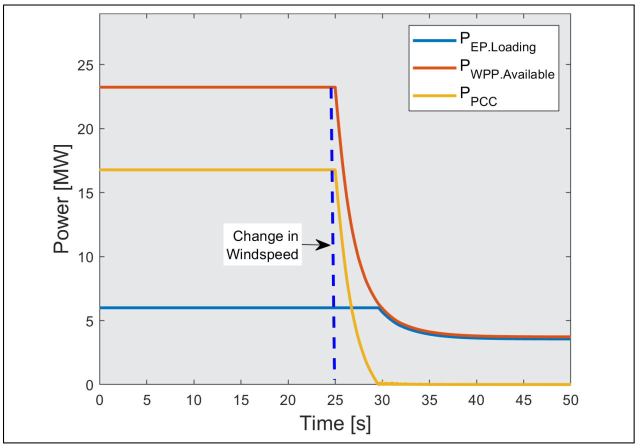


Figure 6.3: Verification of functionalities and logic for Balance of Plant Case: WPP Following

The Figure indicates that the Electrolyzer is fully loaded during high WPP production, and the remaining power is injected into the utility grid. Furthermore, when the wind speed drops and the WPP production is below the Electrolyzer capacity, the Electrolyzer is prioritized, and no injection occurs. The WPP following algorithm can thus be specified as functioning and reliable.

#### 6.1.2.2 Wind Power Curtailment

The HPP has to be able to operate according to the grid demand. Therefore, the grid is prioritized over the green hydrogen production in this scenario. In order to test the logic and functionalities of the design and implemented control scheme, the grid demand is changed stepwise. After 30 seconds, the grid demand decreases from 14 MW to 7 MW, and after 60 seconds, it further decreases to 3 MW, while the wind speed is kept constant at 8 m/s. The results can be seen in Figure 6.4.

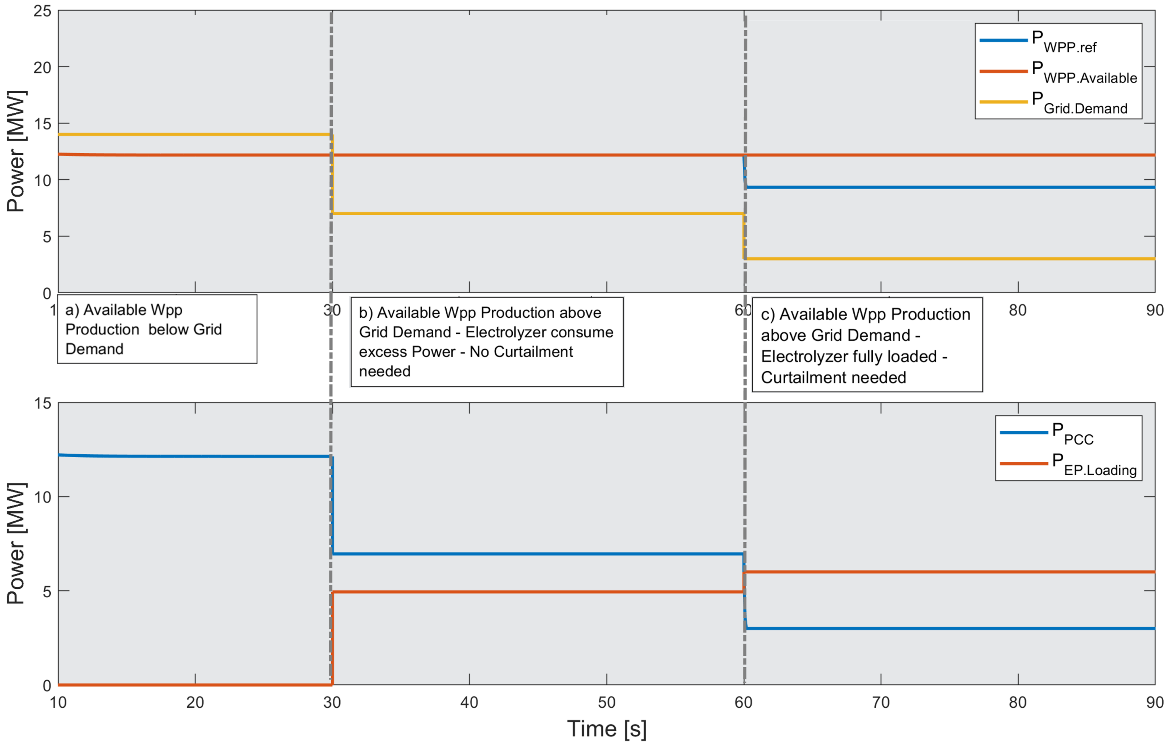


Figure 6.4: Verification of functionalities and logic of Wind Curtailment Operation

The Figure is separated into three sub-cases from ***a to c***, which present the flowchart decisions. Initially, in sub-case ***(a)***, the available production is below the demanded power in PCC. Therefore, all produced power from WPP is injected into the grid. Then, as the grid demand is lowered in sub-case ***(b)***, the available power is greater than the demand. Therefore, the Electrolyzer Plant consumes the surplus power, and no curtailment is needed. Finally, in sub-case ***(c)***, the power difference between grid demand and available power is greater than the Electrolyzer Plant capacity. Therefore, this power is curtailed by WPP to fulfill the grid demand in PCC. Throughout the test, it can be concluded that the functionalities and logic of the Wind Curtailment Operation work as expected during the different sub-cases.

#### 6.1.2.3 FCR Operation

As stated in the Scenario in Section 3.3 the HPP must provide FCR-services when frequency deviates from the reference. In this sub-section, a verification test of the functionality and operational strategy is conducted. The test aims to go through the various decision-makers in the flowchart in Figure 5.15 from Chapter 5. It is conducted by altering the grid frequency, $f_{grid}$ stepwise. After each step, the frequency is brought back to the reference frequency of 50Hz. The produced power from the WPP is kept constant at 12 MW, and symmetrical bid of 1MW is utilized, leading to a nominal Electrolyzer loading of 5MW. The results of the test can be seen in Figure 6.5.

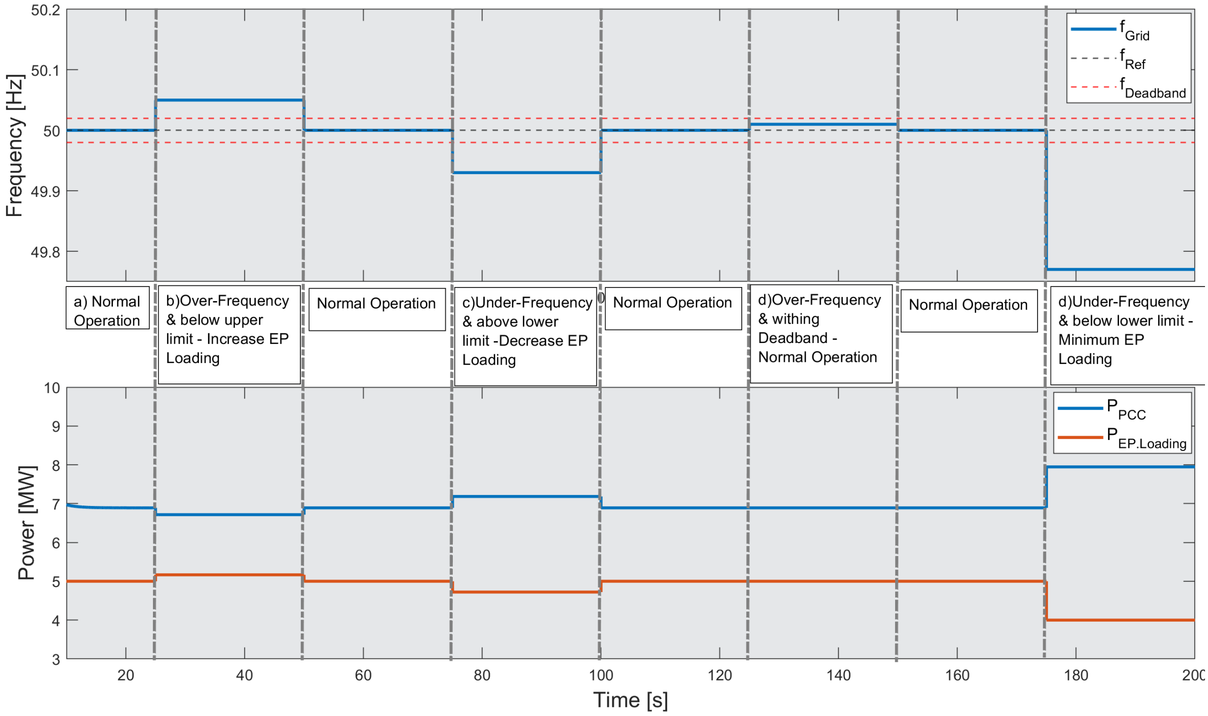


Figure 6.5: Verification of functionalities and logic of FCR Operation

The Figure is divided into a set of sub-cases from ***a*** to ***e*** that specify each of the flowchart decisions. Initially, the system is in normal operation (***a***), which means that the frequency is 50Hz, and the Electrolyzer Plant is loaded with 5MW. After 25s an Over-frequency above the deadband limits and below upper limit, occurs (***b***). This results in the loading of Electrolyzer increases according to the droop-characteristic, thus lowering the power injected in PCC. After 75s an Under-frequency below deadband limits and above lower limit, occurs 8***c***9. In opposition to Over-frequency, the loading of Electrolyzer decreases in accordance to the droop-characteristic, thus increasing the power injected in PCC. After 125s an Over-frequency occurs (***d***). As the frequency is within the deadband limits, the Electrolyzer loading and power injection in the PCC follow the normal operation. Finally, in sub-case (***e***), a large under-frequency occurs after 175s. As the frequency subceeds the lower limit of the droop-characteristic, the Electrolyzer is reduced to minimum loading according to the bid size, which is reflected by the power injected in the PCC. As a result of the test of the different sub-cases, it can be concluded that the functionalities and logic of the FCR Operation functions as desired.

## 6.2 Test of Scenarios

This section evaluates the performance and behavior of the HPP during various realistic test scenarios. The scenarios are based on possible park operations to which the operators may be exposed, including varying electricity prices, seasonal wind changes, operational priorities, power demands, and ancillary services.

### 6.2.1 Seasonal Impact on Green Hydrogen Production

The role of this scenario is to obtain an assessment of the balancing capabilities of the HPP, where the production of green hydrogen is prioritized over power injection to the utility grid. The scenario builds upon a case where there is a greater financial incentive to produce green hydrogen rather than inject power into the grid when the electricity-prices are low (non-negative). This means the power production of WPP is injected into the Electrolyzer, and the surplus power into the utility grid to obtain the highest daily revenue for the HPP.

