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# Electrolyzer Degradation-Power Electronics One -Way Interaction Model

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*Abstract*—The water electrolysis process requires a high DC current supply that can sustain the desired hydrogen production rate over a large period of operation at a competitive cost. During the conversion of electricity from AC to DC, power quality may be affected because of the non-linear effect caused by the power electronics. Most of the recent research has focused on exploring different rectifier topologies. None of them have investigated the influence of cell stack degradation on the performance of power electronics. In this work, we built a one-way interaction model to predict the influence of electrolyzer degradation on power electronics output over multiscale operational time (from milliseconds to years) for proton exchange membrane electrolyzer (PEM). In this model, we assume a constant degradation rate on the electrolyzer that results in a linear increase of internal resistance over time. Counterintuitively, rather than the power quality decreasing, results show that the power quality increased with the electrolyzer degradation for both the AC (power factor and THD) and DC side (ripple) for the 6-pulse thyristor. Furthermore, the influence of three variables (degradation rate, load current, and topology) on AC (power factor and THD) and DC (ripple factor) side power output were investigated. Finally, results were partially validated with experimental data from a 20 MW scale PEM electrolyzer.

*Keywords—power electronics, electrolysis, PEM, rectifiers, stack degradation, power quality, interaction.*

## 1) Introduction

Hydrogen is an industrial gas used for fuel desulfurization, fertilizer, and methanol production. Global hydrogen production is mainly derived from fossil fuels through the reforming of natural gas, this process emits more than 800 million tons of carbon dioxide per year [1]. There has been an exponential interest in the last few years to replace the use of fossil fuels with renewable energy to suffice the future demand for hydrogen.

Green hydrogen has been proposed as an important energy vector in the last few years in order to accelerate the transition into a low-carbon economy. One promising solution is green hydrogen production through water electrolysis powered by renewable energy. Water electrolyzers have become of increasing importance for generating green hydrogen motivated by the declining costs of renewable power and ongoing innovations in achieving cost reductions through economies of scale [1]. Strong governmental policies are being deployed around the world to support the implementation of the hydrogen infrastructure.

Among different water electrolysis technologies, PEM electrolysis has become one of the front-runner technologies for supporting the production of green hydrogen, several PEM electrolyzer plants have been commissioned in the last few years, and there are more that will come online in the next decade [2]. Figure 1 summarizes the development of some of the major MW-level PEM electrolyzers worldwide from 2018 through 2025. As can be seen from the trend, the power scale of the new PEM electrolyzer plants grows exponentially.

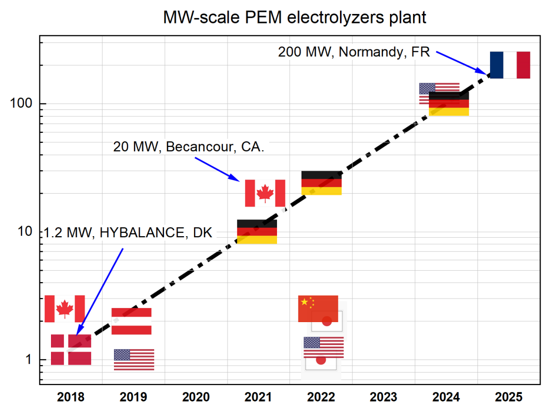



Fig. 1. Development of MW- scale PEM electrolyzers (y-axis is in MW)

Power quality improvements can be made for minimizing the stack-specific energy consumption. This is achievable by using energy-efficient rectifiers. However, the influence of cell stack degradation on the performance of power electronics remains to be investigated.

Water electrolysis faces some challenges that need to be addressed in order to be competitive with other mature hydrogen production technologies. One of the key issues is the nonlinear effect in power switching and conversion losses in the rectifier. Electrolyzer systems require the delivery of low voltage with a high DC input. Therefore, the power generated at the source must be converted from AC to DC [3]. This is done through a power rectifier which can then transmit the converted power to the electrolyzer stack for hydrogen production. Power converters contribute around 15-20% of the CAPEX for PEM electrolyzer systems [3]. Therefore, optimization in this area can bring valuable benefits in making PEM electrolysis more competitive in the market [4].

