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Technical Assessment of Large Scale PEM Electrolyzers as Flexibility Service Providers

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***Abstract*—To counter the inherent intermittent and unpredictable power generation from large amounts of wind and solar, fast-acting resources are required, one of the options being sector coupling via power to gas devices. Industrial Power to Gas (IPtG) resources, such as an electrolyzer, represent an attractive solution to satisfy the rising energy flexibility needs of renewable-rich power systems. Since these electrolyzers can be asked to respond quickly following steep power ramps of renewables, it is imperative to understand their capabilities and limitations in fulfilling such requirements. The contribution of this paper is twofold. First, we introduce a detailed model of a Proton Exchange Membrane (PEM) electrolyzer suitable for power system flexibility studies. Second, using this model we assess large scale electrolyzer as a flexibility service provider (FSP) to the grid. To evaluate electrolyzer performance, we construct the V-I characteristic curve before and after simulating each test case to derive insights on the influence of time and dynamic operation on the electrolyzer system.**

***Index Terms*—power to gas, electrolyzers, industrial hydrogen, modelica, degradation**

I. Introduction

A recent report by the Port of Rotterdam on decarbonization pathways for its industrial complex listed sector coupling between electricity and gas as one of the most viable options [1]. Industrial electrolyzer systems can potentially replace the natural gas-powered systems used to generate hydrogen and other industrial chemicals such as ammonia [2]. In addition to decarbonization, electrolyzers can also be operated flexibly to support the electrical grid. Thus, electrolyzer systems can be useful assets to counter the unpredictable variations from increasing amounts of wind and solar power generators. In an industrial setup where the size of the installations is relatively larger than domestic ones, intelligent demand response from these devices can help to integrate larger amounts of fluctuating renewable energy.

To perform a technical analysis of a system, a key requirement is the identification of stakeholders within the system, determining their viewpoints, and addressing them [3]. In the majority of the sector coupling studies, the key stakeholders are the device owner (DO) and the grid manager (GM). For example, in an industrial setup involving P2X resources, the DO (stakeholder) would want to test various control strategies for their system, its impact on the device wear-and-tear, the monetary gains achieved, etc (viewpoints). The GM (stakeholder) will find it more useful to analyze the impact of operating such a large electrical load flexibly on system metrics such as voltage and line congestion (viewpoints). As will be shown in Section II, most sector coupling studies focus either entirely on the device physics [4], which leads to simplifications on the grid side, or focus on the grid side dynamics [5], simplifying the device physics. A methodology that addresses viewpoints from each stakeholder is missing.

This paper investigates the impact on flexibility service provision by electrolyzer systems on the device and the grid. In particular, the goal is to show technical efficiency, and limitations of electrolyzer systems to provide energy flexibility. This is done by using detailed models for both the electrolyzer and the grid. A co-simulation based methodology is used to assess the viewpoints of different stakeholders in a multi-energy setup. The paper is divided as follows: Section II highlights the previous work and relevant literature on P2X resources being utilized for energy flexibility provision in industrial setups. In Section III, the physical model used for analyzing the electrolyzer is detailed. Section IV develops the case studies on which the detailed model is assessed and discusses the results obtained from evaluating these study cases. Section V provides conclusions.

II. Background

Flexibility provision via sector coupling studies can be divided into three categories. The first category includes studies that focus on the electrical grid side, modeling the flexible resource as a ramping load. In [5], the electrolyzer was used as a fast ramping resource to provide frequency regulation. The focus of there was on the impact of the electrolyzer from a grid perspective, and so the grid was modeled in detail, while the electrolyzer system is simplistically modeled as constant power load with a high ramp rate. Similarly, in [6], the authors model the grid in detail with power converters, and other components, while the electrolyzer is seen as a constant power load. In [7], the authors formulate a centralized dispatch problem for the hybrid energy system with combined heat and power (CHP), electric boilers (EB), and storage. They develop simplified linear models of the components and formulate a dispatch strategy to reduce wind power curtailment by absorbing the variations in EB and storage. The second category includes studies that focus strongly on device physics, ignoring the grid entirely. For example, in [8], the authors develop a detailed model of the electrolyzer cell, and the analysis focuses on how grid signals will affect the device performance. The third category includes studies where the focus is made on energy carrier coupling via P2X devices. Here, the discussions on the multi-energy system tend to ignore the P2X device completely. The concept of energy hub was proposed in [9], to assess multiple energy carriers. The linking between energy carriers is done via a transformation matrix, consisting of energy conversion factors of the energy transformers.