In order to test a realistic scenario, wind data from the Danish Meteorologic Institute (DMI) for the specific area has been collected for a Summer and Winter case with an average wind speed of 6.6 m/s and 8.6 m/s, respectively. During the test, the power in PCC, Electrolyzer loading, and Hydrogen flow rate were studied throughout a day, to see the behavior of the HPP. The results of the test can be seen in Figure 6.6

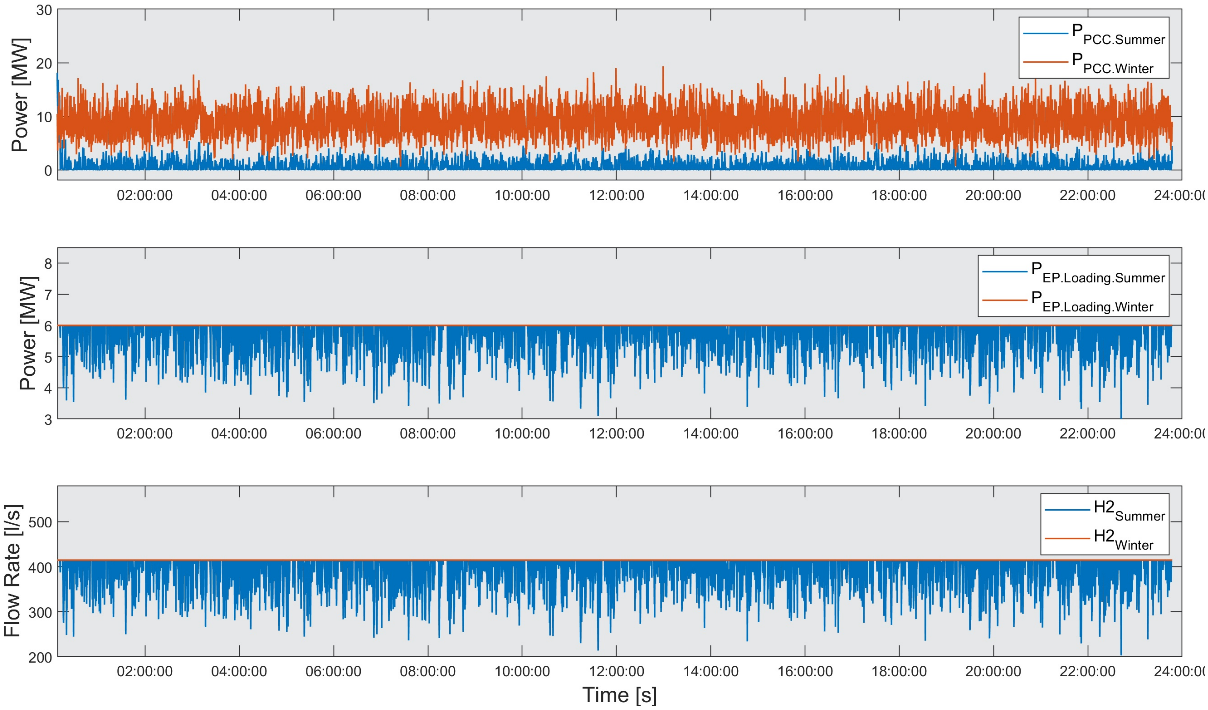


Figure 6.6: The operation of HPP for Summer and Winter scenario, when Electrolyzer is prioritized higher than power injection to utility grid.

The high daily power production during a Winter month causes the HPP to continuously full load the Electrolyzer with 6MW as well as inject a large amount of power to the grid in the PCC. However, in opposition to the Winter case, the summer production is significantly lower. This means that even though the Electrolyzer is prioritized over the grid injection, the production of the WPP is not sufficient to load the Electrolyzer fully. This can be seen in the fluctuating Electrolyzer-loading and Hydrogen flow rate.

Even though the green hydrogen production fluctuates, the accumulated daily H2-mass stored in the Tank is not significantly different for the Summer and Winter scenarios. The total production of the Electrolyzer at Standard Temperature and Pressure (STP) can be seen in Table 6.1

Table 6.1: Accumulated daily H2-Production for test-scenario

| | **Summer-Scenario** | **Winter-Scenario** |
|---|---|---|
| Daily H2-Production at STP [kg] | 3051 | 3125 |

### 6.2.2 Park Operation during Negative Spot Prices in the Electricity Market

The role of this scenario is to obtain an assessment of the operational strategies of the HPP on high wind days, where a combination of low and negative electricity prices is in the spot market. This means that the highest revenue is obtained by prioritizing green hydrogen production combined with momentarily curtailing the WPP production.

The scenario is based upon a high wind day in 2020, April 13th, where the electricity spot prices were negative for the majority of the day [62], and the average windspeed was 10.6m/s [63]. Both the wind profile and the electricity spot prices are shown in Figure 6.7.

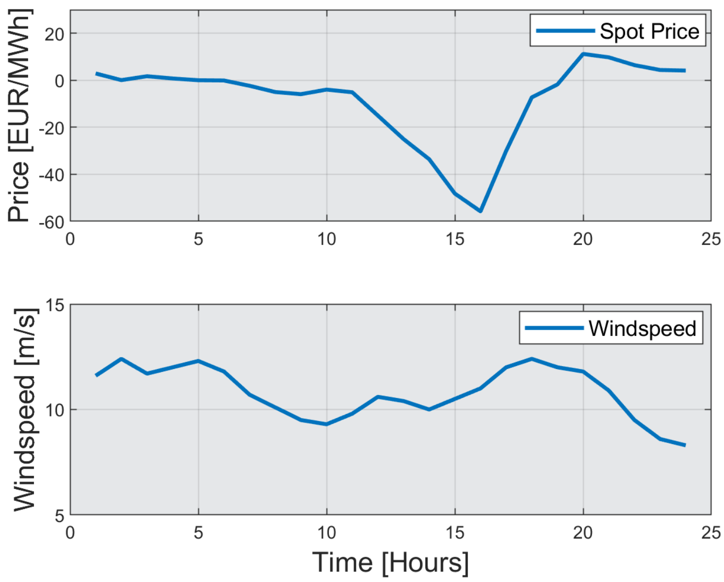


Figure 6.7: Spot Prices and Windspeed on April 13, 2020

When the spot prices are low but non-negative, there is a greater incentive to prioritize production of green hydrogen production first and inject surplus power into the utility grid. However, as the spot prices are negative, there is no incentive to inject power into the utility grid. Therefore, the power in the WPP is curtailed to match the full load capacity of the Electrolyzer. The results of the scenario are shown in Figure 6.8.

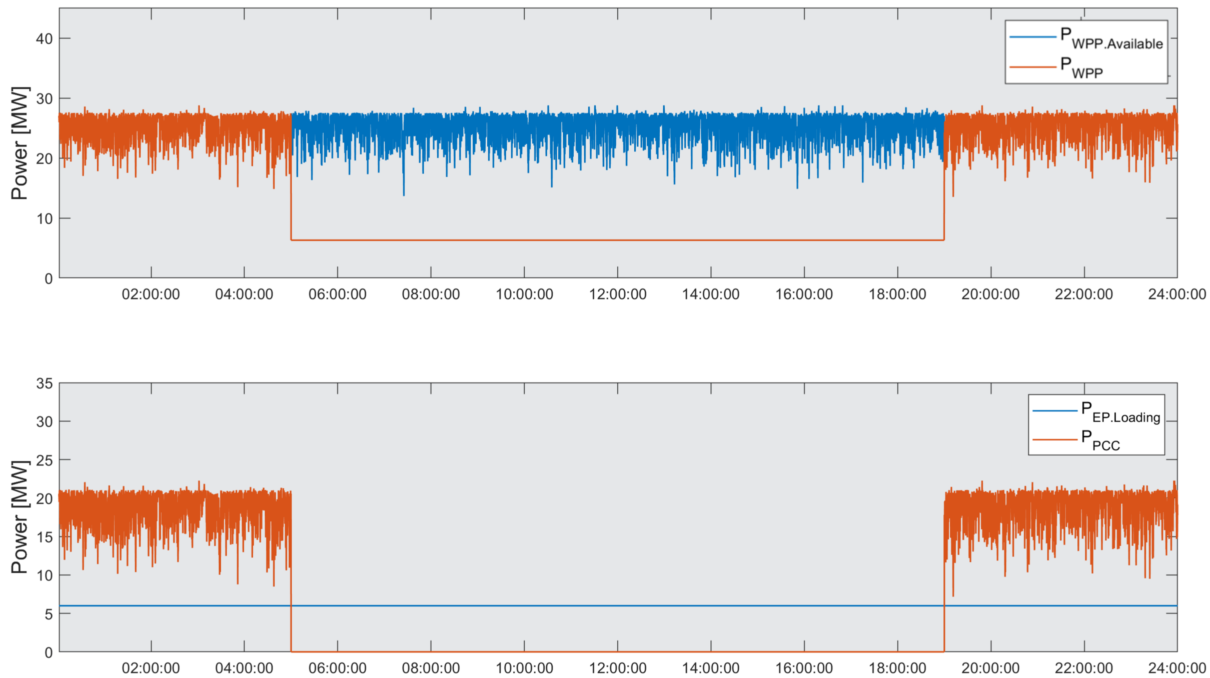


Figure 6.8: The Operation of HPP was on April 13th, 2020, when there were Negative Electricity Prices during the Day.

The Figure shows, the available WPP production, $P_{WPP.Available}$, and the actual production, $P_{WPP}$. As seen in the plot, the available WPP production, $P_{WPP.Available}$, and the actual production, $P_{WPP}$, shows the expected results since the WPP is curtailed to avoid injection to the grid, $P_{PCC}$, during negative electricity spot prices.

Thereby, the Park Operation ensures that the Electrolyzer Plant is prioritized and fully loaded for the day, leading to a green hydrogen production of 3125 kg stored in the Hydrogen Tank.

### 6.2.3 Curtailment of Power Transfer to Utility Grid due to TSO/DSO Commmands

This scenario analyzes the operation of the HPP during a very high wind day, where the power injection to the utility grid is prioritized. However, as mentioned in the Scenarios in Section 3.3, there are occurrences at which the German TSO, TenneT, encounters overproduction. As a result, it can be more feasible to pay Danish turbine owners to curtail or shut down their production rather than curtail German production. Therefore, during the daily operation of the HPP, commands from the Danish TSO/DSO to curtail the production of the power may be received.

Therefore, to obtain a realistic scenario, wind data is taken from DMI for a day in 2020, where the average wind speed was 14.6 m/s leading to a forecasted production from the WPP of 28.8MW for the entire day. However, as the German electricity consumption decreases during the night, a Danish TSO/DSO command is given to limit the injection to the utility grid. Therefore, the operational strategy of the HPP aims to produce green hydrogen instead of curtailing the WPP during these commands. The conducted test is shown in Figure 6.9.