Thyristor-based rectifiers are commonly used for industrial-scale water electrolysis due to their maturity and low cost, including the solution for the world's largest PEM electrolysis system (20 MW at Becancour, CA) operated by Air Liquide. As MW-scale electrolyzers become commercially available, new research on electrolyzer energy management, including the power electronics influence on stack energy consumption and cell degradation have become relevant. As an example, recent literature has explored the use of transistor-based converters for reducing the DC-ripple and total harmonic distortion (THD) while improving the power factor [5]. However, most of these publications have been devoted to alkaline water electrolyzers due to the technology maturity of this type of electrolyzer [4].

A similar approach of using transistor-based rectifiers can be applied to PEM electrolysis to assess what improvements can be made with respect to lowering the stack specific energy consumption while improving power quality [4,6]. Chen et al. [9] compared the AC power quality at the beginning of the electrolyzer's lifetime with the end-of-life performance of various rectifier topologies. Keddar et al. [5] demonstrated the advantages of a three-phase interleaved buck converter (3PIBR) in AC power quality over a 6-pulse thyristor and validated their numerical model using data from a 20 MW PEM electrolysis plant. On the DC side, the produced voltage and current generally contain a ripple in the form of alternating components due to the nature of rectifiers. In the water electrolysis case, the hydrogen production is directly related to the rectifier DC current. In such a process, DC current is of more interest, and ideally, any alternating component should be minimized in a desired direct current waveform. Koponen et al. [7] assessed the power quality of a 12-pulse thyristor rectifier in a PEM electrolysis system subjected to varying sinusoidal ripples. Results showed the cell area should be up to five times higher for a 12-pulse thyristor at low load currents to achieve the same specific energy consumption as compared to an ideal DC power supply. Buitendach [8] conducted a similar study for a 6-pulse thyristor and found that high ripple factors lead to an increase in power consumption while the hydrogen production remains unaffected.

Research shows that the cell resistance increases with time due to cell degradation [10]. However, none of the aforementioned works have assessed the impact of PEM stack degradation on power electronics over a long period of operation under different load current scenarios. In the present paper, we explore the effect of cell stack degradation on the power quality over an extended period of operation at constant degradation rates and load conditions. The power factor, THD, and ripple factor behavior are simulated throughout the electrolyzer lifetime for a 6-pulse thyristor topology. For comparison, we also evaluated the parameter influence on a 3-phase interleaved buck rectifier (3PIBR). Model validation of the power factor for a single stack unit was conducted based on months of operation. Lastly, we elaborate on the limitations of the current modeling scheme.

## 2) Theoretical Background

In the present research, we implemented a constant degradation rate into our existing power electronics-PEM electrolyzer model for two rectifier topologies using the operating conditions of the 20 MW Becancour electrolyzer plant. Figure 2 summarizes the hydrogen production process at the Becancour plant.

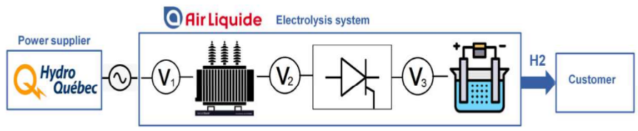



Fig. 2. Air Liquide's Becancour PEMWE plant process scheme [5]

### *a) Rectifier Topologies*

In this research, we focus on two rectifier topologies, the 6-pulse thyristor currently used in the 20 MW Becancour plant and the 3-phase interleaved buck rectifier (3PIBR): a proposed topology. The thyristor rectifier and the 3-phase interleaved buck rectifier models were designed and built using MATLAB/Simulink software. The details of the two topologies and more theoretical background can be found in our previous publication [5].

The architecture of the 6-pulse thyristor consists of a three-phase bridge rectifier with thyristors running in parallel, with each thyristor having a firing angle control signal. This topology achieves great energy efficiency at a low cost with simple control. However, it exhibits high harmonic and reactive power losses that increase the specific energy consumption of the PEM electrolyzer [6, 7, 8].

A three-phase interleaved buck rectifier, permits a higher switching frequency, higher reliability, and fast dynamics. This topology is composed of a diode bridge rectifier followed by a buck inverter. Additionally, this rectifier provides a major advantage by reducing the bulky harmonics filters. Therefore, the DC output current ripple is decreased, contributing to a reduction in specific electrolyzer energy consumption [6]. Furthermore, the leg number of the buck converter can be expanded to increase the topology reliability and decrease the DC current ripple. Despite all these improvements, the 3PIBR topology presents some drawbacks, such as the high voltage stress applied to the power switches and the high cost compared to the 6-pulse thyristor rectifier.

