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A didactic platform dedicated to the characterization and modeling of a PEM electrolyzer under current ripple constraints

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Resumen

El hidrógeno se considera un vector energético clave para descarbonizar los sectores del transporte y la industria, ambos responsables del aumento de la temperatura media global debido al uso intensivo de combustibles fósiles. Actualmente, la mayor parte del hidrógeno se genera mediante el empleo de procesos termoquímicos (gasificación del carbón, reformado de metano con vapor) que pueden combinarse con soluciones de captura, almacenamiento y uso del carbono. Sin embargo, a pesar de que el hidrógeno generado es de bajo costo, el objetivo del este recurso con bajas emisiones de carbono aún no se ha cumplido. En los últimos años, muchos gobiernos y agencias ambientales en países como Colombia y Francia han adoptado una estrategia dedicada a la producción y el uso de hidrógeno bajo en carbono a través de procesos de electrólisis del agua alimentados por fuentes de energía renovables (eólica, solar, hidráulica, geotérmica) para satisfacer la creciente demanda de hidrógeno. El proceso electrólisis del agua consiste en descomponer el agua pura en hidrógeno y oxígeno puros, gracias a la electricidad. Este proceso se lleva a cabo mediante electrolizadores. El acoplamiento entre fuentes de energía renovables intermitentes y electrolizadores implica el uso de convertidores de potencia como convertidores CA-CC y/o convertidores CC-CC. Por su funcionamiento, ambos convertidores de potencia generan ondulaciones de corriente de baja y alta frecuencia (de cien a diez mil Hertz). La onda de corriente generada por los convertidores de potencia ha sido una preocupación importante por los efectos que puede causar en las pilas de combustible y, más

recientemente, en los electrolizadores, por lo que se busca aumentar la comprensión de los procesos de degradación de las celdas y pilas de celdas. Los efectos a largo plazo de las ondulaciones de corriente generadas por la electrónica de potencia sobre el rendimiento de los electrolizadores constituyen una preocupación importante.

Para sensibilizar a los estudiantes sobre estas preocupaciones, se ha desarrollado una plataforma didáctica basada en un sistema electrolizador de membrana de intercambio de protones (PEM por sus siglas en inglés). El sistema electrolizador es alimentado directamente por la red eléctrica a través de dos convertidores de potencia (un puente rectificador de onda completa y un convertidor reductor (CC-CC)). Ambos convertidores de potencia generan ondulaciones de corriente a las que está sometido el electrolizador. Los estudiantes pueden analizar el impacto directo de la ondulación de la corriente en la respuesta de voltaje del electrolizador y darse cuenta de la probable degradación durante un largo período de operación. En el artículo se presenta la plataforma didáctica que incluye el sistema electrolizador PEM y también algunos resultados experimentales. Luego, se propone un modelo de circuito equivalente (ECM por sus siglas en inglés) para simular el comportamiento real del voltaje bajo restricciones de rizado de corriente. Los parámetros del modelo se pueden evaluar utilizando un conjunto de datos experimentales. Este ECM es útil para investigar los efectos de la ondulación de la corriente en el rendimiento de las celdas de electrolizadores. Este trabajo permite concluir sobre las consideraciones de diseño que deben tenerse en cuenta para la utilización de convertidores de potencia para esta aplicación.

Palabras claves : electrolizador de membrana de intercambio de protones; electrónica de potencia; caracterización; modelado; modelo de circuito equivalente.

Abstract

Hydrogen is considered a key energy vector to decarbonize transportation and industry sectors, both responsible of global average temperature increase due to the intensive use of fossil fuels. Currently, most of hydrogen is generated by employing thermochemical processes (e.g. coal gasification, natural gas conversion) that may be coupled with carbon capture, utilization, and storage (CCUS) solutions. However, despite generated hydrogen is low-cost, low-carbon hydrogen objective has not been yet met. Over the last few years, many governments and environmental agencies in countries like Colombia and France have adopted a strategy dedicated to the production and the use of low-carbon hydrogen through water electrolysis process fed by renewable energy sources (e.g. wind, solar, hydro, geothermal) to meet the growing hydrogen demand. Water electrolysis process consists of splitting pure water thanks to electricity into pure hydrogen and oxygen. This process is carried out by electrolyzers operating in different ways according to the type of electrolyte material employed and the ionic species they transport. The coupling between intermittent renewable energy sources and electrolyzers involves the use of power converters such as AC-DC converters and/or DC-DC converters. Both power converters by their operation generate low and high-frequency current ripple (from a hundred to a ten thousand of Hertz). Current ripple generated by power electronics have been a major concern for fuel cells and more recently

on electrolyzers for increasing understanding of cell and stack degradation processes. Long-term effects of current ripple generated by power electronics on electrolyzers performance constitute now a key issue. For this reason, the outcomes of these investigations will allow guiding to an optimal design of power converters from the current ripple point of view.