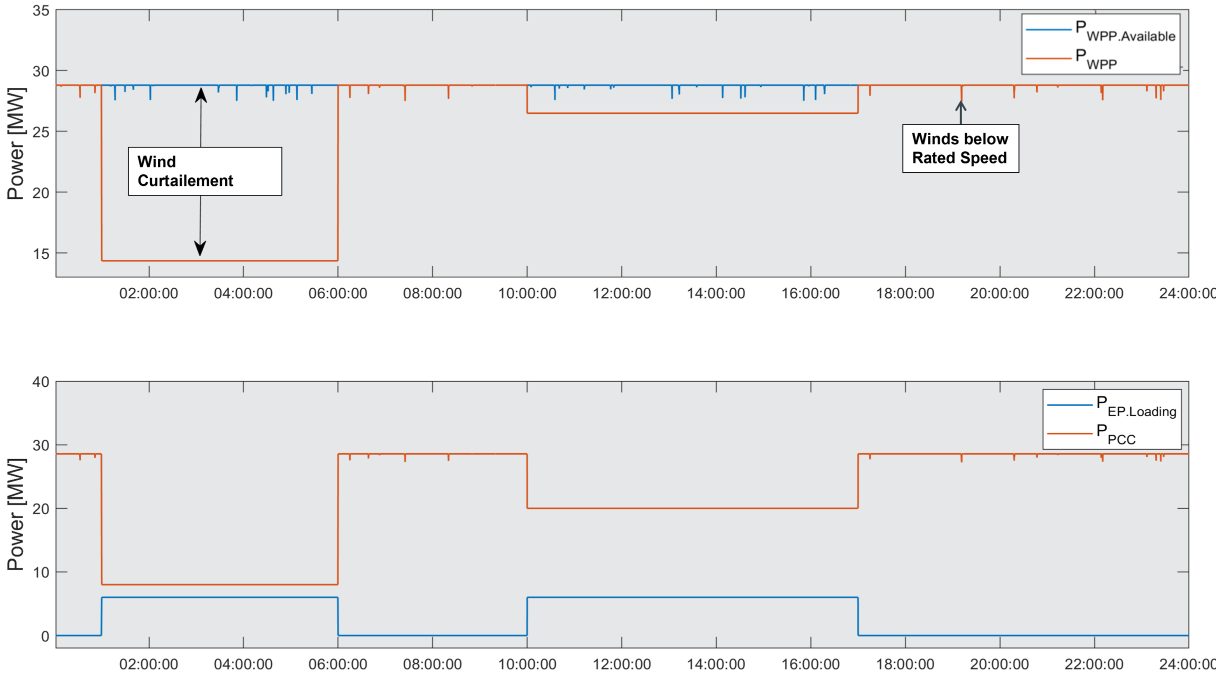


Figure 6.9: Operation of HPP during a day, where power curtailment is commanded.

As seen in the plot, the entire WPP production is initially injected into the utility grid. At 01:00-06:00 in the night, a command to down-regulate the power injection to the utility grid to 9MW is received. During this command, the Electrolyzer is therefore loaded to its capacity to reduce the WPP curtailment. As the command to down-regulate expires at 06:00, the power injection to the grid is ramped to the available production. Similarly, from 10:00-17:00, a new command to down-regulate production to 20MW is received. The Electrolyzer is once again loaded to its capacity to reduce curtailment of the WPP until the command expires.

It can be concluded that the operation ensures that power commands from the TSO/DSO will cause a reevaluation of the system balance and ultimately lower the WPP curtailment. In comparison, in a traditional WPP, the production has to be curtailed alone by turbines to comply with power command. Therefore, implementing an Electrolyzer Plant in the energy mix allows green hydrogen to be produced (1576kg), which provides additional revenue from the park.

### 6.2.4 Participation in the FCR Market

This section intends to investigate the operational strategies when the HPP involves in the FCR-market. As mentioned in the Scenarios in Section 3.3 the Electrolyzer Plant contributes to demand response as an ancillary service provision to the grid. When bidding for FCR-market, it is crucial to ensure that the WPP production is sufficient to cover the droop of the corresponding Electrolyzer loading. Therefore, participation in FCR-market is more feasible during windy days. After an FCR bid has been accepted, the loading of the Electrolyzer Plant is fixed at a new set point corresponding to the bid size.

As mentioned in the Requirements in Section 3.2 it is stated that the lowest bid size in the FCR market is a 1MW symmetrical product which leads to a base loading of 5MW. This scenario is given by Figure 6.10 which shows the behavior of the HPP as frequency deviations in the grid are measured over a 1 hour period.

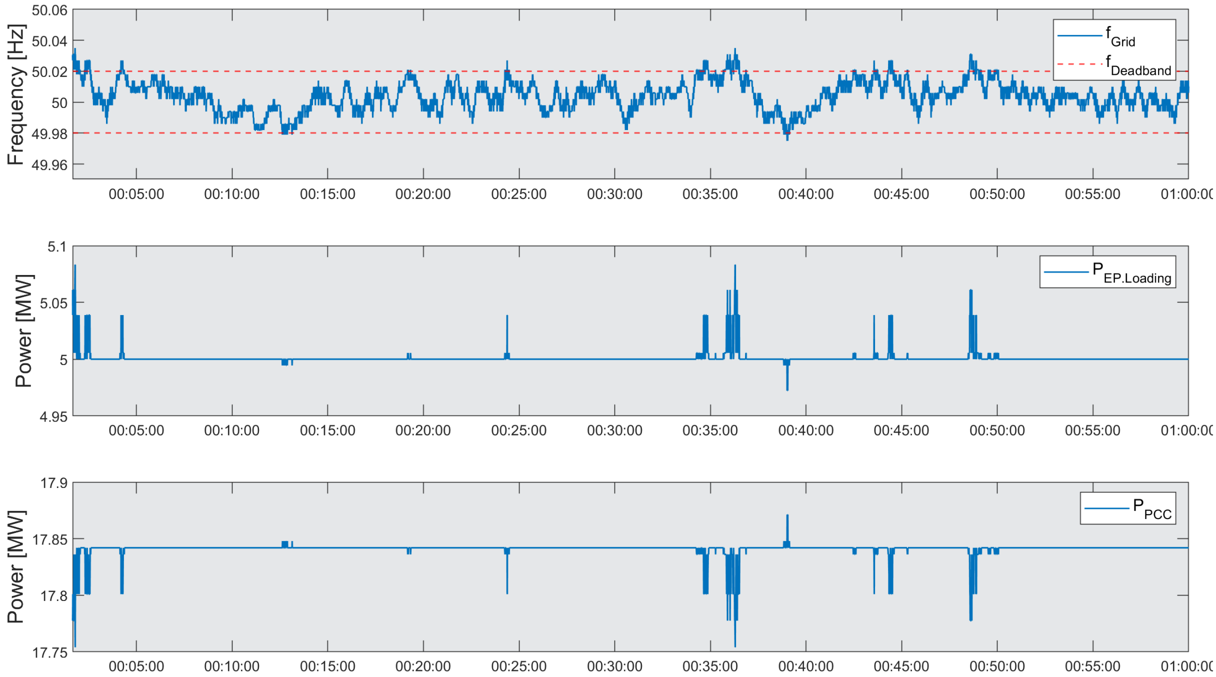


Figure 6.10: Operation of FCR strategy with the Lowest symmetrical bidsize of 1 MW

As expected, when an over-frequency is measured, the loading of the Electrolyzer Plant is increasing and the power injection to the utility grid is decreased under the specified FCR droop. Therefore, due to the 1 MW FCR symmetrical bid size, the produced green hydrogen amounts to be 109.5kg for that particular hour.

The HPP can provide FCR services up to ±50% of the Electrolyzer capacity, which amounts to a bid size of 3MW. This mode of operation is likewise investigated and shown in Figure 6.11. The measured frequency deviations are identical to the previous case.

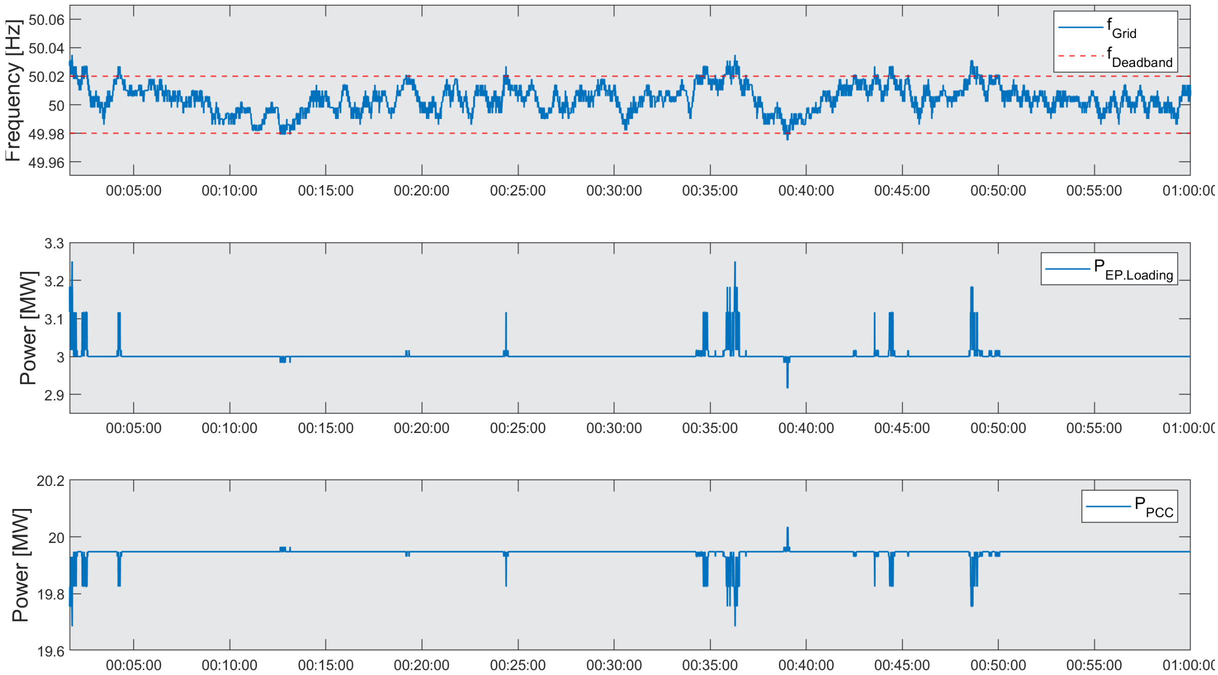


Figure 6.11: Operation of FCR strategy with the Lowest symmetrical bidsize of 3 MW

During this operation, the variation in loading of the Electrolyzer is significantly higher as a result of the larger bid size. However, the green hydrogen produced (65.9 kg) is significantly less than for the 1MW FCR operation due to the lower base loading of the Electrolyzer Plant.

