Modelling of P2X for Grid Integration Studies

Master Thesis
Chang Liu

Aalborg University
Department of Electronic Systems
Fredrik Bajers Vej 7B
DK-9220 Aalborg

Software used in the project: DIgSILENT PowerFactory. The thesis project is in cooperation with Energinet Systemansvar A/S.

Abstract

The increasing penetration of renewable energy sources (RES) presents significant challenges to power system stability due to their intermittency and variability. Power-to-X (PtX) technologies offer a promising solution by converting excess electrical energy into energy storage such as hydrogen, synthetic fuels, or chemicals, thereby enhancing grid flexibility and reducing curtailment. This thesis investigates the role of PtX in improving grid stability, particularly under high-RES scenarios, by developing and evaluating a dynamic PtX model. The model, implemented in DIgSILENT PowerFactory, comprises a modular structure with detailed representations of key components including rectifiers, buck converters, and a 250MW PEM electrolyzer. These modules incorporate electrochemical, thermal, pressure, and mass flow dynamics to reflect realistic operational behavior. Special attention is given to the control strategies that enable PtX systems to act as fast-responding, controllable loads, capable of providing ancillary services such as frequency and voltage support. The model is constructed in accordance with Energinet's grid code requirements, and is intended for use in generic integration studies. Simulation-based stability assessments demonstrate that PtX units, with ramping capabilities up to 60MW/min, can effectively mitigate system disturbances and contribute to maintaining overall power system resilience. This research provides both a technical framework and practical insights into PtX's systemic role in the future low-carbon energy infrastructure.

Resumé

Den stigende udbredelse af vedvarende energikilder (RES) præsenterer betydelige udfordringer for elsystemets stabilitet på grund af deres intermittensitet og variabilitet. Power-to-X (PtX) teknologier tilbyder en lovende løsning ved at omdanne overskydende elektrisk energi til energilagring såsom brint, syntetiske brændstoffer eller kemikalier, hvorved nettets fleksibilitet forbedres og forbrugsafbrydelser reduceres. Denne afhandling undersøger PtX's rolle i at forbedre nettets stabilitet, især under scenarier med høj RES, ved at udvikle og evaluere en dynamisk PtX-model. Modellen, implementeret i DIgSILENT PowerFactory, består af en modulær struktur med detaljerede repræsentationer af nøglekomponenter, herunder ensrettere, buck-konvertere og en 250 MW PEM-elektrolysør. Disse moduler inkorporerer elektrokemisk, termisk, tryk- og massestrømningsdynamik for at afspejle realistisk driftsadfærd. Der lægges særlig vægt på de kontrolstrategier, der gør det muligt for PtX-systemer at fungere som hurtigt reagerende, kontrollerbare belastninger, der er i stand til at levere hjælpetjenester såsom frekvens- og spændingssupport. Modellen er konstrueret i overensstemmelse med Energinets netkodekrav og er beregnet til brug i generiske integrationsstudier. Simuleringsbaserede stabilitetsvurderinger viser, at PtX-enheder med rampekapacitet på op til 60 MW/min effektivt kan afbøde systemforstyrrelser og bidrage til at opretholde den samlede robusthed i elsystemet. Denne forskning giver både en teknisk ramme og praktisk indsigt i PtX's systemiske rolle i fremtidens lavemissionsenergiinfrastruktur.

Contents

Thesis Details

Thesis Title:	Modelling of P2X for grid integration studies
Ph.D. Student:	Chang Liu
Supervisors:	Assoc. Prof. Sanjay Chaudhary, Aalborg University Asst. Prof. Hanchi Zhang, Aalborg University

This thesis has been submitted for assessment in partial fulfillment of the MSc degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Preface

Chang Liu
Aalborg University, April 19, 2026

Chapter 1

Introduction

1 Background

The global transition toward low-carbon energy systems has accelerated the deployment of renewable energy sources (RES), particularly wind and solar power. While this transition supports climate and sustainability goals, it also introduces significant challenges for power system operation. Unlike conventional generation, RES are inherently intermittent and variable, leading to fluctuations in power generation that complicate the maintenance of stable operating conditions.

One of the most critical consequences of high RES penetration is the increased difficulty in maintaining frequency and voltage stability. Power system frequency reflects the instantaneous balance between generation and demand, while voltage profiles depend on reactive power balance and network conditions. During periods of high renewable generation and low demand, excess active power can lead to over-frequency events and voltage rises, threatening system security. Conversely, sudden drops in renewable output can cause under-frequency conditions and voltage instability.

Traditional mitigation strategies, such as renewable curtailment, are widely used to address these issues. However, curtailment is both economically inefficient and environmentally undesirable, as it wastes clean energy that could otherwise be utilized. Therefore, alternative solutions that enhance system flexibility while preserving renewable generation are increasingly required. [1, 2].

1.1 Power-to-X as a Flexible Demand-Side Solution

In this context, Power-to-X (PtX) technologies have emerged as a promising approach to enhance grid flexibility and stability. PtX refers to a class of technologies that convert electrical energy into other energy carriers or products, including hydrogen (Power-to-

Hydrogen, PtH), synthetic methane (Power-to-Gas, PtG), and synthetic fuels (Power-to-Liquid, PtL). Electrolysis, particularly using Proton Exchange Membrane (PEM) or Alkaline Electrolyzers, plays a central role in many PtX applications [3, 4]. These devices consume electrical energy to produce hydrogen from water and can be controlled dynamically, making them suitable for demand-side management and ancillary services [5, 6]. By integrating PtX into the power grid, excess electricity—often generated during periods of high wind or solar output—can be absorbed and stored in chemical form, rather than wasted through curtailment [5, 7].

By integrating PtX into the power grid, surplus electricity—often generated during periods of high wind or solar output—can be utilized rather than curtailed. This not only improves energy efficiency but also supports the balance between generation and demand, contributing to both steady-state and dynamic system stability.

1.2 Role of PtX in Frequency and Voltage Stability

An essential feature of PtX systems in the context of grid integration is their controllability [8, 9]. Recent studies and field applications demonstrate that PtX units can be operated with fast ramping capabilities, allowing them to adjust their power consumption rapidly in response to grid conditions [8, 10]. In Denmark, for example, PtX installations have been studied with a targeted ramp rate of 60MW per minute, enabling fast and effective response to fluctuations in generation or load [10]. This ramping capability positions PtX as a flexible load that can help stabilize frequency and voltage, especially during grid disturbances or in systems with low inertia dominated by inverter-based generation [2, 11].

This capability positions PtX as an effective tool for supporting both frequency and voltage stability:

Frequency stability: By increasing or decreasing power consumption in response to frequency deviations, PtX systems can help restore the balance between generation and demand.

Voltage stability: As large controllable loads, PtX units influence power flow and voltage profiles across the network, particularly in transmission systems with high renewable penetration.

Moreover, PtX systems can be equipped with control strategies such as reverse droop or current-following control modes, which allow them to autonomously modulate their power draw based on grid frequency or power availability [5, 8]. In a reverse droop configuration, for instance, the PtX unit increases its power consumption as system frequency rises—effectively acting as a "virtual generator" on the demand side to mitigate over frequency events. This form of synthetic inertia and fast frequency response can significantly improve system resilience, particularly in networks with reduced contributions from conventional synchronous machines. Simulation studies using standardized grid models, such as the IEEE 9-bus system, have confirmed the beneficial impact of PtX integration. These studies show that PtX units, when properly controlled, can dampen frequency excursions following generator outages or fault events, reduce voltage sags, and maintain system balance even under asymmetrical disturbances [5]. Additionally, their contribution becomes even more pronounced when combined with wind turbines or battery storage systems, forming part of a broader hybrid energy system.

In conclusion, Power-to-X technologies are not only pivotal for decarbonizing sectors beyond electricity—such as heating, transportation, and industry—but also play a strategic role in maintaining power system stability under high-renewable scenarios. By consuming excess active power with high ramping flexibility (e.g. 60MW/min), PtX platforms can serve as fast-reacting, grid-friendly loads that help mitigate the operational challenges posed by variable renewable generation. Their dual role as both energy converters and dynamic grid assets makes PtX a cornerstone of the future energy system.

2 Problem statement

The increasing share of wind and solar in modern power systems has introduced significant operational challenges due to their variable and intermittent nature. These challenges include frequency deviations, overvoltages, and reduced system inertia—particularly during periods of excess generation and low demand. Traditional solutions like curtailment are economically inefficient and environmentally counterproductive. PtX technologies offer a promising alternative by absorbing surplus power and converting it into storable energy carriers, such as hydrogen or synthetic fuels.