A problem with the energy hub approach to multi-energy systems is insufficient model detail. This can severely affect the results for cases where device degradation or operating conditions can not be represented by efficiency factors. It has been shown in [10] that simplifications in model definition can limit system analysis and the results obtained thereon. Examples of such simplifications include neglecting dynamic system interactions between components, incorrect linearization of important non-linear characteristics of physical systems, etc. It is common in flexibility analysis studies, that the domain-specific knowledge plays a crucial role in defining model fidelity, modeling assumptions, and the study setup. This inevitably leads to loss of model detail on some sides.

As elaborated before, a technical analysis must address all stakeholders, while considering component level dynamics. The main focus of this research is therefore on analyzing the impact that the grid has on the electrolyzer, and conversely, the impact that the electrolyzer has on grid supporting strategies. We observe the impact of the dynamic operation of the PEM electrolyzer in short term and long term on its degradation. To achieve this, we develop a detailed model for the electrolyzer and the grid. There exist three main technologies for electrolyzer systems: Alkaline, Proton Exchange Membrane (PEM), and Solid Oxide Fuel (SOF) electrolyzers. Each of these has its pros and cons when it comes to flexibility service provision. [8] provides an exhaustive study on these cell technologies concerning their use as coupling devices for sector coupling and grid balancing services. The motivation to select a particular cell technology is based on our case study: an industrial setup where large scale electrolyzers are used to produce hydrogen for chemical production, while also providing flexibility services to the grid.

In such a case, the important factors to consider for the involved stakeholders (DO, and the GM) are capacity of the electrolyzer system (GM), ability to quickly respond to power set-points (GM), safety and reliability in hydrogen production capability (DO), size of the system (DO). As per [8], the PEM electrolyzer is a compact system, which can be scaled to MW size reliably. It is also well more reliable and safe than alkaline electrolyzers for hydrogen production. Additionally, the fast dynamics of the PEM cell make it a good candidate for grid balancing services. These factors lead us to select the PEM cell for our study.

III. The PEM electrolyzer

A detailed model of the electrolyzer is presented in this section. The developed electrolyzer model will then be used to evaluate the ability of the electrolyzer in serving power system flexibility needs. Since the electrolyzer unit is composed of various cell stacks connected together, we model a single electrolyzer cell and scale it appropriately to achieve the required power rating for our case studies.

A. Losses in electrolyzer

The electrolysis process is never a 100% efficient reaction. The cell efficiency is given by Eq. (1)

$$\eta_{cell} = \frac{E_{cell}}{E_{total}} \cdot 100\% \tag{1}$$

where, E_{cell} is required reversible cell voltage to make electrolysis happen, and E_{total} is the sum of cell potential and cell overpotentials (activation, ohmic, and concentration) that cause losses.

B. Cell Potentials

The cell potential E_{cell} is a function of cell temperature and is given by Eq. (2). The coefficients are taken from [11].

$$\begin{aligned} E_{cell}(T_{cell}) = 1.5148 - 1.5421 \cdot 10^{-3} \cdot T_{cell} + \\ 9.523 \cdot 10^{-5} \cdot T_{cell} \cdot \ln T_{cell} + \\ 9.84 \cdot 10^{-8} \cdot T_{cell}^2 \end{aligned} \tag{2}$$

The three overpotentials in an electrolyzer cell are highly non-linear in formulation. Thus, to simplify the model, activation and ohmic overpotential are linearized, while neglecting the effects of saturation overpotential. This assumption is based on the idea that the internal control of the electrolyzer does not allow the cell to be saturated under any operating condition. The linearized activation overpotential depends on the input current of the cell and is given by Eq. (3). For derivations of linearization of cell potentials, the reader is directed to [12].

$$E_{act} = 0.0514 \cdot I_{cell} + 0.2798 \tag{3}$$

The linearized ohmic overpotential is given by Eq. (4).

$$E_{ohm} = 0.09 \cdot I_{cell} \tag{4}$$

Eq. (1) can now be re-written as Eq. (5).

$$\eta_{cell} = \frac{E_{cell}}{E_{cell} + E_{act} + E_{ohm}} \cdot 100\% \tag{5}$$

C. Voltage degradation

Over time, especially with dynamic use, the wear and tear of the electrolytic cell membrane is inevitable. This results in an increase in the ohmic overpotential in PEM cells over time as electrolysis goes on. According to [8], the ohmic overpotential increases approximately at the rate of 2-3 µV/hr for the duration of its lifetime.