Therefore, the most profitable operation in the FCR-market is decided based on the market prices of the three revenue streams, green hydrogen, electricity, and FCR. It means that if the price for FCR operation is significantly higher than the green hydrogen production, a larger bid is preferable.

## 6.3 Summary

In this Chapter, the verification of logic and functionalities of the developed control schemes has been tested and discussed. It is achieved by comparing the flow-chart decisions for the plant controller with the specific tests, as well as comparing previous loss calculations for the Hybrid Power System Model. Each of the verification tests showed successful results and can therefore be considered reliable.

Furthermore, the complete model implemented in MATLAB/Simulink was tested based on possible park operations and scenarios to which the Operators may be exposed. It includes varying electricity prices, seasonal wind changes, operation priorities, power demands, and/or ancillary services. The active power in the HPP was studied based on different operational strategies and conditions from the test scenarios. This led to various green hydrogen production and power injections to the utility grid and, thus, the foundation for various revenue streams. Therefore, when the wind conditions, prices for green hydrogen and electricity, and grid services fluctuate daily, the operation and control of the HPP have to be selected based on the most favorable revenue stream that particular day.

# Chapter 7

# Conclusion and Future Work

## 7.1 Conclusion

The political interest in P2X is growing significantly, as this technology is predicted to play an essential role in decarbonizing multiple Energy Consumption Sectors. Therefore, this project aims to study a combined Wind- and Electrolyzer Plant connected to a distribution grid. The study evaluates two main topics: The investigation of feasible collector system layouts for large P2H2 installation and the development of operational control strategies for the HPP, including BoP, Wind Curtailment, and FCR, respectively.

In order to find a feasible design for the Electrolyzer Plant, four plant typologies were tested for different voltage levels, voltage types, and configurations. The test cases were investigated through verified load flow algorithms, where equivalent models for the collector system components were considered. Each case was evaluated based on accumulated power losses, voltage drop, and the power factor in PoC, during a full load condition. The results showed that the converters and transformers accounted for the main part of the losses. In addition, the distance to the Electrolyzer Plant was relatively short, and thus no significant losses in the cables were encountered. Furthermore, due to the relatively short distance, the most significant voltage drop was app. 3.5%, and the power factor for all cases was close to unity. Therefore no power-factor correction was needed in PoC. Since all test cases were evaluated compared to the specified requirements, it could be concluded that the DC-configuration with a system voltage of 6kV - Case 3C showed the best performance and, thus, the most feasible collector system layout.

Based on the selected layout of the Electrolyzer Plant, a representative model of the Hybrid AC & DC Power System was developed to determine the electrical quantities and power flow in all nodes and cables within the Plant. In this way, the HPP could be monitored when the production and consumption of the WPP and Electrolyzers change. Furthermore, as the power flow changes due to frequent wind fluctuations and Power-Demands from TSO/DSO, operational control strategies were needed to ensure power balance within the Plant.

The operational control strategy for balancing the HPP was divided into two sub-strategies; WPP Following and Wind Power Curtailment. Each sub-strategies were designed as a flow-chart to decide how the power should flow within the Plant. However, the two sub-strategies differ, as for the WPP Following-strategy, the green hydrogen production was prioritized over the power injection to the utility grid, and in the Wind Power Curtailment-strategy, the prioritization was the opposite. The logic and functionalities of both sub-strategies were tested in a complete model implementation in MATLAB/Simulink, which showed successful results. Furthermore, the control strategies for BoP were tested in different realistic scenarios according to varying electricity prices, seasonal wind changes, operation priorities, and power demands. Similarly, a control strategy for FCR-services was designed and tested for functionalities and in a realistic scenario, where the Electrolyzer regulated the frequency based on a droop-characteristic.

Finally, it can be concluded that the system requirements are fulfilled for the proposed system, and the accomplished work can be summarized and evaluated based on the following two remarks.

1. To obtain a feasible Electrolyzer Plant layout, a set of evaluation criteria must be considered, including physical footprint, power losses, voltage levels, existing installations, etc. However, for this particular research, a 6kV DC-configuration with a separate Electrolyzer module division was the most feasible solution.
2. The implementation of PEM-Electrolyzer in existing/new WPP and associated operational control strategies enables green hydrogen to be produced instead of curtailing the WPP when TSO/DSO commands for down-regulation of production. Furthermore, it enables the HPP to be operated with respect to prioritizing different production sources depending on spot market prices and participation in the FCR-market.

## 7.2 Future Work

This project aimed to investigate and design an Electrolyzer Plant layout and develop operational scenarios using the HPP. However, some measures have to be considered in further development and investigation. Therefore this section will explain the areas of future work and hence the proposed direction of the investigations.

### Implementation in Real-Time Simulator Tool

The design of the proposed system is based on an equivalent model and is developed in MATLAB/Simulink environment. Therefore, it is highly relevant to test the operation control strategies in a real-time simulation tool with a digital twin representation of the system assets. In this way, a similar test can be conducted to verify the results obtained in this project when considering realistic conditions such as communication technologies and data collection infrastructure.

### Individual Asset Models

The WPP and Electrolyzer were developed as aggregated models in this project. This means that the production and loading of the individual turbines and modules were assumed to be balanced and equally distributed. Therefore, it is recommended to study the influence of variations in the production and loading when an equal distribution is not considered. However, as these studies are conducted, it may be necessary to design additional dispatch structures to assign roles between the individual assets. An example may be during the curtailment operation where instead of all the turbines down-regulating, a single or few turbines are responsible for the regulation. Likewise, for the Electrolyzer, individual modules may be responsible for the regulation under an FCR operational scenario.

### Voltage Control

Currently, the HPP only contains active power control capability. Moreover, the investigations of the system were solely performed with the connection to a stiff grid, which is why the demand for voltage control is not considerable. However, there may be applications where the HPP is connected to weaker grids, so the voltage fluctuations may be substantial and require Voltage Control capability. The Plant Controller can be further developed to obtain voltage control due to the capabilities of the Wind Turbines.

### Spot Price Operation

The HPP can operate according to several control strategies depending on the desired functionality. Further development would be selecting an operational strategy based on the economically most adequate operation. In order to have this ability, the system should incorporate a price forecasting scheme utilizing both the electrical spot prices, the price for ancillary service, and ultimately the green hydrogen price and base the operation on this. However, as mentioned in Chapter 2 a Hydrogen Spot Market is expected to be decades away, so the main driving factor in the price forecast operation will be the electrical spot prices and the FCR bidding processes.

### Large Voltage and Frequency Excursions

As mentioned in the Requirements in Section 3.2 the Electrolyzer Plant is designed to operate normally within the voltage range of $\pm$ 10% of the nominal voltage and in the frequency range of 49Hz to 51Hz. However, the operation outside of these limits is currently not investigated. Therefore, it is recommended to study the effects of large voltage and frequency excursions on the overall system.

### Collector System Layout Consideration

The Electrolyzer Plant Layout was determined based on an analysis of the physical footprint and power loss considerations. However, the cost is an essential factor to consider when selecting the layout. There may be a significant economic difference between the different configurations and topologies. From an economic point of view, the most feasible configuration is a trade-off between power losses, establishing- and operational costs, etc. Therefore, it is recommended that for future studies, this aspect is included to nuance the considerations.

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# Chapter 8

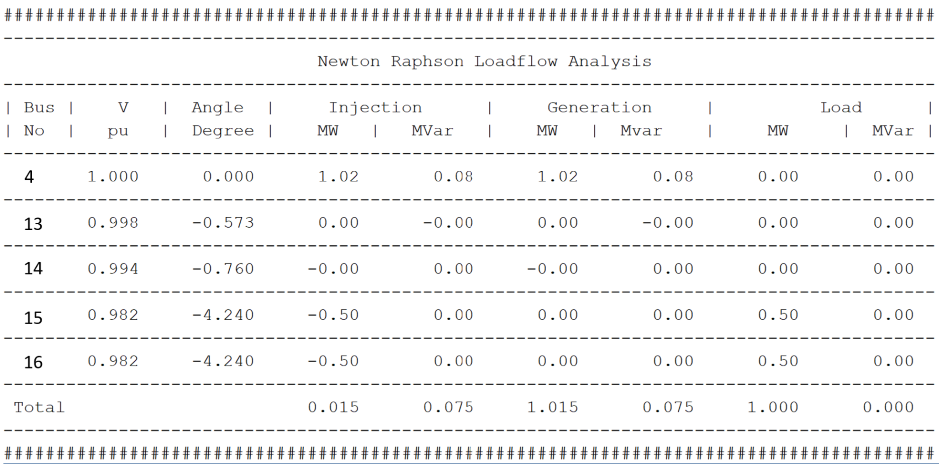
# Appendices

## 8.1 Appendix A

This appendix contains the verification of the Newton Raphson Load Flow Algorithm(NRLFA). It is a comparative analysis that evaluates deviations between the MATLAB model and the power system analysis tool, DIgSILENT PowerFactory.

| **Bus No** | **Load Flow (MATLAB-model)** | | **Load Flow (PF-model)** | | **Deviation** | |
|---|---|---|---|---|---|---|
| | **Vmag [pu]** | **Angle(deg)** | **Vmag [pu]** | **Angle(deg)** | **Vmag [%]** | **Angle(deg)** |
| 4 | 1.000 | 0.000 | 1.0000 | 0.0000 | 0.00 | 0.0000 |
| 13 | 0.998 | -0.573 | 0.9980 | -0.5727 | 0.00 | 0.0003 |
| 14 | 0.994 | -0.760 | 0.9937 | -0.7597 | 0.03 | 0.0003 |
| 15 | 0.982 | -4.240 | 0.9823 | -4.2400 | 0.03 | 0.0000 |
| 16 | 0.982 | -4.240 | 0.9823 | -4.2400 | 0.03 | 0.0000 |

Table 8.1: Verification of NR-LFM - Based on simplified Case 1 system


Newton Raphson Loadflow Analysis

| Bus No | V pu | Angle Degree | Injection MW | Injection MVar | Generation MW | Generation Mvar | Load MW | Load MVar |
|---|---|---|---|---|---|---|---|---|
| 4 | 1.000 | 0.000 | 1.02 | 0.08 | 1.02 | 0.08 | 0.00 | 0.00 |
| 13 | 0.998 | -0.573 | 0.00 | -0.00 | 0.00 | -0.00 | 0.00 | 0.00 |
| 14 | 0.994 | -0.760 | -0.00 | 0.00 | -0.00 | 0.00 | 0.00 | 0.00 |
| 15 | 0.982 | -4.240 | -0.50 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 |
| 16 | 0.982 | -4.240 | -0.50 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 |
| Total | | | 0.015 | 0.075 | 1.015 | 0.075 | 1.000 | 0.000 |