However, the large-scale integration of PtX plants into the electricity transmission grid also raises new questions about their impact on power system stability. While PtX units can act as flexible and controllable loads, their dynamic behavior under various grid conditions remains insufficiently understood. Furthermore, current supplier-provided models are often proprietary and cannot be shared, limiting transparency and collaboration in system-level studies. There is a clear need for a standardized, generic PtX model that captures essential dynamic characteristics and complies with grid code requirements, particularly those set by system operators like Energinet.

This thesis addresses the gap by developing and evaluating a generic, open-access PtX dynamic model. It aims to assess the influence of PtX integration on system frequency and voltage stability, enabling power system operators to better plan and manage the future energy grid dominated by RES and inverter-based technologies.

3 Project objectives and methodology

This thesis aims to investigate the integration of PtX technologies into modern power grids with high shares of renewable energy. The specific objectives are:

1 To analyze the role of PtX systems in enhancing power system stability, particularly in terms of frequency and voltage support.

2 To develop a generic, modular dynamic model of PtX systems suitable for grid integration studies, based on the functional and modeling requirements from Energinet.

3 To implement this model in DIgSILENT PowerFactory, capturing key dynamic behaviors of components such as rectifiers, converters, and electrolyzers.

4 To evaluate the model through stability simulations under different scenarios relevant to Energinet, including cases of large RES penetration and system disturbances.

5 To provide general guidelines on the impact of PtX technologies on system stability, supporting future planning and grid code compliance.

DIgSILENT Powerfactory is the simulation software that are used in the project.

4 Scope and limitations

Limitations were taken in the project to make the model more intuitive. As the physical model of PtX is considered, the grid model is simplified. The limitation includes:

1 The dynamic simulation is mainly running in RMS model rather than EMT

2 The change of preset variables is made by load event rather than a global variable.

3 Part of the power flow transmission process is considered to be lossless

4 Harmonics are ignored, although they could be observed in EMT simulation

Chapter 2

State of the Art

The analysis of the current research status focuses on two aspects: the technical requirements of the power grid for PtX grid connection, and the research on PtX simulation methods. This chapter presents the technical requirements for integrating Power-to-X (PtX) systems into modern power systems, with a focus on their role in supporting grid stability under high renewable penetration. As the share of variable renewable sources continues to increase, maintaining frequency and voltage stability has become more challenging, requiring new forms of flexibility and controllable demand. In this context, PtX technologies, particularly electrolyzers, are gaining attention due to their ability to operate as dynamic and responsive loads. This chapter reviews the key technical aspects governing their integration, including their interaction with frequency dynamics, contribution to voltage regulation, and compliance with existing grid codes. These aspects provide the foundation for understanding how PtX systems can be effectively utilized as grid-supporting assets. [2, 7, 11]

1 Technical Requirements of PtX Integration in Modern Power System

A growing body of literature highlights the increasing importance of Power-to-X (PtX) and, more specifically, power-to-gas (P2G) technologies in supporting the transition toward low-carbon and highly renewable power systems. Recent studies emphasize that the rapid penetration of variable renewable sources (VRS) has significantly increased system complexity, requiring enhanced flexibility, stability, and new forms of grid support. In this context, electrolyzers, the core component of PtX, are emerging as promising assets due to their ability to convert surplus electricity into hydrogen while also acting as flexible and controllable loads, as discussed in Chapter 1.

From a technical and regulatory perspective, current research shows that grid codes (GCs) play a crucial role in enabling the integration of such technologies. [12, 13] However, existing GCs in countries like Denmark and the United Kingdom are primarily designed for conventional and inverter-based generation (e.g., wind, PV, and storage), and only partially address the specific requirements of electrolyzers. While electrolyzers can theoretically comply with requirements related to active power control, frequency response, and fault ride-through, there is still a lack of dedicated standards and clear compliance frameworks tailored to PtX systems. This highlights the need for further investigation into their interaction with grid operation.

Complementing this regulatory perspective, other studies focus on the operational and economic potential of electrolyzers in power systems. Electrolyzers are shown to provide fast and flexible demand response, making them suitable for participation in ancillary services such as frequency containment and balancing markets [5, 6, 14]. Their fast dynamic response enables them to contribute effectively to system stability, improving frequency nadir and damping oscillations following disturbances [15]. In addition, their controllable demand offers opportunities for supporting voltage profiles and mitigating congestion, especially when integrated with renewable generation.

In general, the literature demonstrates that PtX systems can play a significant role in enhancing the flexibility and stability of the power system, while also introducing new challenges related to control coordination and regulatory compliance. These aspects are closely linked to their interaction with system frequency dynamics, voltage regulation mechanisms, and the requirements imposed by existing grid codes, which are discussed in the following sections.

1.1 PtX and Frequency Stability

The imbalance between generation and load will result in frequency and voltage instability. Major disturbances, such as load changing, will lead to frequency and voltage deviation. The power system's response to such deviation is divided into three regions [11, 16].

The frequency control system is responsible for keeping the stability of the grid. Both primary and secondary and secondary control are involved to regulate the power variation of PtX.

The dynamic behavior of the rotor is governed by the swing equation, which links the mechanical and electrical power imbalance to the rate of frequency change

$$(P_m - P_e)\, f_0 = 2H \frac{df}{dt} \tag{2.1}$$

Where H is the inertia of the system A low inertia of the system results in a higher frequency changing speed. The frequency nadir is approximated by the following equa-

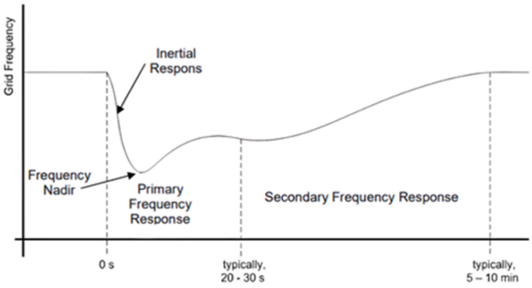

Fig. 2.1: Deviation

tion [11].

$$f_{\text{nadir}} = f_0 \left(1 - \frac{\Delta P}{2H}\right) \tag{2.2}$$

1.2 PtX and Voltage Regulation

Voltage regulation is primarily achieved through the coordination of reactive power control provided by inverter-based resources and conventional power plants [2, 12]. Various inverter facilities are required to participate in voltage support through VQ control strategies. The PtX plant can regulate the reactive power exchanging the grid and maintaining the grid's voltage. Grid codes typically define several control modes for reactive power regulation. The most common approaches include Q control, PF control and voltage control. For voltage control, grid codes generally specify a voltage–reactive power droop characteristic, where deviations in the local voltage trigger reactive power injection or absorption. Typical droop values are around 4%, although adjustable ranges (e.g., 2–7%) are allowed depending on system requirements and the connection level. Through this mechanism, inverter-based resources can contribute to voltage stabilization during both normal operation and disturbances. With the increasing penetration of converter-based technologies and emerging loads such as PtX facilities, voltage–reactive power control has become a critical ancillary service. Therefore, modern power systems rely on coordinated V–Q control strategies from multiple inverter-based devices to maintain voltage stability and comply with evolving grid code requirements.

1.3 Grid Code Compliance and Integration Requirements

PtX facilities, particularly electrolyzers interfaced through power electronic converters, are expected to comply with existing grid code requirements for inverter-based resources in Denmark and the United Kingdom. [13] In both systems, the nominal frequency is 50 Hz and connected facilities must tolerate frequency variations roughly within 47–52 Hz while providing active power response through droop-based frequency control. Voltage operation is also regulated at the point of connection, typically within about -15 % to +10 % of nominal voltage in Denmark and -10 % to +10 % in the UK. These requirements ensure that PtX installations remain connected and support grid stability during normal operation and disturbances.

2 Modeling Approaches for PtX Systems

The growing integration of Power-to-X (PtX) technologies into modern power systems has led to increasing interest in their modelling for grid stability studies. PtX systems, particularly those based on electrolysers and fuel cells, are inherently multi-domain, involving electrochemical, thermal, electrical, and control processes. As a result, a wide range of modelling approaches has been developed, differing mainly in their level of detail and intended application.

At the most detailed level, electrochemical models describe the internal physical processes of PtX components, including reaction kinetics, temperature dynamics, and gas transport. These models provide high accuracy and are valuable for component design and efficiency analysis. However, they are highly nonlinear, computationally intensive, and require parameters that are often difficult to obtain. Consequently, they are generally unsuitable for large-scale power system simulations [17].

To reduce complexity, semi-empirical models [3] have been introduced, relying on experimental data to approximate system behavior. These models capture performance characteristics such as polarization curves and dynamic response under varying operating conditions. While less computationally demanding than detailed models, they still require extensive parameterization and lack general applicability across different systems.