### b) Degradation Model

The performance of a PEM electrolytic cell can be estimated by constructing a linear cell polarization curve using experimental data that accounts for the overall cell resistance based on the following equation:

$$V_{cell} = R_{int} * i_{cell} + V_{int} \quad (1)$$

where $R_{int}$ is the equivalent internal resistance, $i_{cell}$ is the cell current, and $V_{int}$ is the cell reversible voltage and can be defined as

$$V_{int} = \Delta G/zF \quad (2)$$

where, ΔG is the Gibbs energy used to split the water molecules, z is the number of electrons exchanged during the reaction, and F is the Faraday constant. Then, the equivalent electrical circuit of the PEM cell can be modeled as depicted in Figure 3.

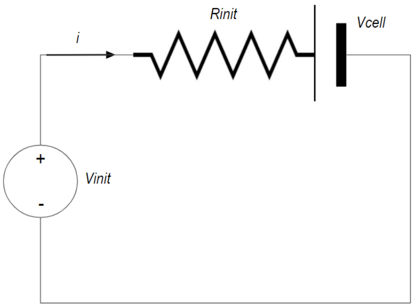



Fig. 3. PEM electrolyzer cell circuit

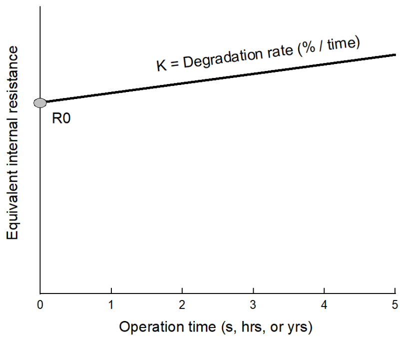



Fig. 4. Resistance model under degradation and long-term operation

It is known that the cell resistance increases with time due to several factors that affect cell degradation [10]. The degradation of the cell stack is assumed to yield a linear relationship as follows:

$$R_t = R_0 + d_{rate} * R_0 \quad (3)$$

where $R_t$ is the resistance over time, $R_0$ is the initial resistance and $d_{rate}$ is the degradation rate (in %/yr) over a period of years as seen in Figure 4.

### c) Model Configuration

The resistance shown for the PEM electrolyzer is based on the DC output current from the rectifier. The power rectifiers are connected to the main electricity grid (120kV, 60Hz) through a 36 MVA two-winding three-phase transformer. Then, another 5.4 MVA transformer is used to reduce the voltage and connected to the rectifiers that transmit power to electrolyzer stacks. The output capacitor value recommended by the manufacturer is used to illustrate the relation. Although this value is smaller than the on-site operation, similar behaviors are observed using the real plant setup. In this paper, we use a MATLAB/Simulink power electronics - electrolyzer static/quasi-dynamic model. Table 1 summarizes the parameters used for the simulation model.

Degradation of the PEM electrolyzer cell stacks can occur due to several effects, including membrane thinning, dissolution/poisoning of the catalyst layers, corrosion of the proton transfer layers, and others [12]. The current state-of-the-art PEM electrolyzers experience a degradation rate of 2-4% per year [11, 13, 14, 15], while the commercial target is to reduce the stack degradation to below 1%/year by 2023 [13].

The base study is done using a 6-pulse thyristor which corresponds to the current topology used in the 20 MW Becancour plant. Based on the assumption that the electrolyzer has a lifetime of approximately 80,000 hours, as given by several stack suppliers [16], the conducted simulation has a span of a 10-year period.

TABLE I. Simulation Parameters

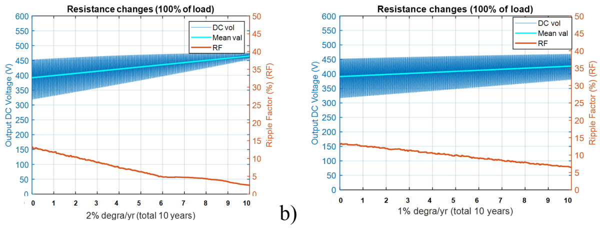
| Parameter | 6 - pulse thyristor rectifier | 3-phase interleaved buck rectifier (3PIBR) |
|---|---|---|
| Input voltage (source) | 25kV, 60 Hz | |
| Output voltage (V) | 330 - 460 | |
| Output current (kA) | 2 - 12.2 | |
| Input voltage (V) | 350 | 550 |
| Diode bridge capacitor (µC) | - | 8000 |
| Output filter inductor (mH) | 44 | 19 |
| Output filter capacitor (µC) | 9000 | 2000 |
| Switching frequency (Hz) | 360 | 1000 |
| Degradation rate (%/yr) | 1 or 2 | |