To raise students' awareness of these issues, a didactic platform relying on a proton exchange membrane (PEM) electrolyzer system has been exploited. The electrolyzer system is fed directly by the power grid through two power converters (i.e. a single-phase full-wave bridge rectifier and a step-down DC-DC converter). Both power converters create current ripple whose electrolyzer is subjected. The students can analyse the direct impact of current ripple on the electrolyzer voltage response and realize the likely degradation over a long period of operation. In the paper, the didactic platform including the PEM electrolyzer system is presented and some experimental outcomes. Then, an equivalent circuit model (ECM) is proposed to simulate the real voltage behavior under current ripple constraints. The parameters of the model can be assessed by using a set of experimental data. This ECM is useful for investigating the effects of current ripple on electrolyzer stack performance. The conclusions of these investigations must be considered to design in a suitable way power converters for this application.

Keywords: proton exchange membrane electrolyzer; power electronics; characterization; modeling; equivalent circuit model.

1. Introduction

To meet the objectives set forth in the 2015 Paris Agreement, many countries have adopted a strategy (commonly called "roadmap") dedicated to the development of low-emission carbon hydrogen such as Colombia and France. Indeed, hydrogen is seen as a key element in the energy transition process. The use of hydrogen allows decarbonizing transportation and industry sectors, both responsible for the global temperature rise and the increase in extreme weather events. To hold a temperature increase of no more than 2°C, Colombia has committed to a 51% reduction in greenhouse gas emissions by 2030 compared to a baseline scenario. The final goal is to reach carbon neutrality by 2050 (Ministerio de Minas y Energía, 2021). In comparison, the 28 member states of the European Union agreed to drop their greenhouse gas emissions by 45% by 2030 (compared to 2010 levels) with the objective of achieving "net zero" emissions by 2050 (European Commission, 2020). For this reason, the energy transition all over the world will require the production and the use of low-carbon hydrogen at large scale.

At present, most of the hydrogen is made by employing thermochemical processes (e.g., coal gasification and steam methane reforming), known as "black" and "grey" hydrogen respectively. These processes may be coupled with carbon capture, utilization, and storage (CCUS) solutions where the produced hydrogen is known as "blue" to decrease the carbon footprint (Yue, Meiling et al, 2021). Besides, Colombia has meaningful oil, natural gas and coal reserves that place it close to fuel self-sufficiency and which could be employed for

instance, to produce blue hydrogen by employing CCUS solutions absorbing CO₂ emissions emitted (Ministerio de Minas y Energía, 2021). Hydrogen can also be generated through a water electrolysis process supplied by renewable energy sources (RES), e.g., wind, solar, hydro, and geothermal. The water electrolysis process consists of splitting pure water thanks to electricity from RES into pure hydrogen and oxygen. It is performed by electrolyzers operating in different ways according to the kind of electrolyte material employed and the ionic species they transfer. In Colombia, hydro power represents roughly 12% of the total energy mix (dominated by oil (45%) and natural gas (22%)). If hydro power was used in the water electrolysis process, the emission factor would be greatly reduced, making the cost of clean hydrogen competitive. The water electrolysis process has reached a commercial maturity as attested by numerous green hydrogen power plants developed all over the world. In this work, water electrolysis process is considered.

Until now, four main electrolyzer technologies exist depending on their electrolyte material and their ionic species they transfer: alkaline, proton exchange membrane (PEM), solid oxide (SO), and anion exchange membrane (AEM). Among these four electrolyzer technologies, only alkaline and PEM electrolyzers run the market; while AEM and SO technologies, despite their late introduction in the electrolyzer market, are nowadays in-depth research and development (Eikeng, Erik et al, 2024). First, alkaline electrolyzers are the most mature technologies. They present the lowest investment cost and higher lifetime than the other electrolyzer technologies available in the market. On the other hand, their alkaline liquid solution, mainly based on potassium hydroxide (KOH), 25-30% KOH, requires redundant maintenance and limits their operational flexibility, i.e., 15-100%. In comparison, PEM electrolyzers, despite of higher costs and specific energy consumption (SEC), i.e., kWh/kgH₂ than alkaline electrolyzers, present an extended current density (>2A.cm⁻²) and larger operational flexibility, i.e., 0-100%, making them particularly fit for their coupling with intermittent renewable energy sources. Because of their technical barriers, e.g., SEC, degradation, and platinum-group metals electrode load decrease, this technology has been chosen for this research work (Sayed-Ahmed, H et al, 2024).

