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Experimental Analysis and Modelling of an AEM Electrolyzer

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Abstract. Anion Exchange Membrane (AEM) electrolysis is a relatively recent technology that is gaining popularity due to its technical advantages over traditional alkaline electrolysis and its closer similarities to Proton Exchange Membrane (PEM) electrolysers. Both AEM and PEM technologies hold significant potential to address future integration challenges in renewable energy systems for green hydrogen production. However, research on AEM is still very limited.

To address this issue, a comprehensive experimental analysis based on a variety of test scenarios has been conducted on a 2.2 kW commercial AEM electrolyser. The proposed test benches cover a range of conditions, from steady-state operation at various power levels to demanding dynamic and transient scenarios, including photovoltaic energy tests. Furthermore, an experimentally validated Anion Exchange Membrane water electrolyser (AEMWE) model has been implemented to simulate the electrochemical properties under these test conditions. The proposed AEMWE electrochemical model integrates the stack voltage, hydrogen production and efficiency simulations based on a classical parametric approach on the MATLAB-Simulink software. Consequently, the proposed experimental analysis and model validation has the potential to successfully simulate and control green hydrogen production based on AEMWE technology under real-word conditions, thus providing greater clarity in this field.

Key words. AEM electrolyzer, Green hydrogen, Renewable energy, modelling.

1. Introduction

The Global Hydrogen Review [1] highlights that green hydrogen production experienced a remarkable 50% growth from 2021 to 2024, achieving a total of 5.2 GW of installed electrolyzer power. The primary electrolyzer technologies leading this advancement include alkaline and Proton Exchange Membrane (PEM), which is currently expanding to higher power scales on the order of megawatts [2]. In contrast, Anion Exchange Membrane electrolysis (AEMEL) is starting to be introduced in low-power applications with good future prospects.

On the one hand, PEM electrolysis (PEMEL) provides clear advantages over traditional alkaline systems in terms of start-up times and response dynamics, thus enhancing the compatibility with fluctuating renewable energy inputs. On the other hand, AEM electrolysis strikes a good balance by offering comparable dynamic responsiveness to PEM, avoiding the need for highly concentrated electrolytes seen in alkaline technology, while reducing reliance on expensive precious metals for electrodes. Its fast response characteristics, good performance and lower cost compared to PEMEL is an attractive opportunity for future AEMEL development, power scalability and applications.

2. State of the art

Alkaline electrolysis has been traditionally the most extended technology for green hydrogen production, and that legacy is still dominant in the present. Its good efficiency characteristics and reliable performance have increased its popularity for large-scale, commercial hydrogen production. This relevant position in the industry translates as well to a higher number of studies on the scientific field. However, alkaline electrolysis is known to have a poor dynamic response and high thermal inertia, thus increasing the time and cost of start-stop operations and limited responsiveness to changes in power demand set-points. With the deployment of renewable energy sources and the challenges driving a transformation in the energy sector, there is a strong demand for more flexible electrolysis solutions. Among the most recent electrolysis technologies, PEMEL is the more mature technology, while AEM is gaining popularity as a more cost-effective solution. However, as the youngest of the three technologies, still ranging between the prototype stage and low-power commercial scales, it remains a relatively scarce topic in the literature, especially in dynamic performance testing and availability of experimental data [3].

Regarding AEMEL modelling, numerical models specifically developed for AEM electrolysers are very scarce in the literature [4]. In fact, studies are mainly focused on the chemical research of the stack internal components such as the electrodes, membrane and charge transfer dynamics [5]. Conversely, a well-established topic in PEM literature is the electrochemical analysis of the stack unit, which focuses on cell voltage [3]. Considering the electrochemical similarities between PEM and AEM, advancements on the PEM field can serve as a foundation for AEM electrochemical modelling.