Figure 8.1: AC Load Flow Verification from MATLAB

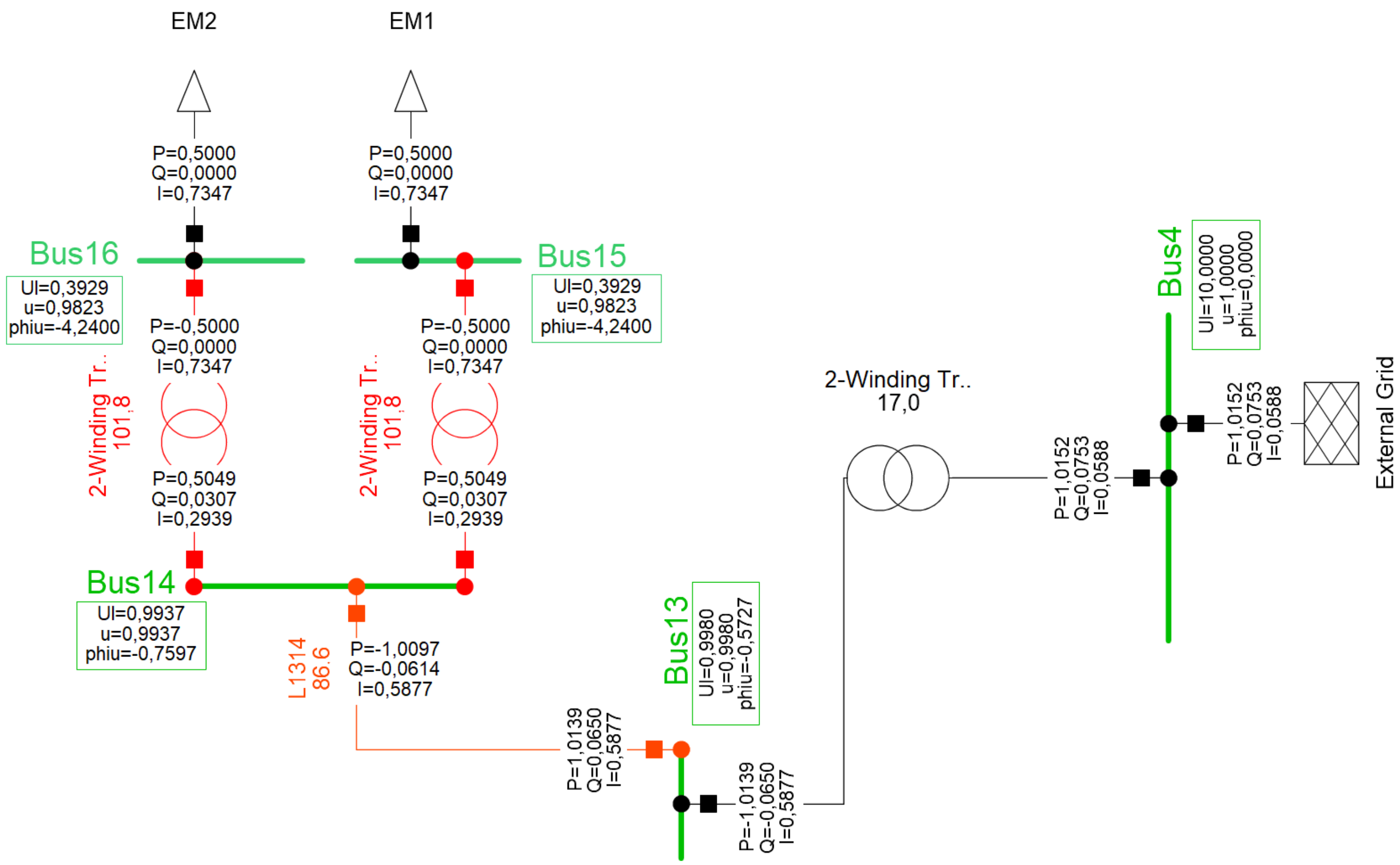



Figure 8.2: AC Load Flow Verification from DIgSILENT PowerFactory

| **Bus No** | **Load Flow (MATLAB-model)** | | **Load Flow (PF-model)** | | **Deviation** | |
|---|---|---|---|---|---|---|
| | **Vmag [pu]** | **Angle(deg)** | **Vmag [pu]** | **Angle(deg)** | **Vmag [%]** | **Angle(deg)** |
| 13 | 0.979 | 0.000 | 0.9791 | 0.0000 | 0.01 | 0.0000 |
| 14 | 0.976 | 0.000 | 0.9763 | 0.0000 | 0.03 | 0.0000 |
| 15 | 0.976 | 0.000 | 0.9758 | 0.0000 | 0.02 | 0.0000 |
| 16 | 0.976 | 0.000 | 0.9758 | 0.0000 | 0.02 | 0.0000 |

Table 8.2: Verification of NR-LFM - Two Electrolyzer Modules with DC Connection

Newton Raphson Loadflow Analysis

| Bus No | V pu | Angle Degree | Injection MW | Injection MVar | Generation MW | Generation Mvar | Load MW | Load MVar |
|---|---|---|---|---|---|---|---|---|
| 13 | 0.979 | -0.000 | -0.00 | 0.00 | -0.00 | 0.00 | 0.00 | 0.00 |
| 14 | 0.976 | -0.000 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 15 | 0.976 | -0.000 | -0.51 | -0.00 | 0.00 | -0.00 | 0.51 | 0.00 |
| 16 | 0.976 | -0.000 | -0.51 | -0.00 | 0.00 | -0.00 | 0.51 | 0.00 |
| Total | | | 0.025 | 0.000 | 1.045 | 0.000 | 1.020 | 0.000 |

Figure 8.3: DC Load Flow Verification from MATLAB

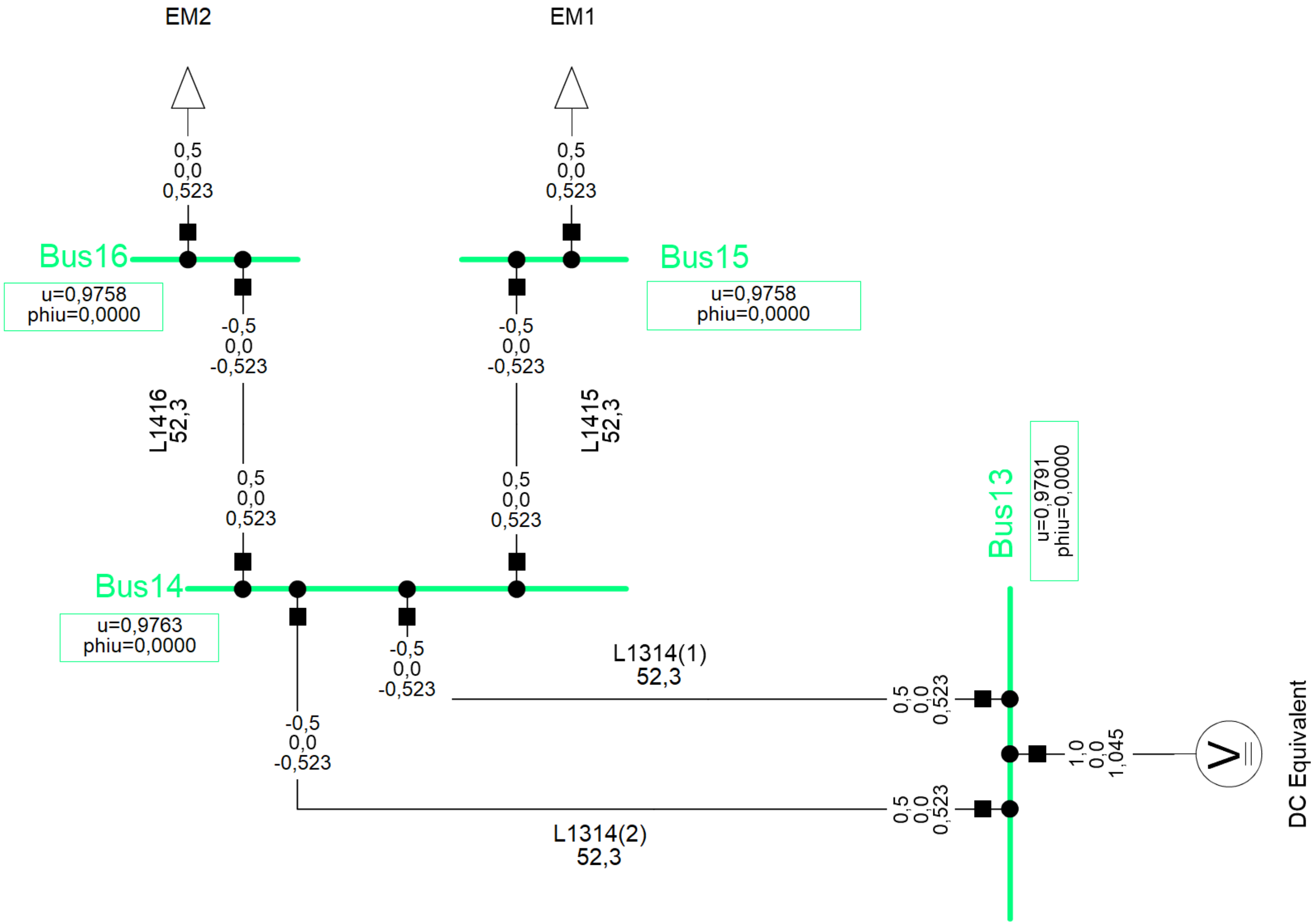



Figure 8.4: DC Load Flow Verification from DIgSILENT PowerFactory

## 8.2 Appendix B

This appendix contains the results of the Electrolyzer Plant test cases. It consist of the overview of the basecases as seen in Table 8.3 and the complete bus voltage profiles of each conducted case.