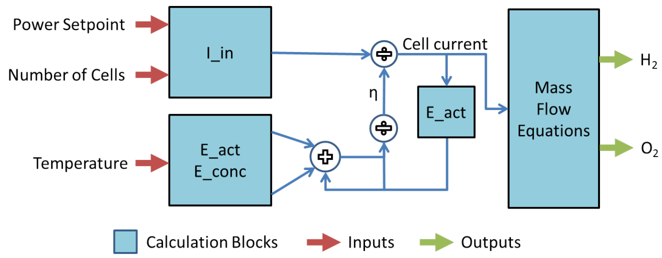

Fig. 1: electrolyzer Model

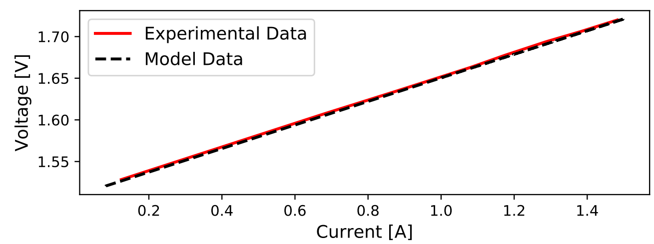

Fig. 2: Validation of the PEM electrolyzer cell model.

D. Cell Current

The power injected into the electrolyzer is equally divided over each cell, thus the cell power (P_{cell}) is equal to the total power injection (P_{elec}) divided by the number of cells (N_{cells}). The total current input into the cell stacks is then determined by Eq. (6).

$$I_{cell} = \frac{P_{cell}}{E_{cell} + E_{act} + E_{ohm}} \cdot \eta_{cell} \tag{6}$$

E. Mass Flow Rates

Faraday's law of electrolysis can be used to determine the amount of hydrogen mass and oxygen mass that will be produced at the outlet of an electrolyzer cell. This is given by Eq. (7).

$$\begin{aligned} H_{2,produced} &= \frac{M_{H2} \cdot I_{cell}}{z \cdot F \cdot \rho_{H2}} \\ O_{2,produced} &= \frac{M_{O2} \cdot I_{cell}}{z \cdot F \cdot \rho_{O2}} \end{aligned} \tag{7}$$

where M_x for the molar mass of the element x, I_{cell} the current flowing through the cell, z is the number of electrons transferred, F is the Faraday's constant (=96485), and ρ is the density of the produced gas. Eq. (7) gives the amount of gas produced in m^3 per second. The volume of gases produced can be calculated by multiplying Eq. (7) by the number of cells (N_{cells}), as given in Eq. (8).

$$\begin{aligned} H_{2,total} &= N_{cells} \cdot H_{2,prod} \\ O_{2,total} &= N_{cells} \cdot O_{2,prod} \end{aligned} \tag{8}$$

F. Parameterisation of electrolyzer

The electrolyzer is first modeled as a single PEM cell as shown in the previous section. Although the cells can be operated between 0-5W, the nominal power of the cell is set at 2W. The PEM electrolyzer cells generally operate around 50°-90° Celsius. In this study, the electrolyzer cell is operating at atmospheric pressure (1 atm) and a temperature of 80° Celsius (353.15 K). The model is expanded to a large scale electrolyzer by multiplying the number of cells required to obtain the desired rated power. For simplifications, the behavior and output of a single cell is not affected by other cells; the behavior and output of a single cell will be simply multiplied by the number of cells.

The nominal power of the electrolyzer is set at 10MW, with the ability to sustain up to 150% of its rated power (equal to 15MW). Though a PEM based electrolyzer can easily be switched off and quickly, cold-started, we define the minimum load as 5MW. This is due to two reasons: firstly, to avoid the cell degradation caused by repetitive cycling of the electrolyzer and secondly, to maintain gas production (since this is an industrial electrolyzer whose main responsibility is to fulfill a gas load demand). The maximum and minimum ramp rate is limited to 500kW/s. Under dynamic operation, the cell potential of the electrolyzer changes constantly. A flexible AC/DC conversion is required to constantly adapt to the fluctuating potential levels. It is assumed for this model that the AC/DC conversion is always optimal, 100% efficient, and always results in a perfect voltage level. The model is shown in Fig. 1.

G. Model Validation

The authors in [13] developed a linearized PEM cell model that was validated against a real PEM cell in an experimental setup. The results demonstrated an excellent fit. Since it is not possible to obtain experimental data, we validate our model with the results obtained from [13] to determine the accuracy of our model. As can be seen in Fig. 2, our model response is similar to that of the model in [13], corroborating our model representation.