As bringing out in several up-to-date review papers, characterization and modeling of PEM electrolyzers under real operating conditions, static, dynamic considering intermittent renewable power sources, and operating variables, i.e., temperature and gas pressure, have become an important research topic (Sayed-Ahmed, H et al, 2024). Indeed, an enhanced understanding of the real behaviors of PEM electrolyzers allows the development of accurate simulation tools, emulators, and optimized controllers for power converters. However, the characterization and modeling of PEM electrolyzers under low and high-frequency current ripple constraints from power electronics have not been yet investigated in the literature. Current ripple caused by power converters have been a significant concern for PEM fuel cells and more recently on PEM electrolyzers for increasing understanding of cell and stack degradation mechanisms (Parache, François et al, 2022). Long-term effects of current ripple induced by power electronics, i.e., AC-DC converter for low-frequency current ripple and DC-DC converter for high-frequency current ripple, on electrolyzers performance constitute now a technical barrier even if some recent works have examined the consequences of current ripple on efficiency, SEC and gas purity, and aging. Leaning on the first outcomes reported in

(Parache, François et al, 2022), triangular current ripple at 10 kHz from DC-DC converters has been pointed out as the most degrading condition, favoring consequently degradations, i.e., high-frequency resistance rise, corrosion, and titanium mesh.

In previous works where PEM fuel cells performance are investigated, the effects of low and high-frequency current ripple have been assessed through the development of equivalent circuit models (ECM). From the amplitude and frequency point of view, the relationship between current ripple and PEM fuel cell performance, such as aging, power losses, and fuel consumption is particularly explored. Despite that, current ripple data have not been yet taken into consideration to assess the parameters of the ECM and their changes according to the amplitude and frequency of the current ripple. For this reason, the main objective of this paper is to raise students' awareness of these issues through the exploitation of a didactic platform relying on a PEM electrolyzer system. This commercial PEM electrolyzer system includes its own power electronics, i.e., AC-DC and DC-DC converters, causing respectively low and high-frequency current ripple affecting the voltage response of the electrolyzer stack. Two sets of experimental data, i.e., stack current and voltage, are used for estimating the parameters of an ECM. The comparison between the obtained results of the ECM and the experimental data has brought out the convenience of ECM in the simulation of the real electrolyzer voltage response under current ripple constraints. This ECM will enable investigation of the effects of current ripple on electrolyzer stack performance. Thus, the conclusions of these investigations are valuable in designing a suitable way power electronics converters for this application.

The structure of this work is divided into five sections. After presenting the state-of-the-art in the introduction, a detailed description of the experimental platform is presented and current ripple issues for PEM electrolyzers are pointed out in Section 2. In Section 3, the development of an ECM for the PEM electrolyzer voltage response and the algorithm to calculate its parameters are explained. Subsequently, the estimated parameters, simulations, and validation of the ECM are presented in Section 4. Finally, the conclusions of this research work are given in Section 5.

2. Experimental test bench and current ripple issues for PEM electrolyzers

For education purposes, the commercial PEM electrolyzer system NMH2 1000 from HELIOCENTRIS Company has been used, as shown in Figure 1. The technical data of this PEM electrolyzer are presented in Table 1. In this table, the hydrogen flow rate at standard temperature (STP) and pressure, 15°C and 1 bar, respectively, are given in standard liter per minute (slpm). The generated hydrogen is stored in metal hydride storage tanks to offer high safety levels (not shown in Figure 1). Furthermore, the PEM electrolyzer stack is directly fed by pure water featuring low conductivity (on the left in Figure 1), i.e., less than $2 \mu\text{S}\cdot\text{cm}^{-1}$.



Figure 1. Investigated PEM electrolyzer system for education purposes

Parameters	Value	Unit
Rated electrical power	400	W
Stack operating voltage range	7.5-8	V
Stack current range	0-50	A
Delivery output pressure	0.1-10.5	bar
Cells number	3	-
Active area section	50	cm ²
Hydrogen flow rate at STP	0-1	slpm

Table 1. Main features of the investigated PEM electrolyzer

Considering the PEM electrolyzer system employed in this work is commercial, it is composed of its own power electronics to supply the electrolyzer as depicted in Figure 2. In this case, the main AC source is the power grid (230 V- 50 Hz) and the DC load is the PEM electrolyzer. The power electronics part relies on a single-phase diode bridge rectifier, a DC-link capacitor, and a DC-DC converter. As introduced in Table 1, the PEM electrolyzer stack requests a very low DC voltage, i.e., 8 V at rated power. For this reason, a step-down DC-DC converter is used.