Table 8.3: Accumulated Power Loss

| | **A** | **B** | **C** |
|---|---|---|---|
| **Case 1** | | | |
| Power Loss [kW] | 393.1 | 371.8 | 367.3 |
| Power Loss [%] | 6.55 | 6.19 | 6.12 |
| **Case 2** | | | |
| Power Loss [kW] | 401.3 | 389.1 | 369.5 |
| Power Loss [%] | 6.68 | 6.49 | 6.16 |
| **Case 3** | | | |
| Power Loss [kW] | 323.1 | 317.0 | 302.9 |
| Power Loss [%] | 5.38 | 5.28 | 5.05 |
| **Case 4** | | | |
| Power Loss [kW] | 321.3 | 312.8 | 305.3 |
| Power Loss [%] | 5.36 | 5.21 | 5.09 |

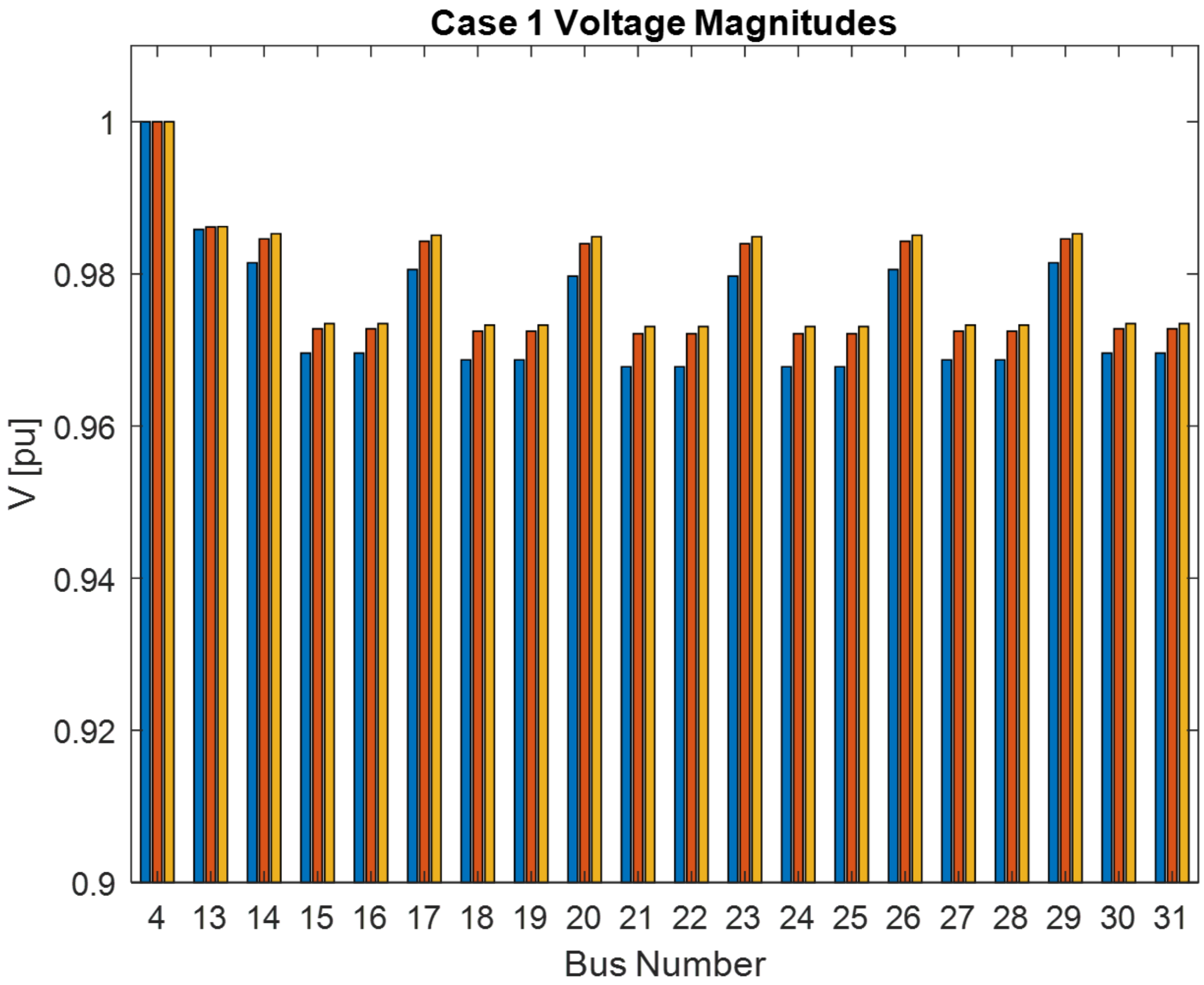



Figure 8.5: Voltage Profile for Case 1 A, B, and C

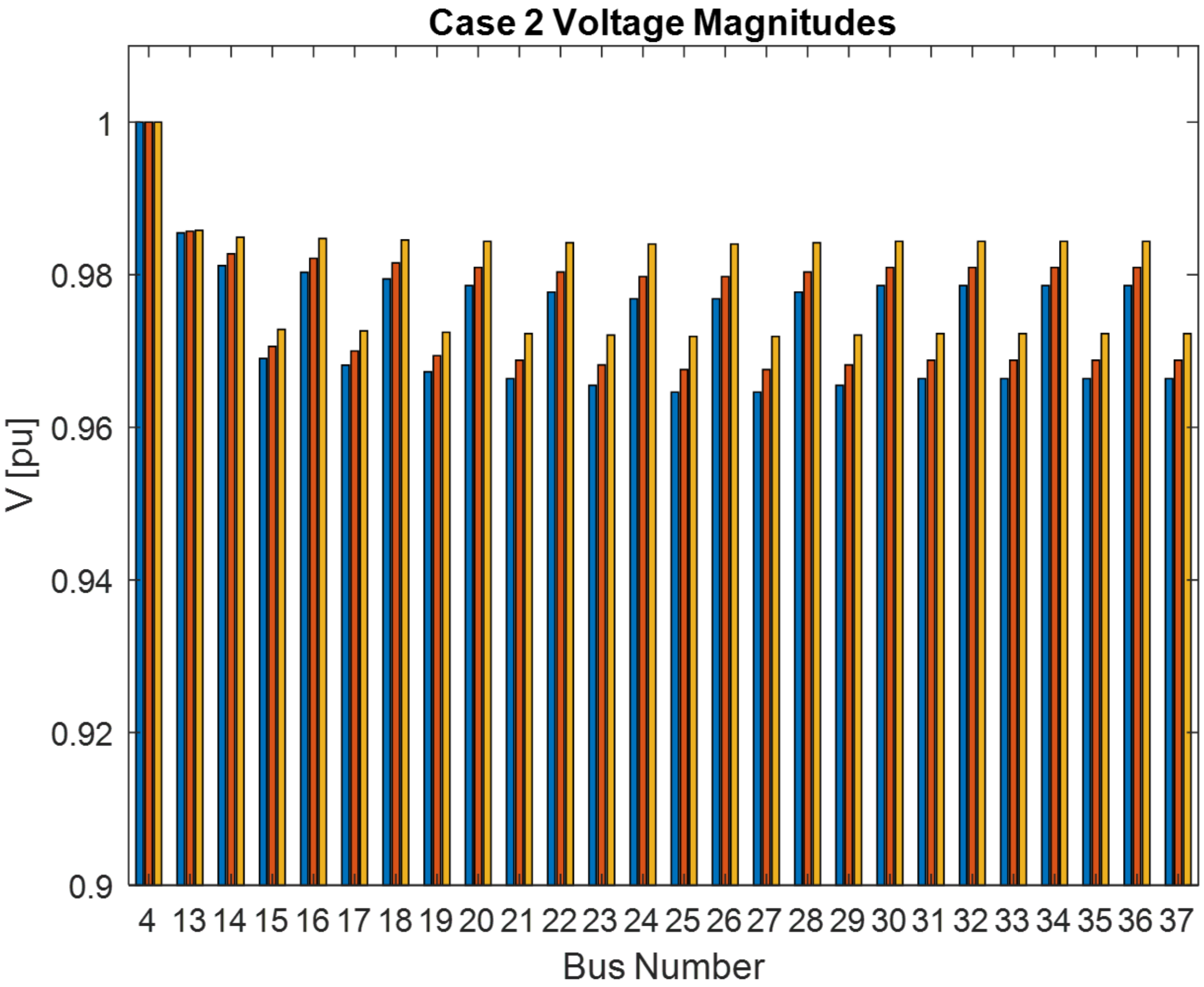



Figure 8.6: Voltage Profile for Case 2 A, B, and C

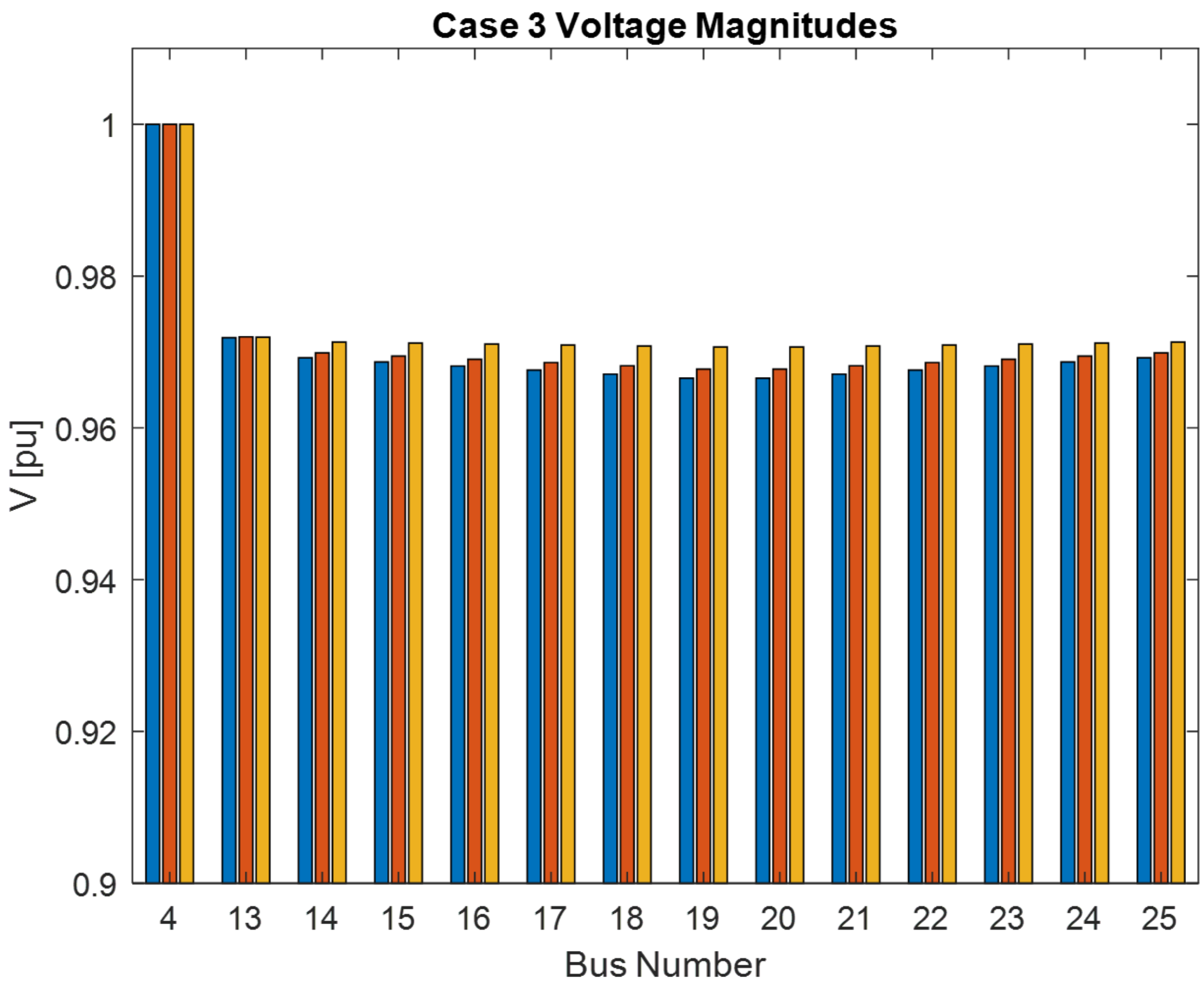



Figure 8.7: Voltage Profile for Case 3 A, B, and C

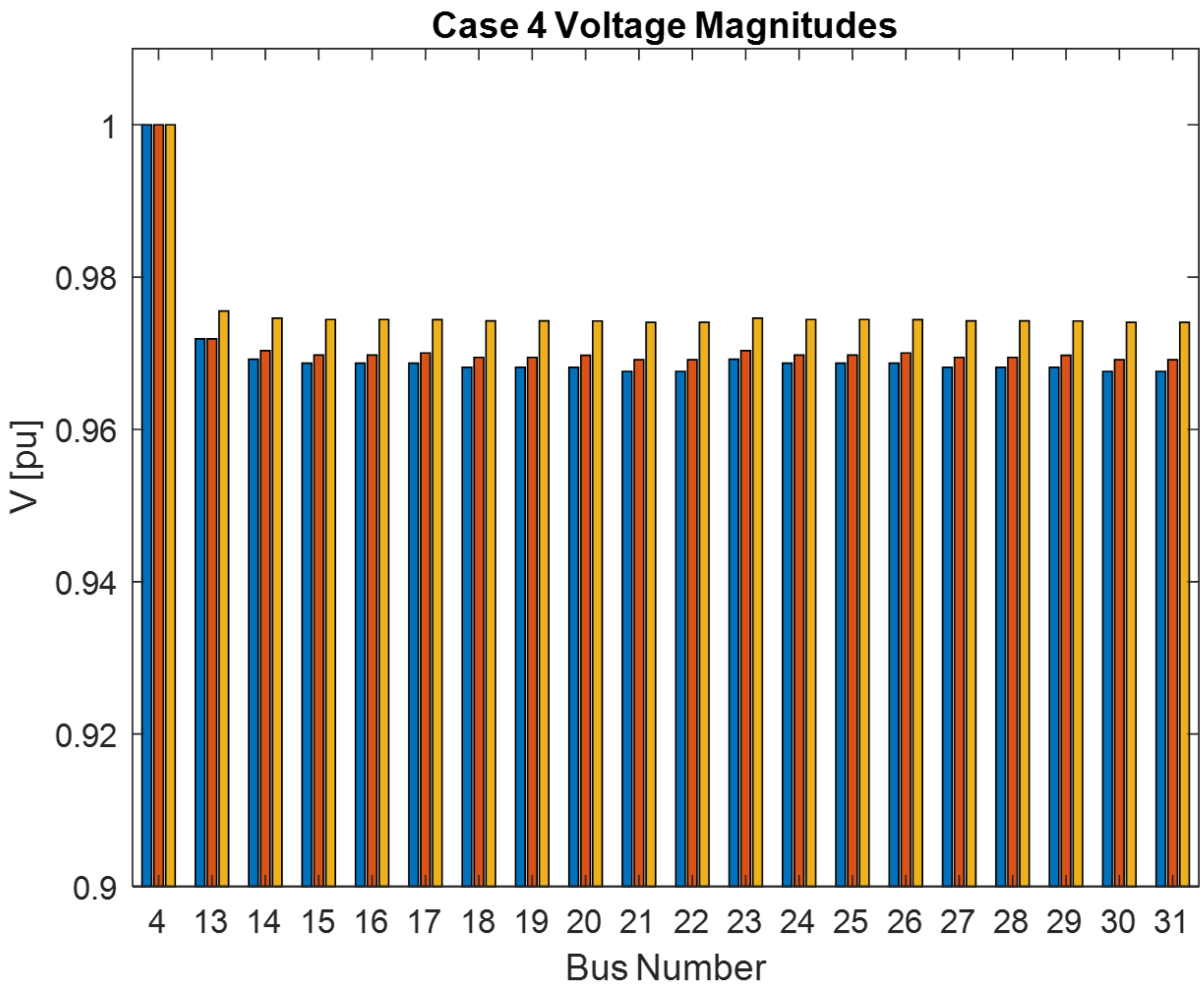



Figure 8.8: Voltage Profile for Case 4 A, B, and C

## 8.3 Appendix C

This appendix contains an overview of the values used for modeling the Collector Grid and the Hybrid Power System Model. The collector grid is divided into the WPP collector grid and the Electrolyzer Plant collector grid.

### WPP Collector Grid

In the WPP collector Grid, the values used for the cables are the NKT AXAL-TT PRO 3.0 Endurance 6/10 (12) kV datasheet [50]. In contrast, the transformer values are from a 10MVA transformer found in the Element library of DIgSILENT PowerFactory.

Table 8.4: Values used in the ACLF Algorithm

| **Asset** | **Length** | **Size** | **Resistance** | **Reactance** | **Capacitance** |
|---|---|---|---|---|---|
| WTG 1 - WTG 2 | 295 m | 95 $mm^2$ | $0.32\Omega/km$ | $0.11\Omega/km$ | $0.19\mu F/km$ |
| WTG 2 - WTG 3 | 289 m | 300 $mm^2$ | $0.10\Omega/km$ | $0.091\Omega/km$ | $0.30\mu F/km$ |
| WTG 3 - WTG 4 | 289 m | 2x240 $mm^2$ | $0.12\Omega/km$ | $0.094\Omega/km$ | $0.27\mu F/km$ |
| WTG 4 - WPP Substation | 1326 m | 2x300 $mm^2$ | $0.10\Omega/km$ | $0.091\Omega/km$ | $0.30\mu F/km$ |
| WTG 5 - WTG 6 | 294 m | 95 $mm^2$ | $0.32\Omega/km$ | $0.11\Omega/km$ | $0.19\mu F/km$ |