The present work explores one of the most recent electrolyzer technologies, AEM, to provide some insights about its operating procedure, ramp-up times, as well as an experimental analysis of the unit under diverse conditions (steady-state, dynamic) of varying nature (constant, step, photovoltaic power profiles). Furthermore, an electrochemical AEM model has been developed and experimentally validated with up to 100 hours of real-world data with good results. In this model, advanced data analysis techniques and algorithms such as neural networks, are being used to provide better accuracy and potential for a generalized model approach, with an emphasis on performance under steady-state conditions. This is a relevant step in the field, as experimental validation and advanced modelling techniques still fall short in both PEM and AEM electrolysis, especially for the latter.

3. Methodology

This work comprises two main aspects of AEMEL. Firstly, an experimental analysis of the unit has been conducted through several test procedures following a multi-objective criteria: stack operational characterization via a polarization curve and stationary tests, as well as the dynamic performance of AEMEL under photovoltaic renewable energy profiles. Furthermore, the operating procedure and start-up times have been included. Secondly, results obtained from an experimentally-validated AEMEL electrochemical model are presented. In this case, the methodology followed by the model is explained below.

The present AEM electrochemical model has been developed in the MATLAB-Simulink software under a classical parametric approach, which utilizes first principles and semi-empirical algebraic equations. In this sense, the input of the model is the stack current, and the stack voltage is the target variable to be predicted. The influence of stack temperature has also been considered in the equations of this model. The stack current determines the hydrogen production rate. Furthermore, instantaneous stack power and efficiency parameters are derived from the previous model.

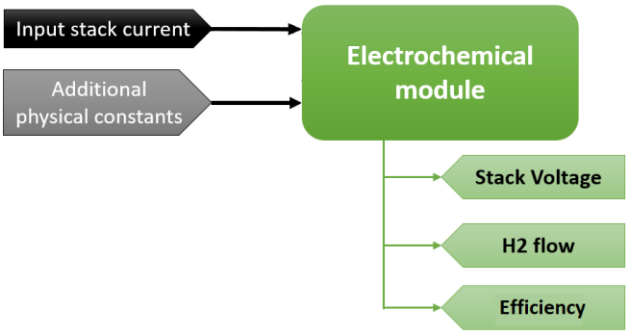

Fig. 1. Block diagram of the proposed model.

Figure 1 shows the general block diagram of the model. In addition to the input stack current, the electrochemical module considers additional physical constants that are distinctive to AEM electrolysis. After these coefficients are appropriately calibrated during the model tuning process, they become transparent to the end user.

The present Simulink model has been tuned to provide the best accuracy at nominal power in steady state, that is, 2.2 kW for the AEMEL utilized in this experiment. This condition ensures good performance under the most frequent operating conditions for maximum H2 production. Moreover, the time resolution of the model has been set to 60 seconds.

4. Experimental analysis of AEMEL

A Start-up times

Regarding the start-up times of the stack, two different approaches can be applied: cold start or warm start. The faster method to reach steady-state is the cold start, where the AEMEL studied is capable of start-up times of 20 minutes. However, in order to preserve the lifespan of the system, warm starts are preferred whenever possible. In this scenario, a 45-60 min preheat mode is activated to increase the electrolyte temperature from 25 to 40 °C. Once preheat has finished, the AEMEL is able to perform a faster, less stressful start-up of 8 min to reach steady-state.

B Experimental test procedures

The present AEM model has been validated with experimental data from a commercial 2.2 kW electrolyzer made by Enapter, product EL 4.1. The main technical specifications can be seen in Table 2. This unit has a fixed range of operating conditions for hydrogen production over 60% of nominal power, and a temperature control system that ensures a stable set point of 55 ° C.

Table 1. Enapter EL4.1 technical specifications.

Parameters	Value and units
Nominal H2 production	8.3 NL/min
Max. output pressure	35 bar
Max. operating power	2.4 kW
Water consumption	400 mL/h
Water input pressure	1-4 bar
Dimensions	266 x 482 x 635 mm
Input Voltage (AC version)	210-240 V

The experimental validation comprises a wide variety of operating conditions for the AEM electrolyser that can be classified into three categories:

1) Long-term stationary tests: The AEM electrolyser operates at a fixed power level for several hours to capture highly stable values at operating temperature. Therefore, 5 experiments at 1.32, 1.54, 1.76, 1.98 and 2.2 kW have been conducted with a duration of 5 hours each.