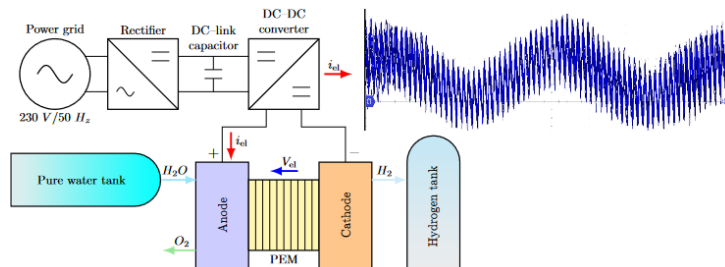
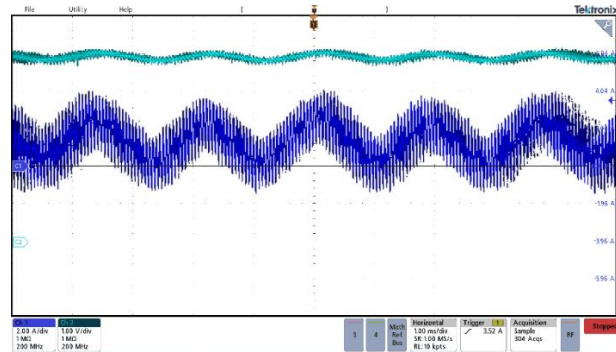


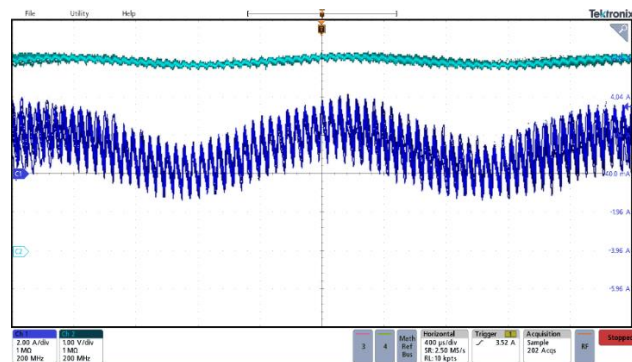
Figure 2. Power conversion configuration of the studied PEM electrolyzer system and current ripple waveform.

In this system, the single-phase diode bridge rectifier creates a low-frequency current ripple, i.e., 100 Hz, while the step-down DC-DC converter induces a high-frequency current ripple,

i.e., 10 kHz. To evaluate the parameters of the developed model, two sets of data from the PEM electrolyzer, i.e., stack current i_{el} and voltage v_{el} , have been exploited. Stack current and voltage are acquired using voltage and current probes. These data correspond to two different operating points, $i_{el} = 2$ A and $i_{el} = 40$ A, where the PEM electrolyzer system can operate independently. The obtained experimental results are represented in Figure 3 related both to the first operating point, $i_{el} = 2$ A, and Figure 4 related to the second operating point, $i_{el} = 40$ A. In Figure 3a, the low-frequency AC component of the current can be observed, whereas in Figure 3b the high-frequency AC component can be underlined. For this first operating point, the current ripple constitutes 200%, i.e., 4 A of the average current value. Besides, a small AC component in the stack voltage response can be observed, i.e., around 0.3 V. Regarding the second operating point shown in Figure 4, the current ripple represents 96%, i.e., 38 A of the average current value. Like in the first operating point case, an AC component can be perceived in the stack voltage response, approximately 1.26 V, four times higher compared to the measure voltage ripple for the first database. The waveforms of the stack voltage responses match those of the current.