| WTG 6 - WTG 7 | 292 m | 300 $mm^2$ | $0.10\Omega/km$ | $0.091\Omega/km$ | $0.30\mu F/km$ |
| WTG 7 - WTG 8 | 287 m | 2x240 $mm^2$ | $0.12\Omega/km$ | $0.094\Omega/km$ | $0.27\mu F/km$ |
| WTG 8 - WPP Substation | 111 m | 2x300 $mm^2$ | $0.10\Omega/km$ | $0.091\Omega/km$ | $0.30\mu F/km$ |
| WPP Substation - PoC EP (Transformer) | | 6MVA | 0.0076Ω | 0.05952Ω | 0F |

### Electrolyzer Plant Collector Grid

In the Electrolyzer Plant collector Grid, the values used for the cables are the NKT AXAL-TT PRO 3.0 Endurance 6/10 (12) kV datasheet [50] whereas the transformer values are from Transformers found in the Element library of DIgSILENT PowerFactory.

Table 8.5: Values used in the ACLF Algorithm - WPP Collector Grid

| **Case** | **Size** | **Resistance** | **Reactance** | **Capacitance** |
|---|---|---|---|---|
| Case 1 | | | | |
| | 240 $mm^2$ | $0.0787\Omega/km$ | $0.0723\Omega/km$ | $0.96\mu F/km$ |
| | 95 $mm^2$ | $0.32\Omega/km$ | $0.097\Omega/km$ | $0.28\mu F/km$ |
| | 50 $mm^2$ | $0.641\Omega/km$ | $0.11\Omega/km$ | $0.22\mu F/km$ |
| Case 2 | | | | |
| | 120 $mm^2$ | $0.1556\Omega/km$ | $0.0723\Omega/km$ | $0.90\mu F/km$ |
| | 25 $mm^2$ | $1.20\Omega/km$ | $0.119\Omega/km$ | $0.18\mu F/km$ |
| Case 3 | | | | |
| | 185 $mm^2$ | $0.1013\Omega/km$ | $0\Omega/km$ | $0\mu F/km$ |
| | 25 $mm^2$ | $1.20\Omega/km$ | $0\Omega/km$ | $0\mu F/km$ |
| Case 4 | | | | |
| | 185 $mm^2$ | $0.1013\Omega/km$ | $0\Omega/km$ | $0\mu F/km$ |
| | 95 $mm^2$ | $0.32\Omega/km$ | $0\Omega/km$ | $0\mu F/km$ |
| | 35 $mm^2$ | $0.8765\Omega/km$ | $0\Omega/km$ | $0\mu F/km$ |
| | 25 $mm^2$ | $1.20\Omega/km$ | $0\Omega/km$ | $0\mu F/km$ |
| Transformers | | | | |
| | 6MVA | 0.0076Ω | 0.05952Ω | 0F |
| | 500kVA | 0.0076Ω | 0.05952Ω | 0F |

## 8.4 Appendix D

This appendix shows the Power Curve and the PQ capability curve of the project-related Wind Turbine. The specific power curve and PQ-Capability curve for the V117-3.6MW turbine is not commercially available, so similar power curves are utilized.