IV. Study Case and Results

Three use cases (UC) are developed to assess the electrolyzer performance as a FSP and analyze the impact that this has on the electrolyzer itself. These are discussed in more detail in the following subsections.

A. UC1: Frequency regulation

In this UC, we evaluate the performance of the electrolyzer system as a frequency regulation device. The electrolyzer setup has a control system in place to regulate its operation. Technically, a large electrolyzer system, such as the 10 MW system used in our case, is made up of smaller stacks of cells that can individually be controlled within 0-100% of its power range very quickly, with overloading to 150% of nominal power allowed. In this use case, we provide the electrolyzer system with a continuous 40-minute regulation signal (Reg-D) obtained from PJM [14] and observe the system response. The regulation signal is given in pu and it ranges between -1.0 and

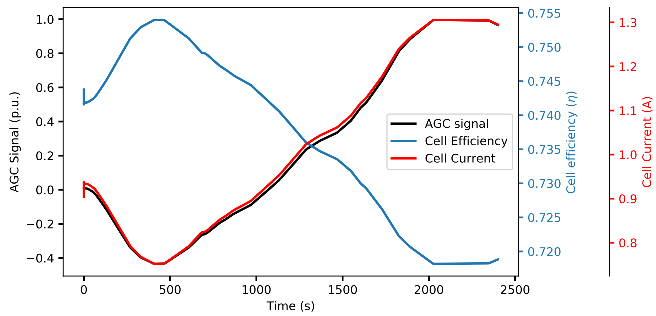

Fig. 3: electrolyzer cell performance given the AGC signal.

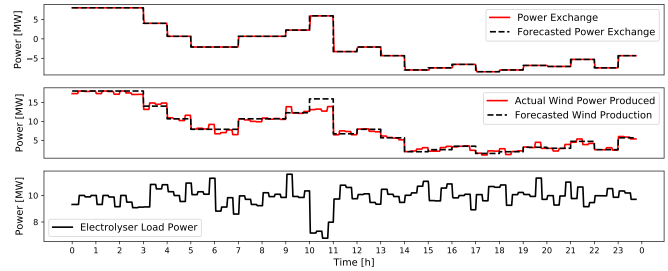

Fig. 4: The top figure shows forecasted Bus power and actual bus power exchange. The middle figure shows the actual wind and forecasted wind. The bottom figure shows load setpoints for electrolyzer.

1.0. To obtain the power reference, we multiply this signal by the regulation capacity R MW (=5MW) plus the regulation baseline B MW =(10MW). The R+B MW is then the input power for the electrolyzer system.

To measure the performance of the cell, the correlation between electrolyzer cell current and efficiency versus the AGC signal is observed. The response is shown in Fig. 3. The electrolyzer system can continuously follow the AGC signal accurately over the 40-minute duration. This implies that the cell dynamic response is adequate for using it as a frequency regulation device since it responds quickly to changes in the AGC signal. To measure the electrolyzer degradation, we plot the cell V-I curve before and after simulation in Fig. 5. Since both the curves are almost identical, we can conclude that almost no degradation of the cell took place in providing the regulation service over 40 minutes. Thus, from a power system point of view, a constant power load with high ramping requirements can be used to model the electrolyzer system in grid studies for a short duration of time.

B. UC2: Flexibility Provision

In this UC, we evaluate the electrolyzer system as an FSP to correct wind forecast errors throughout the day to help maintain grid balance and avoid imbalance costs. If we assume the role of an aggregator responsible for managing the energy use within the grid, the DO and the GM (as mentioned in Section II) become the two stakeholders in this UC. We already have the model for the electrolyzer, and for the electrical grid, we use the CIGRE MV grid (taken from [15]). The MV network with 18 loads is modified and two wind power parks (WPP) with rated powers of 21 MW and 18 MW are connected at Bus 1 and Bus 12 respectively. The 18 MW WPP is supported by a 10 MW electrolyzer described in Section III. The electrical grid is modeled in Python-based PANDAPOWER.

The performance of electrolyzer to respond within seconds to regulate frequency was analyzed in the last section, hence, in this case, we assume that the wind power forecast is constant over the 15 minute Program Time Unit (PTU) to focus on the ability of electrolyzer to correct errors. To absorb the wind forecast errors, we need to control the electrolyzer power set-point such that operational constraints for the electrolyzer system and the grid are not violated. Since the electrolyzer and the grid are modeled in different programs and operate in different ways (electrolyzer system is a dynamic continuous-time model, while the electrical grid is a static-time power flow model), we use co-simulation based methodology for analysis. The co-simulation tool used is ENERGYSIM, (previously FMUWORLD) [16]. The choice is motivated by the fact that this co-simulation tool is tailor-made for multi-energy system studies. It allows users to focus on high-level tasks such as model development, use case definition rather than setting up low-level co-simulation tasks such as time management, message exchange, etc.