For power system studies, simplified models based on equivalent electrical circuits have become the preferred approach. In these representations, electrolysers and fuel cells are modeled as controllable electrical components using basic elements such as voltage sources and resistances. This approach significantly reduces computational burden and allows integration into simulation tools such as DIgSILENT PowerFactory or PSCAD. Importantly, studies have shown that simplified models can accurately reproduce the active power response required for frequency and transient stability analysis [17].

In the context of electrolyser modelling, recent research emphasizes the importance of representing not only the electrolysis stack but also the power conversion system and balance of plant. Generic models developed for large-scale electrolysers have demonstrated that capturing the active power dynamics and ramping behavior is sufficient for grid studies. For example, models validated against a 1 MW pilot electrolyser show that electrolysers can respond rapidly to frequency deviations and positively contribute to system stability [14].

Similarly, fuel cell models used in power system analysis often adopt simplified representations that focus on external electrical behavior rather than internal electrochemical processes. Comparative studies indicate that reduced-order models can provide results equivalent to more complex formulations in dynamic simulations, supporting their use in large-scale grid studies [17].

Recent developments have focused on creating generic PtX models suitable for stability analysis. These models integrate electrolysers, fuel cells, power converters, and control systems into a unified framework, enabling the evaluation of ancillary service provision. In particular, PtX systems have been shown to effectively support frequency regulation through fast power adjustment, often outperforming conventional generators in response speed [15]. Moreover, integrated PtX plants can participate in services such as frequency containment reserve, contributing to stability in low-inertia grids [16].

In summary, the state of the art shows a clear transition from detailed electrochemical models toward simplified, system-oriented representations. For grid stability studies, models that accurately capture active power dynamics while maintaining computational efficiency are most appropriate. This understanding forms the basis for the modelling approach adopted in this thesis.

3 Challenges and Research Gap

Despite the progress in PtX modelling, several challenges remain. One of the main issues is the lack of standardized modelling approaches, leading to inconsistencies across different studies. Additionally, there is an inherent trade-off between model accuracy and computational efficiency, which must be carefully managed depending on the application.

Another important limitation is the lack of large-scale validation. Although some models have been validated using pilot-scale systems, there is still limited evidence of their performance in full-scale installations. Furthermore, many models focus on individual components rather than integrated PtX systems, neglecting interactions between electrolysers, fuel cells, and other system elements.

These challenges highlight the need for modelling frameworks that are both generic and scalable, capable of accurately representing PtX behavior in power system studies while remaining computationally efficient.

Chapter 3

Modeling of Electrolyzer

1 Modeling of Electrolyzer

This chapter presents the modeling framework developed for the PtX system, focusing on its integration and dynamic behavior in power system simulations. Different modeling approaches have been proposed for electrolyzers, ranging from detailed electrochemical models to simplified representations for system-level studies [3–6, 9]. The PtX unit is divided into two principal components: the rectifier, which converts AC to DC power, and the electrolyzer, which uses DC power to produce hydrogen. In addition to these core devices, the modeling also includes the internal electrical bus structure and the plant-level step-down transformer necessary for grid interfacing. Each main component is represented in DIgSILENT PowerFactory using a collection of DSL sub-models. These sub-models capture detailed operational characteristics, including current control, droop behavior, and response to system disturbances. Furthermore, the chapter elaborates on the mathematical models, control strategies, and physical principles underlying the PtX operation. Together, these form a comprehensive and modular representation of the PtX system, suitable for analyzing its impact on grid stability and dynamic performance.

The model shown above represents the main power conversion chain used to supply a DC-based PtX system [3, 4]. It starts with a 132kV AC grid (Terminal2), which is stepped down to 0.6kV via a two-winding transformer. The AC voltage is then rectified by a PWM-based converter, converting it into a medium-voltage DC output. This intermediate DC voltage is further processed by a DC/DC converter, which regulates the voltage to a lower level suitable for the electrolyzer and associated DC loads. The final DC bus (Terminal4.2) operates at 1kV and supplies three parallel-connected DC loads, including a constant power load and an electrolyzer unit modeled as a 1MW DC load.

The entire configuration reflects a typical multi-stage AC/DC/DC conversion ar-

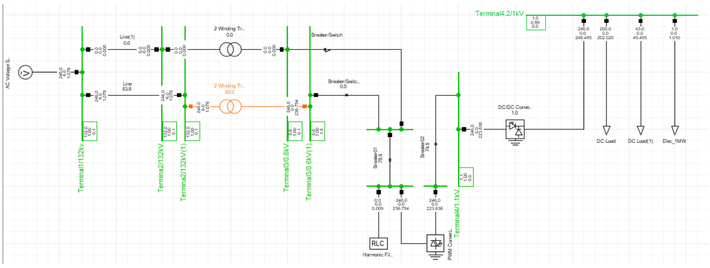

Fig. 3.1: Grid

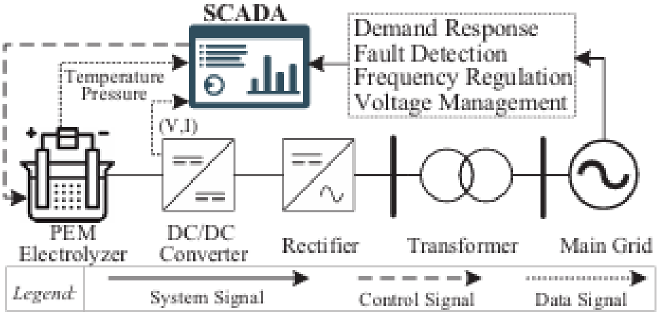

Fig. 3.2: PtX

chitecture used in high-power PtX applications, with clearly defined transformation, rectification, and regulation stages. Shunt capacitors are used to improve the power factor and determine the K_I and K_P gain factors in the PWM rectifier.

$$K_P = L \cdot \omega_c \tag{3.1}$$

$$K_I = R \cdot \omega_c \tag{3.2}$$

The PWM rectifier is used to determine the current AC bus voltage according to the set active power, the electrolyzer controller is used to determine its current according to the DC bus voltage and the set active power, and the buck is used to maintain the stability of the DC voltage on both sides to avoid system swing and oscillation.

The primary limitation of this model lies in its rated power capacity of 250MW, with a maximum allowable active power ramp rate of 60MW per minute. To achieve this dynamic regulation, independent control modules are implemented within the PWM converter, buck converter, and the electrolyzer system. Each stage contributes to coordinated power adjustment, enabling the system to respond flexibly to grid demands

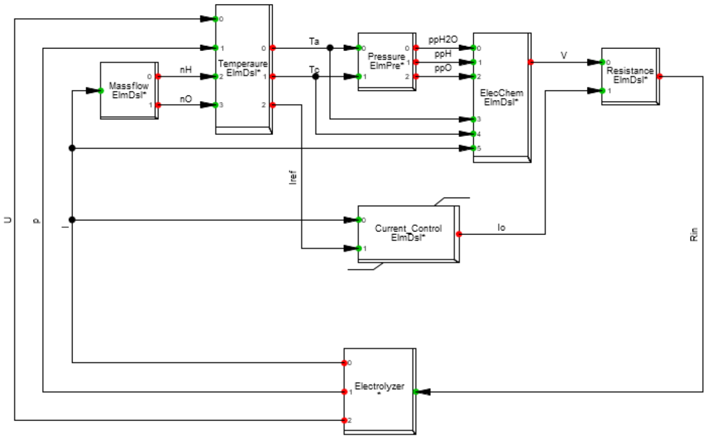

Fig. 3.3: Electrolyzer Control Frame

while respecting the ramping constraint. This structure ensures both steady-state operation within rated limits and smooth dynamic behavior during load variations.

1.1 Electrolyzer

The developed model aims to establish the dynamic model and analyze the stability of PtX, as a function of temperature, pressure and load. A 250MW PEM electrolyzer is modeled. The stacks of electrolyzer cells are considered to have similar behavior to a single one. The electrolyzer is mainly divided into 4 function submodules, including electrochemical model, pressure model, massflow model and thermal model. The submodules are connected with DSL models. These function submodules give voltage, power, current output signals, and the other slots transfer these signals to the Electrolyzer slot, which is connected to the grid and requires certain input parameters. Process-based modeling approaches for alkaline electrolyzers have also been extensively studied [4].

The electrolyzer model shown above captures the dynamic interaction between electrical inputs and electrochemical behavior, focusing primarily on the relationship between voltage, current, and active power. A set of auxiliary submodules further accounts for the influence of key physical parameters, including pressure, temperature, and mass flow, on the system's internal state and hydrogen/oxygen production rates. The electrochemical reaction model integrates feedback from temperature and pressure modules to compute the actual cell behavior and gas outputs. Control of the electrolyzer is realized through independent voltage and power control modules, which regulate the reference current and ensure stable operation under varying grid or system conditions.