2) An operation curve to analyze the steady-state response of the system: In our test, a sequential step current input with an amplitude of 0.5 A ranging from 32 to 53 A has been applied for a high-resolution capture. The settling time for each step has been set to 3 minutes.

3) A solar-powered photovoltaic scenario to test the dynamic response, including a cloudy winter profile.

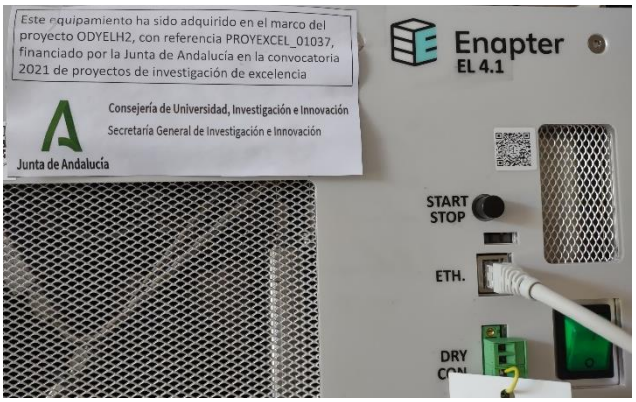

Fig. 2. AEM electrolyzer unit used in this work (Enapter, model EL 4.1).

5. Model development

The AEMEL electrochemical model follows a classical parametric approach derived from first-principles. As the starting point, the cell voltage of a generalized electrolyzer can be expressed in Eq. 1:

$$V_{cell} = V_0 + V_{act} + V_{ohm} + V_{ion} \quad (1)$$

Where V_0 is the reversible voltage, V_{act} the activation potential, being V_{ohm} and V_{ion} the ohmic and polarization voltages, respectively. The former two terms are a function of the stack temperature, the partial pressures of hydrogen and oxygen products, anode and cathode current density contributions and membrane thickness and conductivity. In contrast, the latter two terms are not influenced by temperature. As a final step, the cell voltage is multiplied by the number of cells present in the AEM stack.

The oxygen flow rate is expressed in Eq.2 as follows:

$$F_{O2} = \frac{\eta_{far} \cdot I \cdot n \cdot 22{,}4 \cdot 60}{4 \cdot F} \quad (2)$$

Where I is the stack current, n the number of cells, η_{far} the Faraday efficiency and F the Faraday constant (C/mol). In our case, the AEM stack is composed of 23 cells. Finally, the hydrogen flow is derived directly from the 2:1 stoichiometric relationship between hydrogen and oxygen in water.

In order to calculate the instantaneous stack efficiency, both the electrical power applied to the stack and the produced hydrogen energy, as included in Eq. 3:

$$\eta_{stack} = \frac{33{,}33 \cdot 2 \cdot V_{H2} \cdot (R \cdot T_{nc})^{-1}}{V_{stack} \cdot I} \quad (3)$$

Where V_{H2} represents the hydrogen volume produced in normal-liter, R the ideal gas constant in atm·l/mol·K) and T_{nc} the temperature in normal conditions expressed in kelvin. In this formula, the lower heating value (LHV) of hydrogen is considered. As for the denominator terms, V_{stack} is the stack voltage and I the stack current.

6. Validation results

The results obtained from model simulations are presented below.

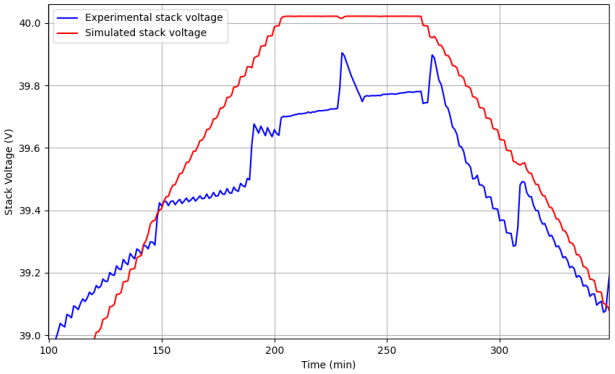

Fig. 3. AEMEL model results for the polarization curve.