## 3) Results

The influence of three variables (degradation rate, load current and topology) on AC (power factor and THD) and DC (ripple factor) was investigated for 6-pulse thyristor and 3PIBR converter topologies. Additionally, a cell stack degradation rate of 1% and 2% per year was introduced into the model to investigate the impact over a long period of operation. Three load current conditions were also investigated for two different topologies.

### *a) Degradation rate influence on 6-pulse thyristor*

Inclusion of the cell stack degradation rate in the model provides a new perspective to analyze the impact on the power quality performance. Figure 5a depicts how an assumed constant degradation rate of 2%/year leads to a linear increase in the cell voltage accompanied by a decrease in the ripple factor at nominal load conditions. At the beginning of the operation, the ripple factor is as high as 10%. As time evolved, the ripple factor decreased to below 5%. This decrease in ripple factor should have an effect of decelerating the cell degradation. Based on a constant overall degradation rate assumption, the contribution of degradation caused by the ripple effect decreases with time for the 6-pulse thyristor topology.



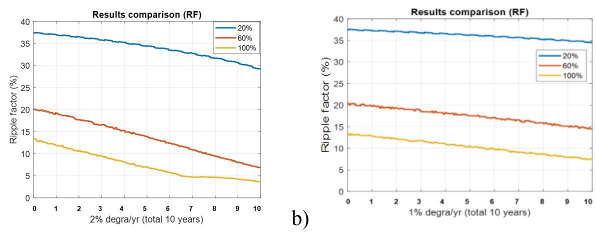

a) b)

Fig. 5. Long-term power quality performance for 6-pulse thyristor at 2%/yr degradation rate (a) and 1%/yr degradation rate (b)

As for a different degradation rate of 1%/yr as shown in Figure 5b, the voltage and ripple factor behaves similarly but with a smaller ripple factor decrease. By comparison, the ripple profile (in blue) in Figure 5 (b) is less significant than in Figure 5 (b). This is because the faster the degradation takes place the better the power quality improvement is.

### *b) Load percentage influence on a 6-pulse thyristor*

The influence of three load conditions was investigated to understand how the ripple factor changes over time. Figures 6a and 6b display the decrease of the ripple factor while accounting for a constant rate of cell degradation. As the electrolyzer ages, it is clear that the power quality improves for both scenarios with the 2%/yr degradation rate providing the fastest decline in the ripple factor to the end of life of the electrolyzer. The slower degradation rate of 1%/yr presents a ripple factor of approximately 7.5% at the last year of operation, indicating that the slower the degradation rate, the slower the ripple decline will be.

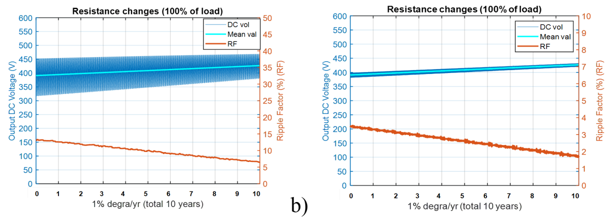



a) b)

Fig. 6. Ripple factor at different degradation rate and load conditions for 2%/yr degradation rate (a) and 1%/yr degradation rate (b)

### *c) Topology Influence*

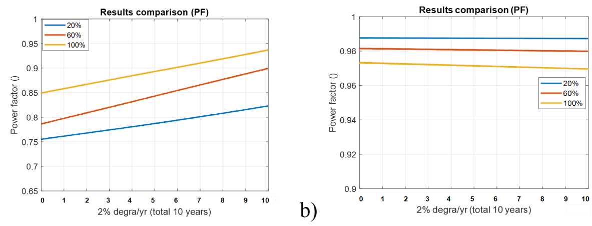
Figures 7a and 7b, depict the increase in cell voltage over time when a 1% cell stack degradation rate is assumed per year for the 6-pulse thyristor and 3PIBR topology. The ripple factor for both topologies decreases to the end of life of the electrolyzer due to the increase in cell resistance. As the electrolyzer ages at a constant degradation rate, the 3PIBR topology outperforms the 6-pulse thyristor as it needs less energy to produce the same amount of hydrogen throughout years of operation.