This modular structure enables flexible integration into multi-level PtX systems, while also providing visibility into both electrical and thermodynamic performance.

1.2 Electricalchemical Model

Electrochemical models provide a detailed representation of internal physical and chemical processes, including reaction kinetics, mass transport, and thermodynamics [3, 4]. The electrochemical behavior of the PEM electrolyzer is described using a standard voltage decomposition model reported in the literature [3, 9]. The voltage of electrolyzer cells is given by the equation

$$V_{\text{cell}} = E_{\text{rev}} + \eta_{\text{act}} + \eta_{\text{diff}} + \eta_{\text{ohm}} \tag{3.3}$$

Where V_ocv is the open circuit voltage while neglecting other overpotential, V_act is the electrochemical reaction overpotential, V_diff is the diffusion overpotential, and V_ohm is ohmic overpotential.

- E_{rev}: reversible (open circuit) voltage,
- η_{act}: activation overpotential,
- η_{diff}: concentration (diffusion) overpotential,
- η_{ohm}: ohmic overpotential.

The open circuit voltage is also called reversible voltage. It's the minimum voltage for the electrolysis can be carried out in the electrolyzer. The potential is expressed as

$$E_{\text{rev}} = \frac{\Delta G}{nF} \tag{3.4}$$

- ΔG: Gibbs free energy,
- n: number of electrons transferred (typically $n = 2$),
- $F = 96,485Cmol(-1)$: Faraday's constant,
- $Vocv = 1.229V$: standard condition.

The Gibbs free energy is expressed

$$E_{\text{tn}} = \frac{\Delta H}{nF}, \quad \eta_V = \frac{E_{\text{rev}}}{E_{\text{tn}}} \tag{3.5}$$

where $V_th = 1.48$ V at standard condition.

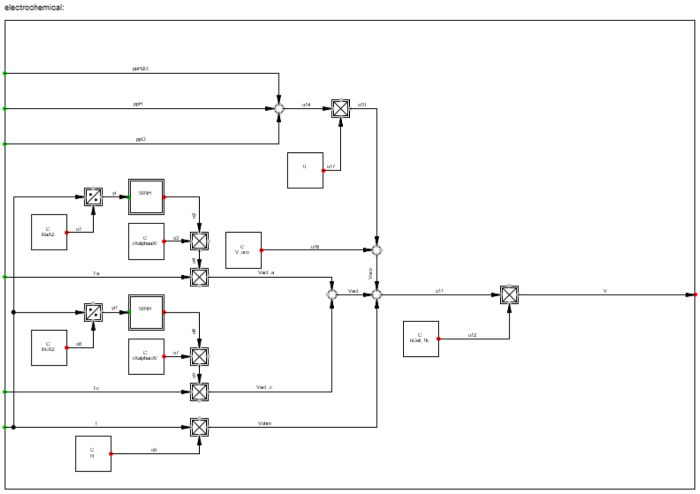

Fig. 3.4: PtX

The activation overpotential represents the voltage loss associated with electrochemical reaction kinetics in the PEM electrolyzer. It is commonly described using the Butler–Volmer equation, which captures the relationship between current density and reaction rate at both the anode and cathode [9]. For a symmetric reaction, the activation overpotential can be expressed as:

$$\eta_{\text{act}} = \frac{RT}{\alpha n F} \ln \left(\frac{i}{i_0} \right) \tag{3.6}$$

Alternatively, for anode and cathode separately:

$$\eta_{\text{act,a}} = \frac{RT}{\alpha_a n F} \ln \left(\frac{i}{i_{0,a}} \right), \quad \eta_{\text{act,c}} = \frac{RT}{\alpha_c n F} \ln \left(\frac{i}{i_{0,c}} \right) \tag{3.7}$$

where:

- R: universal gas constant,
- T: operating temperature,
- α: charge transfer coefficient,
- i: current density,
- i_0: exchange current density.

The diffusion voltage is also called the concentration overpotential.

$$\eta_{\text{diff}} = \frac{RT}{nF} \ln \left(\frac{C^*}{C} \right) \tag{3.8}$$

where C^* is the bulk concentration and C is the surface concentration of the reactant.

The ohmic overpotential is the sum of resistance in bipolar plate, electrode resistance, membrane resistance, and interfacial resistance. The total ohmic loss can be expressed as:

$$\eta_{\text{ohm}} = i \cdot (R_a + R_c + R_m + R_{\text{interface}}) \tag{3.9}$$

or more compactly:

$$\eta_{\text{ohm}} = i \cdot R_{\text{total}}, \quad R_{\text{total}} = R_a + R_c + R_m + R_{\text{interface}} \tag{3.10}$$

where:

- R_a: anode resistance,
- R_c: cathode resistance,
- R_m: membrane resistance,
- $R_{\text{interface}}$: interfacial resistance.

1.3 Pressure Model

In the dynamic modeling of a PEM electrolyzer, pressure and temperature are originally controlled by two separate control loops. However, both controllers essentially influence the same underlying process—namely the internal state conditions that affect gas production and system stability. Since pressure typically reacts faster to system changes while temperature adjusts more slowly, it is reasonable to simplify the model by merging these two controllers into a single composite model. This approach retains the essential dynamics of the system while reducing complexity and computation load.

The gas pressure dynamics can be expressed by a simplified mass balance equation:

$$\frac{dp}{dt} = \frac{RT}{V} \cdot (\dot{n}_{\text{in}} - \dot{n}_{\text{out}}) \tag{3.11}$$

where:

- p: internal pressure of the electrolyzer,
- R: ideal gas constant,

- T: operating temperature (assumed constant in simplified model),
- V: control volume (chamber volume),
- $\dot{n}_{\text{in}}$: molar flow rate of gas generated (hydrogen/oxygen),
- $\dot{n}_{\text{out}}$: molar flow rate of gas removed from the system.

The hydrogen production rate is calculated based on Faraday's law, relating the electrical current to the molar production rate of hydrogen [6].

$$\dot{n}_{\text{in}} = \frac{I}{nF} \tag{3.12}$$

Combining this with pressure dynamics provides a first-order approximation of pressure behavior in response to electrical input, enabling the controller to stabilize internal pressure based on current draw while implicitly accounting for temperature-induced effects.

1.4 Thermal Model

The temperature inside the electrolyzer is a key factor that affects electrochemical reaction rates, voltage efficiency, and system stability. Accurate modeling of thermal dynamics is essential for understanding how temperature influences hydrogen production and electrochemical behavior over time.

The thermal model considers both the heat generated by electrochemical reactions and the heat exchanged with the environment. The core heat balance equation is:

$$C_p \cdot \frac{dT}{dt} = \dot{Q}_{\text{gen}} - \dot{Q}_{\text{loss}} \tag{3.13}$$

where:

- C_p: effective thermal capacitance of the system,
- T: temperature of the electrolyzer,
- $\dot{Q}_{\text{gen}}$: heat generation rate,
- $\dot{Q}_{\text{loss}}$: heat loss to the environment.

The heat generated by the electrochemical process can be expressed as:

$$\dot{Q}_{\text{gen}} = I \cdot (V_{\text{cell}} - E_{\text{tn}}) \tag{3.14}$$

where:

- I: current supplied to the electrolyzer,

- V_{cell}: actual cell voltage,
- E_{tn}: thermal-neutral voltage.

Heat loss is typically modeled using Newton's law of cooling:

$$\dot{Q}_{\text{loss}} = h \cdot A \cdot (T - T_{\text{env}}) \tag{3.15}$$

where:

- h: heat transfer coefficient,
- A: effective heat exchange surface area,
- T_{env}: ambient (environmental) temperature.

In simplified implementations—especially for grid-level simulations—the thermal model may be represented as a first-order lag system. This captures the slow thermal response compared to fast electrical dynamics:

$$\frac{dT}{dt} = \frac{1}{\tau_T}(T_{\text{ref}} - T) \tag{3.16}$$

where τ_T is the thermal time constant and T_{ref} is a reference temperature setpoint. This simplification enables the thermal behavior to be integrated into the overall dynamic PtX model with minimal computational burden, while still capturing the essential impact of temperature on electrochemical efficiency and dynamic stability.

1.5 Current Control Model

The current control mechanism is designed to regulate the input current of the electrolyzer according to a dynamic reference signal I_{ref}, thereby ensuring that the electrical load responds appropriately to system-level demands. This mechanism mimics the thermal and pressure regulation processes, using a closed-loop feedback structure to minimize tracking error and adjust the load dynamically.