(a)



(b)

Figure 3. First database $i_{el} = 2$ A, Ch1: current (2 A/div), Ch2: voltage (1 V/div), (a) current and voltage waveforms, time scale (1 ms/div), (b) zoom to observe the high-frequency AC component of the current, time scale (400 μs/div)

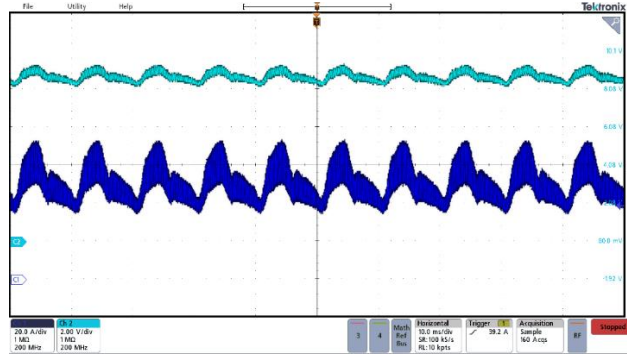


Figure 4. Second database $i_{el}=40$ A, Ch1: current (20 A/div), Ch2: voltage (2 V/div), current and voltage waveforms, time scale (10 ms/div).

The research work presented in (Fontes, Guillaume et al, 2007) focuses on the interactions between PEM fuel cells and power converters, the authors have brought out the key role of double-layer equivalent capacitance in mitigating current ripple caused by power electronics. In previous works (Sayed-Ahmed, H et al, 2024), high values of double-layer equivalent capacitance have been found; therefore, a large part of the current ripple can be mitigated. This analysis could consequently explain the fact that the stack voltage ripple is low despite the significant amplitude of the current ripple for both operating points. But, as reported in the conclusions of the work of (Fontes, Guillaume et al, 2007), a crucial concern stands, namely the maximum current allowable by the double-layer capacitance, making it possible to guarantee the mitigation of these current ripple.

3. Equivalent circuit model for modeling purposes

The proposed ECM is based on recent works in which the authors have modeled the PEM electrolyzer voltage in terms of electronic components, i.e., one DC voltage source, two capacitors, and three resistors, as depicted in Figure 5.

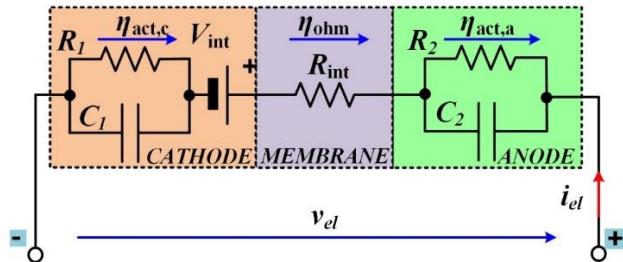


Figure 5. Equivalent circuit model to simulate the voltage response of the PEM electrolyzer under current ripple constraints

The ECM is composed of the following components:

- A DC voltage source V_{int} . This voltage source is used to model the reversible voltage.
- A resistance R_{int} to model the electrolyzer membrane.
- Two resistor-capacitor branches. These branches are used for modeling the activation voltage $\eta_{act} = K \cdot (\eta_{act,c}, \eta_{act,a})^T$, one branch for the activation voltage in the cathode $\eta_{act,c}$ and the other branch for the activation voltage in the anode $\eta_{act,a}$. $K = (k_1, k_2)$ is a constant two-input vector that depends on the input current i_{el} . Besides, as reported in the literature, the activation voltage is responsible for the dynamics present in the PEM electrolyzer voltage. The dynamic equations are defined as:

$$\frac{d\eta_{act,c}}{dt} = \frac{1}{C_1} i_{el} - \frac{1}{\tau_c} \eta_{act,c} \quad (1)$$

$$\frac{d\eta_{act,a}}{dt} = \frac{1}{C_2} i_{el} - \frac{1}{\tau_a} \eta_{act,a} \quad (2)$$

where C_1 and C_2 are the capacitors for the cathode and the anode in [F], respectively. τ_c and τ_a are the electrical time constants that depend strongly on the operating conditions at the cathode and the anode in [s], respectively. Furthermore, the resistances R_1 (cathode) and R_2 (anode) from the two resistor-capacitor branches vary depending on the current input and can be calculated using the expressions (3) and (4) summarized below:

$$R_1 = \frac{\tau_c}{C_1} \quad (3)$$

$$R_2 = \frac{\tau_a}{C_2} \quad (4)$$

The differential equations (1) and (2) can be rewritten as a linear system:

$$\begin{pmatrix} \frac{d\eta_{act,c}}{dt} \\ \frac{d\eta_{act,a}}{dt} \end{pmatrix} = A \cdot \begin{pmatrix} \eta_{act,c} \\ \eta_{act,a} \end{pmatrix} + B \cdot i_{el} \quad (5)$$

Where:

$$A = \begin{pmatrix} -\frac{1}{\tau_c} & 0 \\ 0 & -\frac{1}{\tau_a} \end{pmatrix} \text{ and } B = \begin{pmatrix} \frac{1}{C_1} \\ \frac{1}{C_2} \end{pmatrix}$$

Finally, from the ECM, the PEM electrolyzer voltage is given by the following expression:

$$v_{el} = V_{int} + R_{int} i_{el} + K \cdot (\eta_{act,c}, \eta_{act,a})^T \quad (6)$$

Starting from the ECM, the array parameters defined in matrices A et B from (5) and the following parameters V_{int} , R_{int} , and K from (6) can be assessed using an algorithm based on the gradient method.