Figure 3 shows the AEM polarization curve simulation. The envelope of the characteristic curve has been well captured, achieving an absolute error of 0.2 V and 0.1 V at the lowest and highest operating voltages, respectively. The experimental curve, however, displays a slightly distinct behavior due to the influence of temperature perturbations on the real-world system. Moreover, Figure 4 shows the simulation results for hydrogen flow rate and stack efficiency for this test procedure.

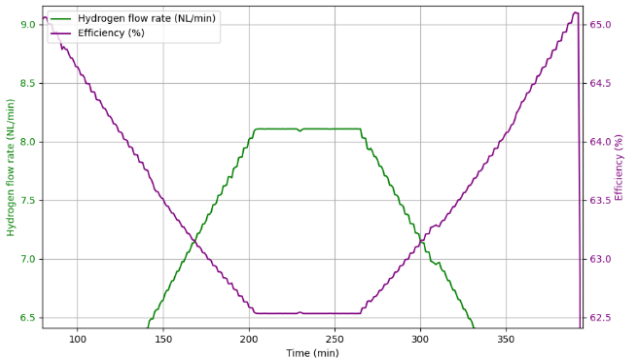

Fig. 4. AEMEL flow rate and efficiency results for the polarization curve.

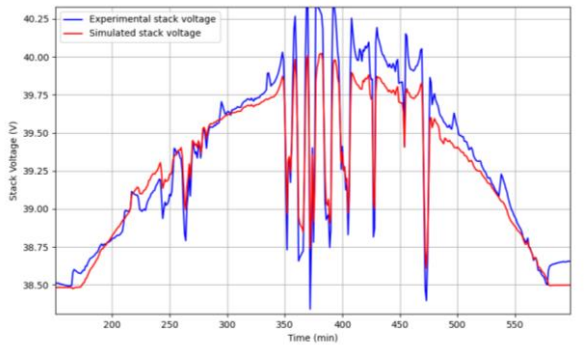

Fig. 5. AEMEL model results for the solar winter profile.

Figure 5 presents the simulated stack voltage results for a solar winter profile under unstable weather conditions, representing the most demanding test performed on the current model. In this scenario, a maximum voltage deviation of 0.5 V is observed. Regarding the transient response, the model demonstrates very good performance during rapid electrochemical dynamics.

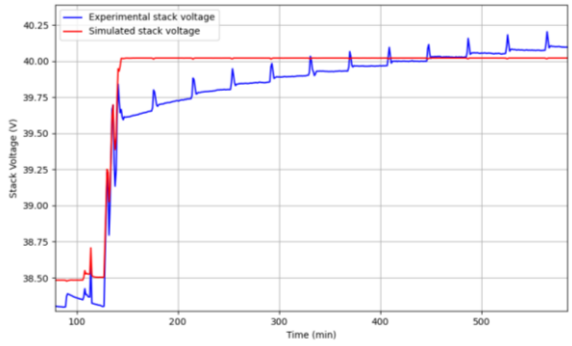

Fig. 6. AEMEL model results for the polarization curve.

Figure 6 shows the stack voltage results from the prolonged stationary test conducted at a nominal power of 2.2 kW. The model accurately converges to the steady-state behaviour at the long-term electrochemical equilibrium, with an absolute error of 0,1 V.

7. Conclusion

AEM electrolysis is an emerging technology for green hydrogen production. Despite the performance similarities to PEMEL, this technology is in transition from prototype to the small-scale commercial stage. This work presents a comprehensive AEMEL model that integrates the electrochemical properties, validated with over 100 hours of real-world experimental data and 48 hours of photovoltaic-specific data. Moreover, the short start-up times typical of AEMEL further complement its good dynamic performance and adaptability to fluctuating renewable power sources. The model demonstrates very good performance under different scenarios with a maximum absolute error of 0.1 V and 0.5 V for steady-state and dynamic inputs, respectively. Future advancements may focus on improving transient response, using larger datasets, and addressing stack degradation to enhance long-term reliability of AEM electrolysis.

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