The overall structure follows a standard PID framework, augmented with anti-windup protection and saturation limits. The control error is defined as:

$$e(t) = I_{\text{ref}}(t) - (I_c + I_s) \tag{3.17}$$

where I_c is the filtered measured current and I_s represents an internal signal offset. The PID controller output is composed of three components:

$$u_P(t) = K_p \cdot e(t) \tag{3.18}$$

$$u_I(t) = \int_0^t K_i \cdot e(\tau)\, d\tau \tag{3.19}$$

$$u_D(t) = K_d \cdot \frac{d}{dt} e(t) \tag{3.20}$$

The total control action is constrained by upper and lower bounds $I_{\text{pid,min}}$ and $I_{\text{pid,max}}$, such that:

$$I_a = \text{sat}(u_P + u_I + u_D, I_{\text{pid,min}}, I_{\text{pid,max}}) \tag{3.21}$$

This signal is further scaled through a gain K_a and filtered to produce the ramped reference current I_r:

$$\frac{dx_a}{dt} = \frac{I_a K_a - x_a}{T_a}, \quad I_r = \text{sat}(x_a, I_{r,\text{min}}, I_{r,\text{max}}) \tag{3.22}$$

The controller also includes a secondary filtering process for smoothing the measured output current I:

$$\frac{dx_r}{dt} = \frac{I - x_r}{T_r}, \quad I_c = x_r \tag{3.23}$$

Additionally, an internal error signal ΔI is generated between the rectifier output I_{fe} and filtered current I_r, modulated by a gain K_e. This contributes to a limited first-order response:

$$I_{\text{fe}} = K_e \cdot I_o, \quad \frac{dx_e}{dt} = \frac{I_{\text{fe}} - x_e}{T_e} \tag{3.24}$$

All integral and dynamic elements are protected by limiters to prevent numerical instability and ensure control signal feasibility.

This controller architecture allows the electrolyzer system to dynamically and safely follow grid frequency or load variations by modulating its power draw through current control.

1.6 Summary

The developed PtX system model demonstrates a hybrid control architecture that tightly integrates both electrical and physical subsystems. Among the various components, the **current control loop** plays a pivotal role in linking high-level grid commands to internal electrolyzer operation. It achieves this by dynamically regulating the input current based on reference signals, emulating classical pressure and temperature regulation processes, but implemented entirely within the electrical control domain.

In contrast, other subsystems—especially the **thermal and pressure models**—are grounded in physical principles, modeling heat exchange, gas dynamics, and thermodynamic behavior with respect to electrochemical activity. Notably, the temperature model acts as a core structural block in the system, as it not only reflects the internal energy state of the electrolyzer, but also provides the reference current signal that governs the electrical controller.

This hierarchical structure establishes a feedback pathway where physical processes such as heat accumulation directly influence electrical behavior, and vice versa. The result is a coupled electro-physical system in which energy conversion, control, and system stability are co-optimized. By bridging fast-reacting electrical regulation with slower, process-driven thermal and pressure dynamics, the model captures the essential characteristics required for realistic simulation of PtX plants in grid stability studies.

This approach not only enhances simulation fidelity but also lays the foundation for integrated design of future PtX controllers—ones that must satisfy both electrical grid requirements and physical process constraints in real time.

Chapter 4

Modeling of PtX

1 Modeling of PtX

This chapter describes the process of establishing a power grid, using a single-machine infinite system and assuming that changes in PtX have no significant impact on the grid.

1.1 Grid Model

To evaluate the integration performance of the PtX system under realistic grid conditions, a detailed grid-connected model was developed in DIgSILENT PowerFactory. As shown in Figure 4.1, the system comprises a 132kV AC source representing the transmission grid, two 132/0.6kV step-down transformers forming a double-busbar configuration, and a series of power electronic converters interfacing with DC loads including a 1MW PEM electrolyzer.

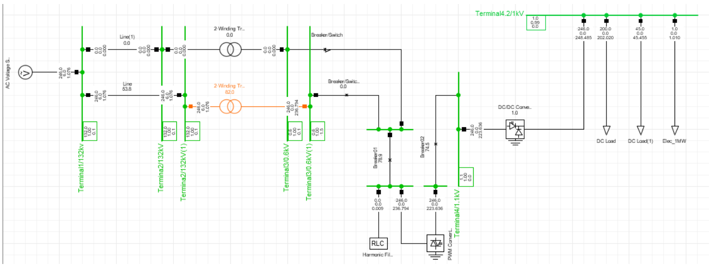

Fig. 4.1: Grid Model

The dual transformer setup provides redundancy and operational flexibility, ensuring reliability during maintenance or fault scenarios. To more accurately capture the dynamic behavior of the AC network, a parallel RLC circuit is included at the point of common coupling. This RLC branch emulates the grid's short-circuit impedance and resonance characteristics, which significantly influence the frequency response and voltage stability of the converter terminal. The impedance profile also directly affects the gain and performance of the PWM controller. Furthermore, a phase-locked loop (PLL) is deployed to extract the voltage phase angle, enabling synchronization with the external AC grid. The PLL ensures that converter control operates in proper phase alignment, which is essential for stable V_{dc}–ϕ regulation during dynamic grid events.

Following the AC interface, a PWM-based rectifier converts the 0.6 kV AC to an intermediate 1 kV DC voltage, with harmonic filtering applied to suppress high-frequency switching effects. This DC voltage is regulated via a DC/DC converter and distributed through a centralized DC bus. Connected to the bus are several DC loads, including a constant power load and a dynamically modeled PEM electrolyzer.

The control architecture of the system is modular yet tightly coordinated through a shared active power reference signal. Each of the three major control blocks, the PWM converter, the DC / DC converter, and the electrolyzer, operates with a distinct functional focus. The PWM converter governs the active power absorbed from the AC grid by modulating the phase angle and terminal voltage. The DC/DC converter stabilizes the intermediate DC voltage, acting as a buffer that isolates the grid side dynamics from the load side response. The electrolyzer, in turn, behaves as a current-controlled load: Tt monitors the DC voltage and computes the required electrochemical current to optimize hydrogen output and system efficiency.

This layered control structure reflects a clear division of objectives —— power control at the grid interface, voltage regulation on the DC bus, and current management within the electrochemical system. Such a design not only simplifies control tuning and model stability, but also facilitates physical realism by preserving the natural causality between electrical inputs and physical reactions. It enables the PtX system to respond coherently to grid-level control signals while dynamically managing internal constraints and conversion demands.

1.2 PWM Rectifier Control Frame

The control structure of the PWM rectifier is designed to regulate the power exchange between the PtX system and the AC grid. The system is divided into four main blocks: the Phase-Locked Loop (PLL), the power control module, the current control module, and the PWM converter interface.

1. Phase-Locked Loop (PLL): The PLL block estimates the fundamental phase angle of the grid voltage by measuring the AC voltage at the point of common coupling.

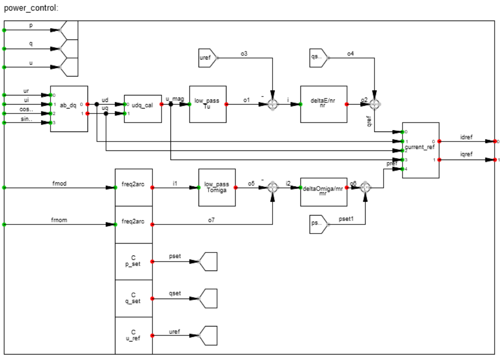

Fig. 4.2: Power Control

It outputs `cosref` and `sinref`, which are used to transform three-phase AC quantities into a rotating reference frame (d-q frame). This transformation enables decoupled control of active and reactive power components.

2. Power Control Module: The power control block receives inputs such as the reference active power p, reactive power q, and measured DC and AC voltages. Based on the PLL signals, it performs Park transformation and calculates the desired d-axis and q-axis current references ($i_{d,\text{ref}}$, $i_{q,\text{ref}}$). These references represent the target power to be injected into or drawn from the grid, with i_d typically linked to active power and i_q to reactive power.

3. Current Control Module: The current control block implements a closed-loop controller (typically PI or PD) that compares the actual currents (i_d, i_q) with their references. It generates voltage references in the d-q frame ($u_{d,\text{ref}}$, $u_{q,\text{ref}}$) required to track the desired current. This stage also receives the PLL's synchronization signals to maintain correct reference frame alignment.

4. PWM Converter Interface: The final block represents the PWM converter itself. It takes the voltage references and generates gate signals for switching devices using a modulation algorithm (e.g., sinusoidal PWM or space vector PWM). The converter outputs the controlled three-phase AC voltages and currents, as well as the DC link voltage (u_{DC}).