As is shown in Fig. 4 the actual power exchange at the point of common coupling is maintained equal to the forecasted power exchange (derived from the wind power forecasts). This is achieved despite the wind power fluctuating from its forecasted value by controlling the flexible electrolyzer. The electrolyzer power setpoints are shown at the bottom of Fig. 4, highlighting its dynamic operation throughout the day. At the end of the day, total energy deviations in the electrolyzer operation are calculated and thus, the energy flexibility is quantified. This quantified energy can be used to remunerate the DO for providing flexibility to the aggregator. The total energy flexibility provided by the electrolyzer during the day, in this case, is calculated to 12.91 MWh from the simulations.

To observe the device health, we construct the V-I curve as is shown in Fig. 5. Comparing the V-I curve before and after full day simulation shows that the difference between two curves is still negligible, and is very similar to UC1. This implies that the dynamic operation of the cell does not degrade the cell, even when operated dynamically throughout the day.

C. UC3: Long term impact analysis

Most energy system planning tools that optimize system operation over a longer time, use simplistic models of energy conversion systems. For example, PLEXOS, TIMES, etc. Even tools that do take care of short term variations into long term planning models, like OESMOSYS, do not take into account the impact of variability on the resource itself. Thus, the valuation of demand response flexibility from the said resource can be under- or over-estimated. In this UC, we

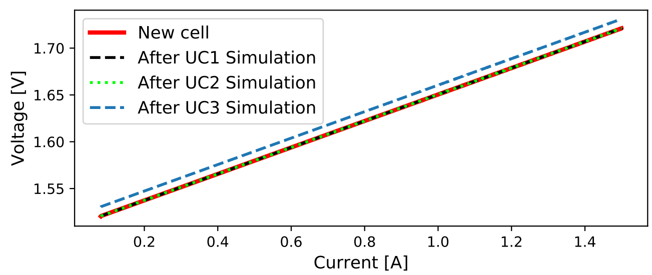

Fig. 5: Effect on device for the three UCs.

derive insights from the detailed electrolyzer model regarding how the electrolyzer dynamics alter the ability of the resource to offer flexibility services.

UC1 and UC2 showed little correlation between cell degradation and dynamic operation. Nonetheless, another form of degradation comes from continuous use and wear-and-tear, which may affect the device's ability to provide flexibility. To analyze this, we operate the electrolyzer in a constant current mode for 1 year. Fig. 5 shows a shift of the V-I curve from the original curve for UC3, signaling cell degradation. With the input current of 1.2A, the new cell voltage is 1.6V, increased from 1.58V. The efficiency of the cell, as calculated by Eq. (1), now becomes 73.6 % compared to 74.4%. Therefore, to produce the same amount of hydrogen, the current, and hence, the power required will increase. Since the flexibility band remains fixed around the original nominal power of the 10MW, the flexibility available will change as well. The efficiency drop in cell performance is more pronounced over a longer duration (for example, over a 5-year duration, the cell efficiency drops by almost 3.5%). Since the amount of flexibility provided by the electrolyzer is determined by the fixed band within which the power set-point can be varied, this drop in efficiency will impact operations in UC1 and UC2 as well over the long term.

V. Conclusions

In this paper, we performed a technical analysis of the ability of large scale PEM electrolyzer to provide grid balancing services. This was done by creating detailed models for the PEM electrolyzer and grid. Three use cases were defined that assessed the PEM electrolyzer under various operating conditions and the impact on both the grid and the electrolyzer was measured. It was seen that the PEM electrolyzer cell is well suited to provide balancing services to the grid. Its fast dynamic response can help in providing frequency regulation services, while its efficient and safe part-load operation can be used to correct wind forecast errors throughout the day. It was shown that dynamic operation has a negligible impact on degradation. Additionally, co-simulation based analysis was shown to be an effective tool for technical analysis of a multi-energy system involving multiple stakeholders. The wear-and-tear of the cell was noticeable in the third case, where the cell was operated for a full year. The drop in cell efficiency, as well as cell current, were noted. It was concluded that this efficiency drop needs to be incorporated in the long term strategy of the short term balancing service models, to avoid incorrect assessment of flexibility.

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