4. Obtained outcomes

The ECM was validated using the two databases introduced in Section 2 (Figures 3, 4, and 5). The first PEM electrolyzer voltage database is generated by an input current that varies between 0 A and 4.88 A in a period of 0.01 seconds, obtaining a minimum of 4.76 V and a maximum of 5.06 V. The second PEM electrolyzer voltage database is generated by an input current that varies between 21.20 A and 59.60 A in a period of 0.1 seconds, obtaining a minimum of 8.24 V and a maximum of 9.5025 V.

To adjust the ECM parameters to the first database, values are defined for the resistors $R_1=0.1205 \Omega$, $R_2=0.1 \Omega$, and the capacitors $C_1=0.83 \text{ F}$, $C_2=1.25 \text{ F}$ to generate matrices A and B (equation (5)). These initial values allow determining $\tau_c=0.0001 \text{ s}$, $\tau_a=0.000125 \text{ s}$, and the matrices A and B:

$$A = \begin{pmatrix} -10000 & 0 \\ 0 & -8000 \end{pmatrix} \text{ and } B = \begin{pmatrix} 1200 \\ 800 \end{pmatrix}$$

Then, using the obtained matrices A and B, the input current i_{el} from the first database, and the initial values of the activation voltage $\eta_{act}=(\eta_{act,c}(0), \eta_{act,a}(0))$ for cathode $\eta_{act,c}(0)=0.255 \text{ V}$ and for anode $\eta_{act,a}(0)=0.215 \text{ V}$, the solution of equation (5) is generated. The fourth-order Runge-Kutta iterative method with a step $h=10^{-7}$ is used to generate the solution of equation (5). Figure 6 shows the simulation outcome and allows a comparison of real and simulated data. It can be observed that ECM with the assessed parameters can replicate accurately the real voltage behavior under current ripple constraints. The same algorithm can be employed to evaluate the parameters of the ECM for the second database. In this case, the parameters of the ECM change due to the current data (amplitude, ripple).

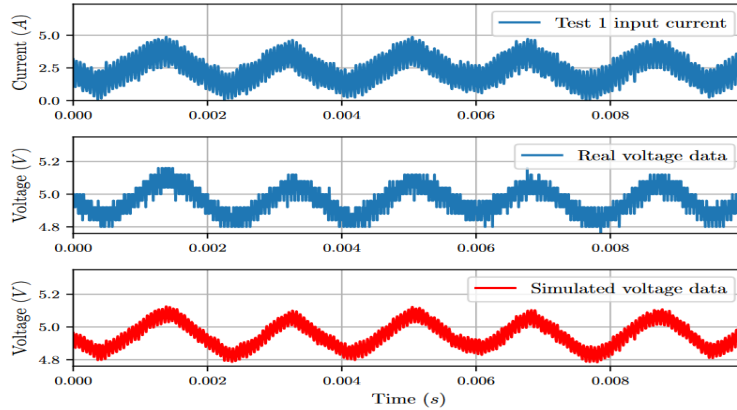


Figure 6. Comparison between the simulated and real stack voltage for the first database

5. Conclusions and perspectives

In this work, a didactic platform dedicated to the characterization and modeling of a PEM electrolyzer under current ripple constraints was developed. An equivalent circuit model was proposed to simulate the voltage response of a PEM electrolyzer subjected to low and high-frequency current ripple caused by power converters. To ease the assessment of the ECM parameters, an algorithm based on the gradient method was employed. The obtained outcomes demonstrated the effectiveness of the equivalent circuit model together with its assessed parameters in duplicating the real voltage response of a PEM electrolyzer. Finally, this work will lead to further investigations concerning the relationship between the current ripple (amplitude, frequency, and waveform) and PEM electrolyzer aging. Thus, the outcomes of these studies will guide the proper design of power electronic converters to slow down the accelerated aging of PEM electrolyzers.

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