This hierarchical control structure ensures that the PWM rectifier can operate as a controllable power interface. Regulates power flow in response to grid-side commands while maintaining voltage stability and synchronization with the AC grid. The modular design also enables clear decoupling between control layers, allowing the system to scale

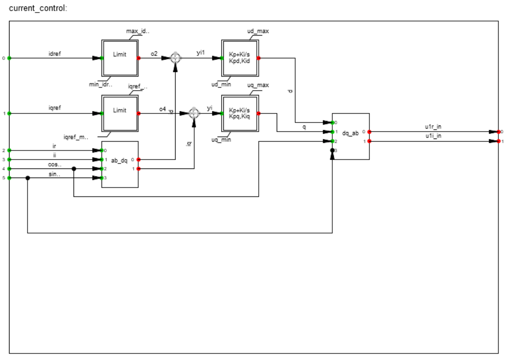

Fig. 4.3: Current Control

or adapt to different operating conditions.

1.3 Summary

This chapter presented the structural and control modeling of the PtX grid-connected system, with a focus on the power conversion chain and its corresponding control architecture. Starting from a dual-busbar AC interface, the model incorporates realistic electrical dynamics using transformers, line impedances, and a parallel RLC filter to emulate grid-side behavior. A PLL unit ensures precise phase synchronization with the AC voltage, providing a stable reference for subsequent control stages.

Three key control modules were introduced and functionally separated: the PWM rectifier controls active power exchange with the grid, the DC/DC converter stabilizes the intermediate DC voltage, and the electrolyzer operates as a current-following load based on the applied voltage. Despite their different objectives, these modules share a unified power reference signal, ensuring coherent operation across electrical and physical domains.

By integrating synchronized grid-side measurements, voltage regulation, and electrochemical response models, the chapter laid the foundation for detailed stability analysis and controller evaluation. The layered, modular control design ensures that the PtX system is both grid-responsive and physically accurate, making it suitable for dynamic simulations under varying operating conditions.

Chapter 5

Ch5.Grid Integration and Simulation Study on the Dynamic Behavior of PtX

1 Simulation Study on the Dynamic Behavior of PtX

This chapter focuses on the dynamic simulation of the grid and PtX model described in the previous chapters. In accordance with the project proposal, the PtX system is subject to a ramp rate limitation of 60 MW/min, equivalent to 1 MW/s. In addition to assessing this ramping constraint, the system's response to two fault scenarios is also investigated: a three-phase-to-ground fault and a single-phase-to-ground fault.

1.1 Active Power Ramping Constraint Simulation

This simulation investigates the PtX system's ability to follow a ramped active power command within the specified limit of 60 MW/min (1 MW/s). The test emulates realistic grid-side setpoint updates by incrementing the active power reference by 0.5 MW every 0.5 seconds, resulting in a step-wise increase in demand.

The objective of this experiment is to assess whether the coordinated control of the PWM converter, DC/DC converter, and electrolyzer can accurately and stably track the active power reference under ramping conditions. Key observables include the actual active power drawn by the system and voltage variations on both AC and DC sides of the conversion chain.

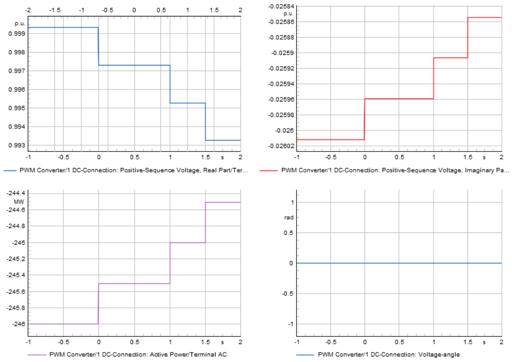

Fig. 5.1: P-V response of AC bus

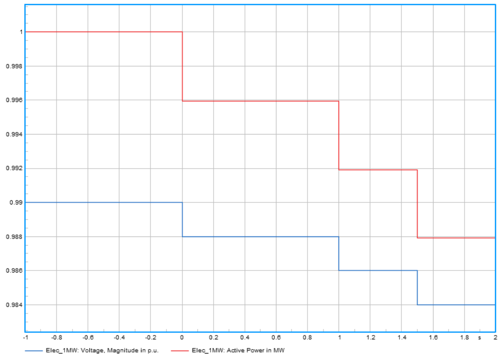

Fig. 5.2: P-V response of Electrolyzer

PWM Converter Response The first plot shows the real and imaginary parts of the positive-sequence voltage, the active power at the AC terminal, and the phase angle at the output of the PWM rectifier. Throughout the simulation, the terminal voltage exhibits minimal deviation, with both the real and imaginary parts showing smooth, quantized steps. The voltage angle remains constant, further confirming stable synchronization with the grid. The active power tracks the reference increment accurately, with each 0.5 MW increase clearly reflected in the measured output. These results indicate that the PWM converter prioritizes voltage stability while allowing power to ramp in a controlled manner, consistent with its primary role in AC-side regulation and phase alignment.

Electrolyzer Performance The second plot presents the active power and voltage magnitude at the input of the electrolyzer model. Similar to the PWM converter, the

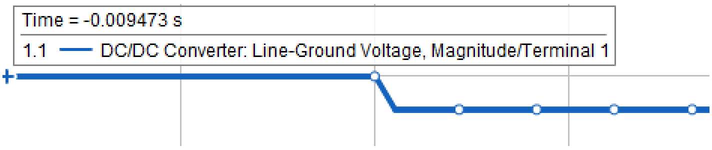

Fig. 5.3: Delay of the Electrolyzer

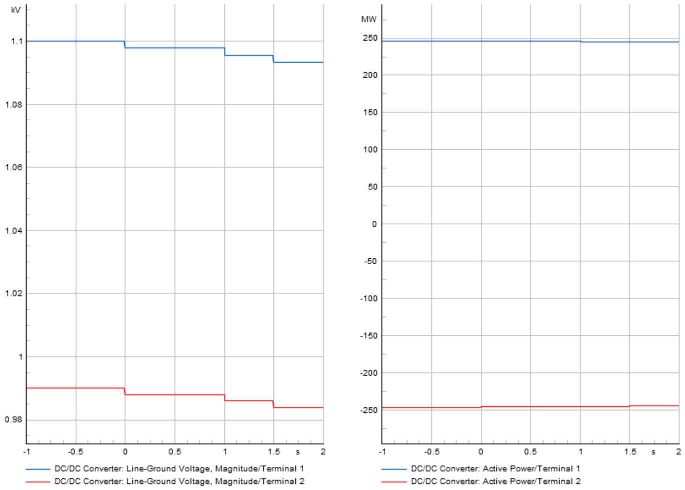

Fig. 5.4: P-V response of DC-DC converter

power follows the stepwise reference; however, the observed values are slightly lower than ideal at each step. This is attributed to the electrolyzer's internal current-controlled logic, which computes current based on applied DC voltage while enforcing electrochemical constraints such as temperature, pressure, and Faraday efficiency. The voltage also shows a downward trend corresponding to increasing load, indicating voltage drop due to converter impedance or regulation margin. Overall, the electrolyzer responds realistically, absorbing more power as voltage adjusts, without deviating from stable operation.

Additionaly, it is noticed that there is a short delay of the voltage drop of electrolyzer, and the power flow follows closely, which suits the assumption in the modeling. The electrolyzer is designed to simulate the physical behavior including pressure and temperature. These two process are much slower than the current droop control.

DC/DC Converter Stability The third plot illustrates the line-to-ground voltage at both terminals and the active power transferred through the DC/DC converter. The

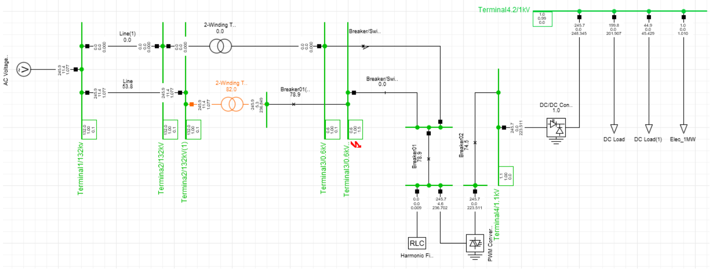

Fig. 5.5: P-V response of DC-DC converter

voltage remains largely stable at each terminal, with only minor drops aligned with load increases. The active power remains balanced on both sides of the converter, confirming energy conservation and steady-state tracking. These results suggest that the DC/DC converter successfully regulates the intermediate DC voltage, acting as an effective buffer between the PWM rectifier and the electrolyzer. The converter maintains voltage within acceptable limits while transmitting the required power without delay or instability.