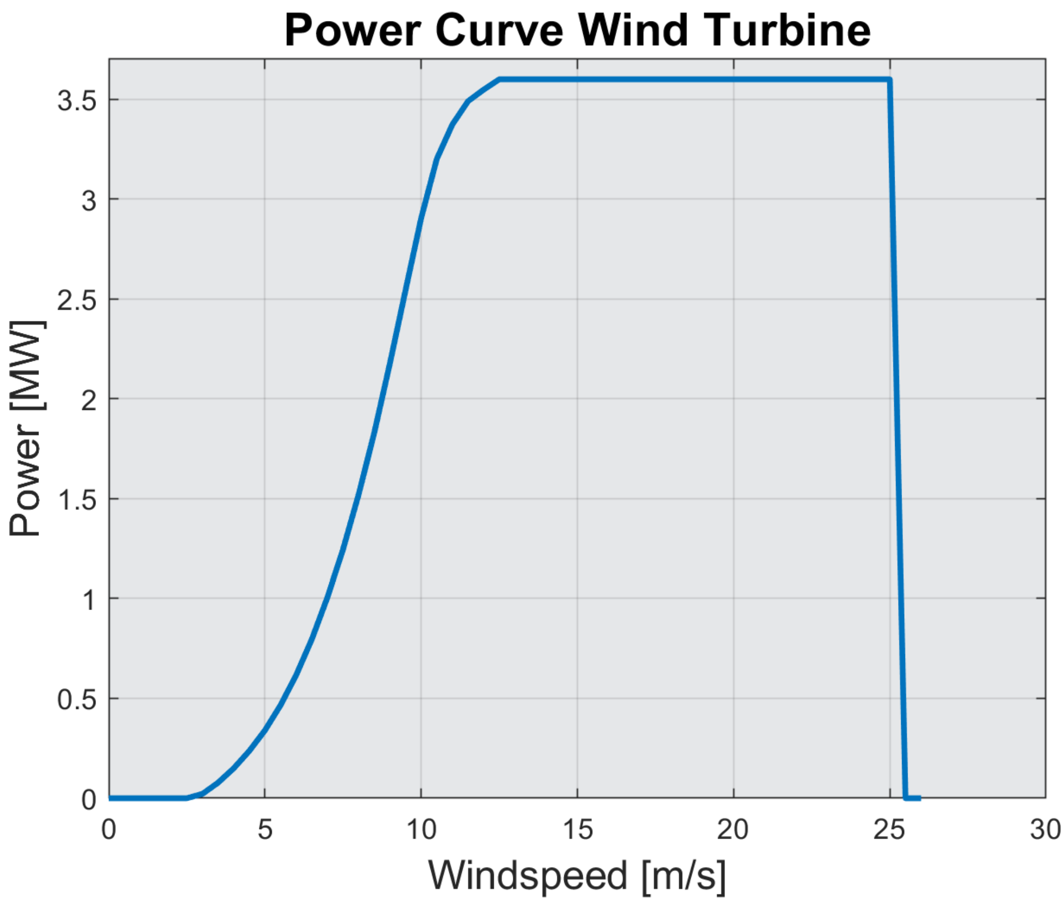



Figure 8.9: Power Curve for 3.6MW Wind Turbine

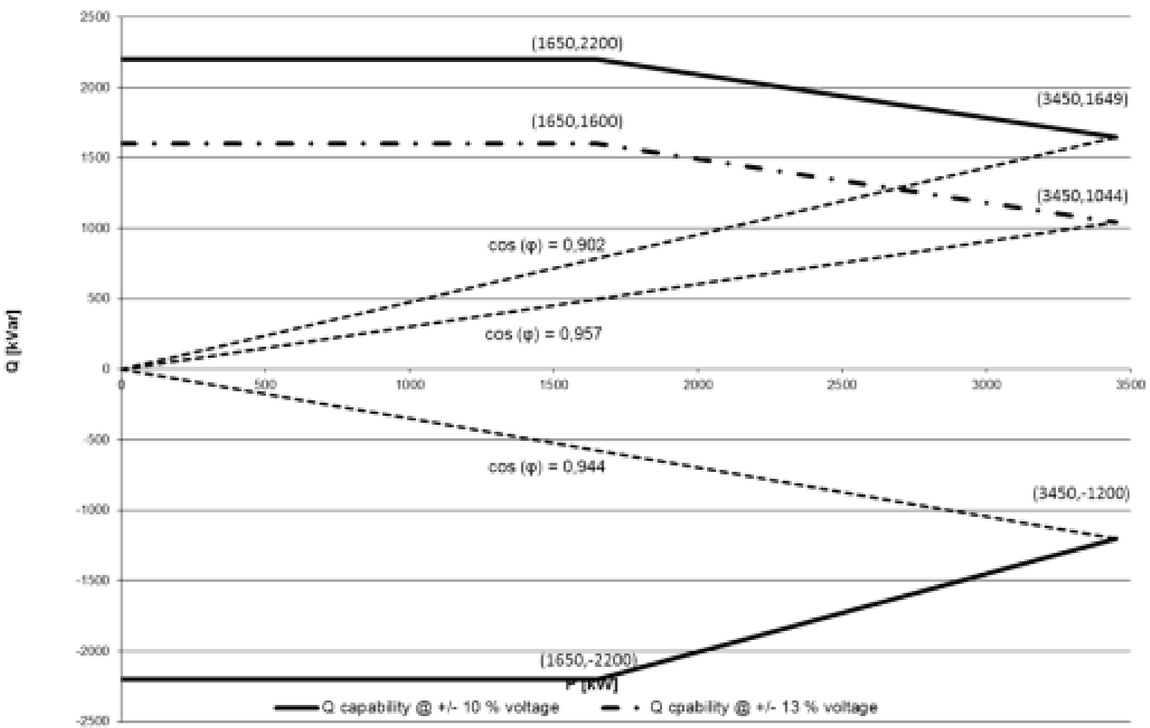



Figure 8.10: PQ Capability Curve for Similar Wind Turbine

## 8.5 Appendix E

When modeling a PEM Water Electrolysis, it is important to capture the electrochemical behavior of the system. This Appendix contains the essential equations to build a mathematical model and analyze the system for a single cell PEM Electrolyzer. The equations are based upon an equivalent circuit model, and chemical reactions are explained in section 5.2.2. The following equations and values are based on reference [59] and [64].

The PEM-Electrolyzer cell can be obtained by its I-V characteristic. It is non-linear until the current reaches steady-state at app. 0.02A. The I-V characteristic can be expressed as:

$$V(T,P) = e_{rev}(T,P) - e_{rev}(T,P)e^{-\frac{5I}{0.02}} + IR_i(T,P) \tag{8.1}$$

An illustration of the I-V Characteristic can be seen in Figure 8.11

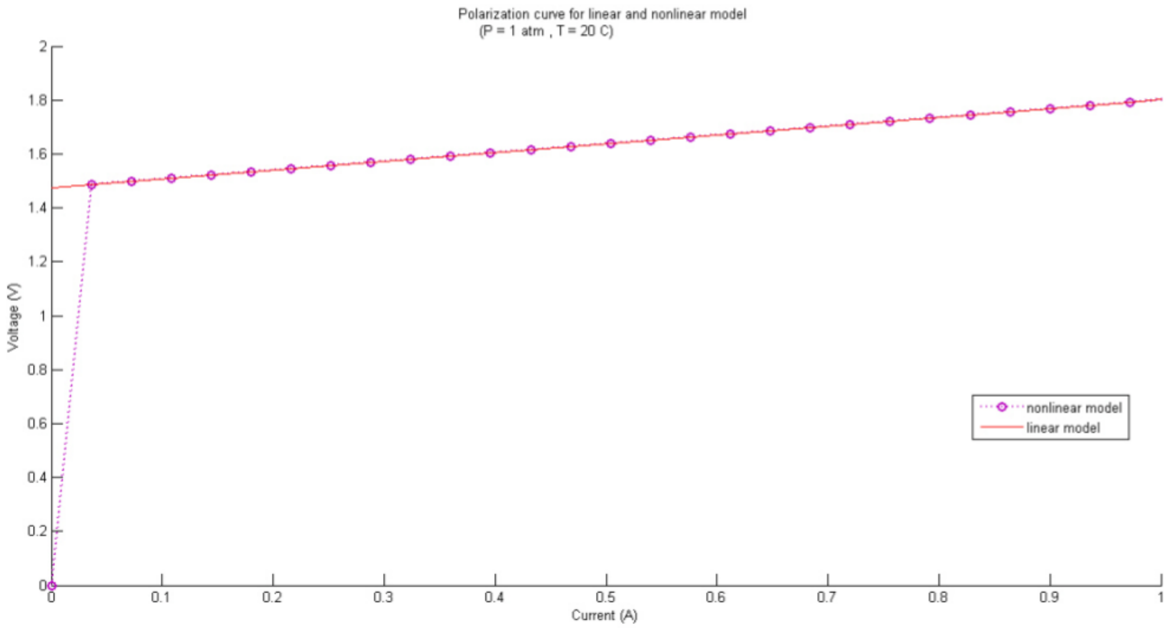



Figure 8.11: I-V Characteristic for a single PEM-Electrolyzer cell

However, a linear function can be described when the current reaches 0.02A. The steady-state operation can be simplified to define the I-V characteristic as a function of pressure and temperature:

$$V(T,P) = IR_i(T,P) + e_{rev}(T,P) \tag{8.2}$$

The resistive heat losses $R_i$ can be expressed as a function of temperature and pressure. Where $k = 0.0395VA^{-1}$, is the derived fitting parameter $p_0 = 1atm$, $R_{io} = 0.326\Omega$, $T_0 = 20^oC$ is the reference pressure, temperature and resistance and $dR_t = 0.0038\Omega C^{-1}$ is the resistance coefficient.

$$R_i(T,p) = R_{i0} + k * ln(\frac{p}{p_0}) + dR_t(T - T_0) \tag{8.3}$$

The reverse voltage $e_{rev}$, represented in the equivalent model, is the minimum required energy barrier of the cell. It can be modeled as a function of pressure and temperature in relation to reference values. $e_{rev0} = 1.486V$ is the reference voltage at the reference temperature and pressure, and R, F is the universal gas constant and Faraday constant, respectively.

$$e_{rev}(T,p) = e_{rev0} + \frac{R(273+T)}{2F} ln(\frac{p}{p_0}) \tag{8.4}$$

For electrolysis and hydrogen production, the ideal voltage $V_i$ can be defined by the equation below.

$$V_i = \frac{\Delta G}{2F} \tag{8.5}$$

Whereas $\Delta G = 285.84 - 163.2(273+T)$ is the Gibbs free energy change of hydrogen gas. The hydrogen production rate $V_H$ in (mL/min) can be defined as:

$$V_H = \frac{60000 V_m I}{2F} \tag{8.6}$$

where $V_m$ is the one molar volume given by:

$$V_m = \frac{R(273+T)}{p} \tag{8.7}$$

The useful power $P_{H2}$, which is the electro-chemical hydrogen energy per second, corrosponding to the production of hydrogen is given by;

$$P_{H2} = \frac{V_H \Delta G}{V_m} = IV_i \tag{8.8}$$

Lastly the efficiency of the PEM single cell can found as:

$$\eta = \frac{P_{H2}}{P} = \frac{IV_i}{IV} = \frac{V_i}{V} \tag{8.9}$$

For multiple cell PEM-Electrolyzer with $n_s$ series and $n_p$ parallel, the simplified linear voltage can be expressed as:

$$V(T,p) = \frac{n_s}{n_p} IR_i(T,p) + n_s e_{rev}(T,p) \tag{8.10}$$