Summary The simulation results demonstrate that all three major subsystems—the PWM rectifier, DC/DC converter, and electrolyzer—perform as expected under ramped active power input. Each module fulfills its control objective: the PWM converter maintains grid-aligned voltage control, the DC/DC converter preserves voltage stability across its terminals, and the electrolyzer responds to the voltage by regulating current in accordance with internal physical models. The system as a whole shows coordinated behavior, validating the hierarchical control structure under dynamic but bounded input conditions.

1.2 Three-Phase-to-Ground Fault Response

This experiment investigates the transient behavior of the PtX system under a symmetrical three-phase-to-ground fault. The fault is applied at the 0.6 kV AC bus downstream of the transformer, between the grid and the PWM converter input. To isolate the effect of the fault, key breakers are opened and closed in sequence, as shown in the corresponding diagram snapshots.

The aim of this test is to evaluate the fault ride-through capability of the PtX system and its control response during a sudden voltage collapse. The simulation tracks the reaction of the AC-side voltage, converter status, and DC-side power delivery. Key metrics include terminal voltages, breaker operation status, and power flow continuity across the AC/DC/DC chain.

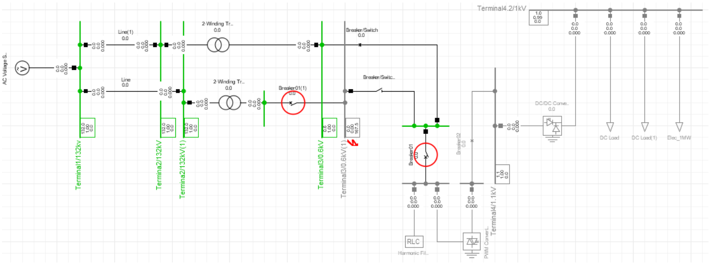

Fig. 5.6: P-V response of DC-DC converter

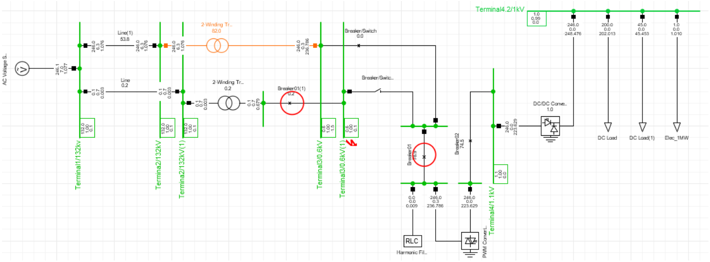

Fig. 5.7: P-V response of DC-DC converter

Results and Analysis As illustrated in Figures 5.5 to 5.7, the application of a three-phase fault causes an immediate voltage collapse at the 0.6 kV terminal. The breaker status indicators confirm that the faulted segment is quickly isolated through the tripping of Breaker01 and Breaker01(1), effectively disconnecting the fault from the main power path. This action prevents fault current propagation into the downstream converter chain.

Conclusion The simulation confirms that the PtX system, when properly protected, can successfully disconnect from the faulted AC network and avoid damage to downstream components. The breaker coordination ensures rapid isolation, while the converter controllers respond safely by ceasing operation under faulted voltage conditions. This validates the system's basic fault tolerance and highlights the importance of protective device settings in ensuring PtX system stability and survivability during severe grid disturbances.

1.3 Single-Phase-to-Ground Fault Response

This experiment examines the PtX system's response to an asymmetrical fault scenario, specifically a single-phase-to-ground fault applied on phase A at the 0.6 kV AC bus.

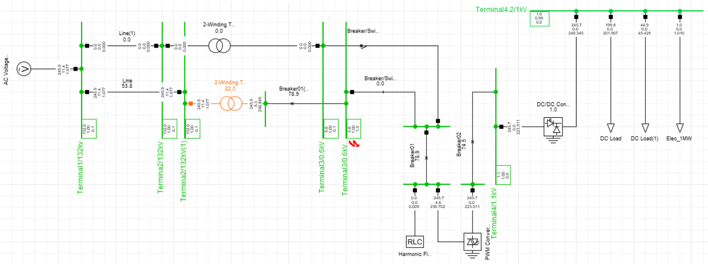

Fig. 5.8: P-V response of DC-DC converter

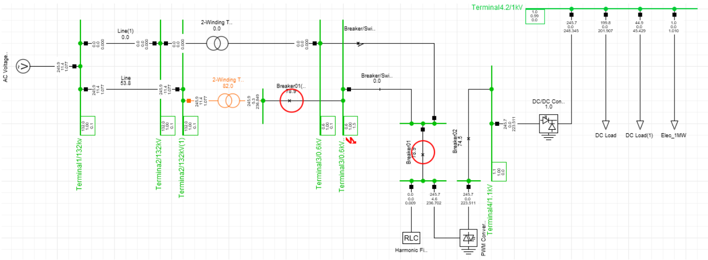

Fig. 5.9: P-V response of DC-DC converter

Compared to the symmetrical three-phase fault, a single-phase fault introduces voltage and current imbalance without full system collapse, thus offering insights into how the converters and electrolyzer behave under unbalanced conditions.

The fault is introduced through the grounding of A phase, and breaker actions are used to isolate the faulted section. The simulation aims to evaluate the system's transient behavior, fault detection, and isolation strategy, as well as the impact of voltage asymmetry on the downstream power electronic interface and DC load chain.

Results and Analysis Figures 5.8 to 5.10 illustrate the sequence of breaker operations and network status before, during, and after the fault. Upon initiation of the A-phase ground fault, the system exhibits partial voltage collapse on the affected phase while the remaining two phases remain nominal. This creates a low-voltage, unbalanced condition at the 0.6 kV bus.

The protection system detects the abnormal current and triggers the disconnection of the faulted line by tripping Breaker01 and Breaker01(1). Simultaneously, the input to the PWM converter is removed, isolating the converters from the unbalanced supply. Downstream components such as the DC/DC converter and electrolyzer subsequently cease operation, as reflected by the zero or near-zero values in voltage and power.

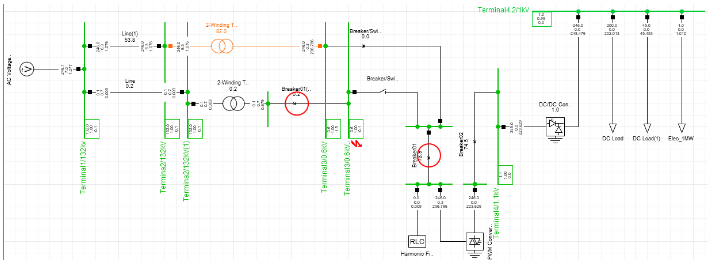

Fig. 5.10: P-V response of DC-DC converter

Conclusion The simulation confirms that the PtX system is capable of safely detecting and isolating asymmetrical disturbances. The converter-based interface reacts properly by shutting down under unbalanced conditions, thus avoiding internal damage or controller instability. The experiment also highlights the importance of phase-level fault protection and the robustness of control logic in asymmetrical voltage environments.

Summary and Comparison

This chapter presents three simulation studies to evaluate the dynamic response and fault tolerance of a PtX-integrated power system. The first experiment verified the system's ability to follow a ramped active power reference within a predefined slope limit. Both the converters and the electrolyzer demonstrated stable and coordinated control, with voltage regulation and current tracking performing as expected.

The second and third experiments introduced grid disturbances in the form of a symmetrical three-phase-to-ground fault and an asymmetrical single-phase-to-ground fault, respectively. In both cases, the system protection mechanisms operated effectively: the faulted section was isolated promptly via breaker tripping, and the converters entered safe shutdown modes to prevent damage or instability.

A comparison between the two fault scenarios reveals important distinctions. During the three-phase fault, the entire AC supply collapsed, resulting in an immediate cessation of both active and reactive power flows. This full disconnection led to a clean and predictable system response with all power flows dropping to zero. In contrast, the single-phase fault caused unbalanced voltage conditions. As a result, although the active power delivered to the PtX system was significantly reduced, it did not drop to exactly zero. Additionally, nonzero reactive power was briefly observed—likely induced by the phase imbalance and asymmetrical loading—before the system was isolated.

These observations highlight a key difference: symmetrical faults lead to uniform, total shutdown behavior, whereas asymmetrical faults can generate complex voltage and current responses. The presence of transient reactive power during the single-phase event underscores the importance of robust phase-sensitive control and protection schemes, especially in inverter-dominated systems. Overall, the simulation results validate the PtX system's capacity for both dynamic power control and fault ride-through, while also identifying areas for future controller refinement under asymmetrical fault conditions.

While the simulation results demonstrate the basic robustness of the PtX system under fault conditions, the current configuration exhibits a critical limitation: the entire load depends on a single PWM rectifier path. Consequently, a single fault or breaker trip in the AC-side interface results in a complete loss of power delivery to the downstream DC system and electrolyzer. This "all-or-nothing" behavior may not be acceptable in practical large-scale PtX deployments, especially where high availability is required.

To address this issue, several parallel or redundant converter configurations can be considered:

- **N+1 Redundancy:** One or more additional PWM converter units are installed in parallel but normally idle. In the event of a primary converter failure, a backup unit is activated to take over the load.
- **Static Parallel Operation:** Multiple PWM converters operate in parallel continuously, each sharing a portion of the load. If one unit fails, the others automatically increase their output to compensate. This configuration improves reliability and reduces thermal stress.
- **Modular Multi-Port Design:** The PtX system is split into multiple modular converter-load subsystems, each independently connected to the AC grid. Local failures do not affect the entire system, improving both fault tolerance and maintainability.
- **DC Bus Coupling with Isolation:** Separate converter units supply a shared DC bus with interposing isolation and protection devices. This enables dynamic load sharing and localized fault isolation.

Implementing any of these schemes would increase the system's resilience by ensuring that a single point of failure—such as a fault in one converter path—does not lead to a complete interruption of hydrogen production. Future studies should explore these configurations and assess their impact on dynamic control coordination, protection logic, and cost-effectiveness.

Chapter 6

Conclusion and Future Work

1 Conclusion and Future Work

1.1 Conclusion

This thesis investigated the modeling, control, and grid-integration performance of PtX systems with a focus on dynamic behavior under realistic operating conditions. A modular, physics-informed PtX model was developed and implemented in DIgSILENT PowerFactory, including detailed representations of PWM-based rectification, DC/DC voltage regulation, and a PEM electrolyzer with thermal and pressure dynamics.

Three simulations were conducted to assess the system's performance in different dynamic scenarios. The first experiment validated the system's ability to track a ramped active power reference under a slope limit of 60 MW/min. The results demonstrated that all control layers—the PWM rectifier, DC/DC converter, and electrolyzer—functioned in coordination, with each module fulfilling its designated role: power tracking, voltage stabilization, and current regulation, respectively.

The second and third experiments introduced grid faults: a three-phase-to-ground fault and a single-phase-to-ground fault. In the case of the symmetrical fault, the system experienced a complete collapse of AC voltage and an immediate shutdown of the DC-side loads. The response was clean and predictable, with both active and reactive power dropping to zero. In contrast, the asymmetrical fault led to a more complex behavior: the system experienced phase imbalance, partial power delivery, and a brief presence of reactive power before protection devices isolated the fault. This comparison highlights that asymmetrical faults pose unique challenges for converter-based systems, especially with regard to maintaining voltage symmetry and stable current injection.

While the simulation results confirm that the modeled PtX system is capable of reliable operation and effective fault ride-through, a critical limitation was observed: the entire load is connected through a single PWM rectifier. As a result, any fault on the AC side leads to a total shutdown of the hydrogen production process. This architecture, while suitable for demonstration and analysis, lacks the redundancy required for real-world deployments.

1.2 Future Work

To improve the reliability and resilience of PtX systems in practical applications, future research should explore enhanced topologies with built-in redundancy. Several possible strategies include:

- **N+1 Redundancy:** Standby PWM units can be automatically activated when a primary unit fails.
- **Static Parallel Operation:** Multiple PWM converters operate in parallel and share the load. Upon failure, others can ramp up without system interruption.
- **Modular Multi-Port Design:** PtX loads are distributed among multiple independently-controlled converter modules, improving fault isolation and scalability.
- **DC Bus Coupling with Protection:** Parallel PWM units feed a common DC bus with interposing protection devices to allow selective fault isolation.

Additionally, future work should incorporate:

- EMT-level modeling for harmonic and transient impact analysis,
- Integration of reactive power control strategies and fault current limiting functions,
- Experimental validation of the model in hardware-in-the-loop or laboratory-scale setups,
- Application of more advanced fault detection and self-healing control logic under phase-selective disturbances.

These developments would further enhance the applicability of PtX systems for grid-support functions and reinforce their role in future low-carbon, high-renewables power systems.

References

[1] Y. Dong, H. Wang, Q. Li, Y. Wang, J. Chen *et al.*, “Identifying the system-related conditions and consequences of power-to-x solutions for a high renewables penetration in denmark,” in *2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)*, 2020, pp. 955–960.

[2] C. Breyer, S. Khalili, D. Bogdanov, M. Ram, A. S. Oyewo, A. Aghahosseini, A. Gulagi, A. A. Solomon, D. Keiner, G. Lopez, P. A. Østergaard, H. Lund, B. V. Mathiesen, M. Z. Jacobson, M. Victoria, S. Teske, T. Pregger, V. Fthenakis, M. Raugei, H. Holttinen, G. Bardi, and A. Hoekstra, "On the history and future of 100% renewable energy systems research," *IEEE Access*, vol. 10, pp. 78 105–78 132, 2022.

[3] D. S. Falcão and A. M. F. R. Pinto, "A review on pem electrolyzer modelling: Guidelines for beginners," *Journal of Cleaner Production*, vol. 261, p. 121184, 2020.

[4] P. Haug, B. Kreitz, M. Koj, and T. Turek, "Process modelling of an alkaline water electrolyzer," *International Journal of Hydrogen Energy*, vol. 42, no. 23, pp. 15 689–15 707, 2017.

[5] R. Sarrias-Mena, L. M. Fernández-Ramírez, C. A. García-Vázquez, and F. Jurado, "Electrolyzer models for hydrogen production from wind energy systems," *International Journal of Hydrogen Energy*, vol. 40, pp. 2927–2938, 2015.

[6] A. Awasthi, K. Scott, and S. Basu, "Dynamic modeling and simulation of a proton exchange membrane electrolyzer for hydrogen production," *International Journal of Hydrogen Energy*, vol. 36, no. 22, pp. 14 779–14 786, 2011.

[7] J. F. Manwell and J. G. McGowan, "Modelling energy storage, electric vehicles and power-to-x in a large scale hybrid offshore wind power system," in *7th Offshore Energy & Storage Symposium (OSES 2023)*. The Institution of Engineering and Technology (IET), 2023.

[8] A. Fathollahi and B. Andresen, "Power quality analysis and improvement of power-to-x plants using digital twins: A practical application in denmark," *IEEE Transactions on Energy Conversion*, 2025.

[9] B. Han, S. M. S. III, J. Mo, and F.-Y. Zhang, "Electrochemical performance modeling of a proton exchange membrane electrolyzer cell for hydrogen energy," *International Journal of Hydrogen Energy*, vol. 40, pp. 7006–7016, 2015.

[10] A. P. Fitrah, "Grid stability studies of electrolyzer-based energy storage integration," 2022.

[11] H. Holttinen, J. Kiviluoma, D. Flynn, J. C. Smith, A. Orths, P. B. Eriksen, N. Cutululis, L. Söder, M. Korpås, A. Estanqueiro, J. MacDowell, A. Tuohy, T. K. Vrana, and M. O'Malley, "System impact studies for near 100% renewable energy systems dominated by inverter based variable generation," *IEEE Transactions on Power Systems*, vol. 37, no. 4, pp. 3249–3258, 2022.

[12] J. Riofrio, S. You, and T. Weckesser, "Navigating grid challenges: Voltage-reactive power control in the integration of power-to-x facilities," in *2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Europe, 2024.

[13] ——, “Power-to-x (ptx) integration in modern power systems: Exploring grid code compliance and technical requirements in denmark and the united kingdom,” in *22nd Wind & Solar Integration Workshop (WIW)*, Copenhagen, Denmark, 2023.

[14] B. W. Tuinema, E. Adabi, P. K. S. Ayivor, V. G. Suárez, L. Liu, A. Perilla, Z. Ahmad, J. L. R. Torres, M. A. M. M. van der Meijden, and P. Palensky, “Modelling of large-sized electrolysers for real-time simulation and study of the possibility of frequency support by electrolysers,” *IET Generation, Transmission & Distribution*, vol. 14, no. 10, pp. 1985–1992, 2020.

[15] F. Alshehri, V. G. Suárez, J. L. R. Torres, A. Perilla, and M. A. M. M. van der Meijden, “Modelling and evaluation of pem hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems,” *Heliyon*, vol. 5, p. e01396, 2019.

[16] N. S. Sahan and A. Khalil, “Provision of frequency containment reserve from ptx plant in a low inertia grid,” in *2025 7th Global Power, Energy and Communication Conference (GPECOM)*, Bochum, Germany, Jun. 2025, pp. 476–481.

[17] B. Barać, M. Krpan, and T. Capuder, “Modelling of pem fuel cell for power system dynamic studies,” *IEEE Transactions on Power Systems*, vol. 39, no. 2, pp. 3286–3296, 2024.