a) b)

Fig. 7. Long-term power quality performance for 6-pulse thyristor (a) and 3PIBR (b)

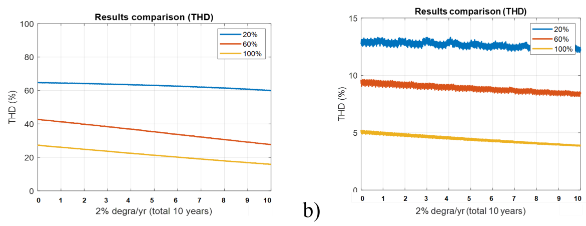
Cell stack degradation also has an influence on the power factor and total harmonic distortion (THD). Figure 8a depicts how for a stack degradation rate of 2%/yr at different loads, the power factor improves considerably over time for the 6-pulse thyristor, whereas for the 3PIBR the power factor remains almost constant for the period of operation, as shown in Figure 8b.




a) b)

Fig. 8. Long-term power factor performance for 6-pulse thyristor (a) and 3PIBR (b)

Consequently, the THD at the same degradation rate of 2%/yr will experience a linear decrease over time and lead to a reduction in reactive power losses for both topologies as shown in Figures 9a and 9b. Electrolyzer aging improves power quality parameters at the expense of higher specific energy consumption.

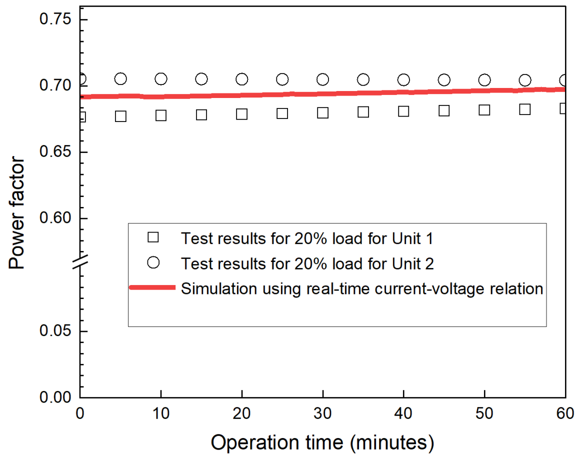



a) b)

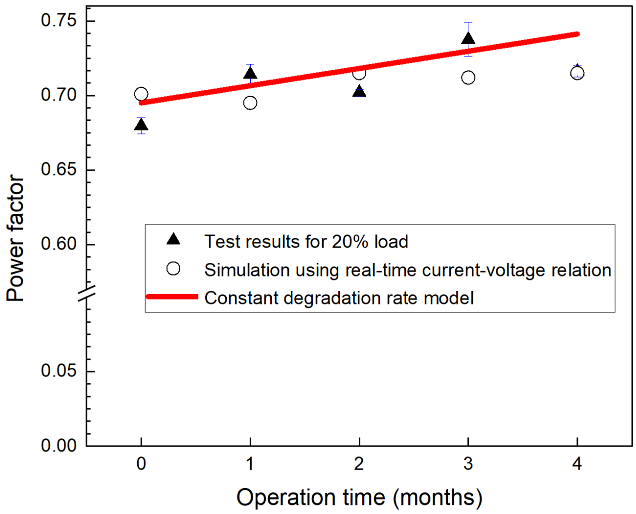
Fig. 9. Long-term THD performance for 6-pulse thyristor (a) and 3PIBR (b)

### 4) Model Validation

The power factor- operation time relation has been validated with data from the 20 MW PEM electrolyzer at the Becancour site for one hour operation in Figure 10 (a) and over a span of 5 months of continuous operation at a 20% load condition for one unit (5 MW). As seen in Figure 10, the simulation results from the current-voltage relation have approximately ~5% error discrepancy when compared to the actual plant measurement. The constant degradation model is able to predict the increasing trend of power factor throughout time. However, its mathematical representation is not accurate since the degradation rate is assumed to be constant over the period of validation when in fact, it is varying due to the dynamics of the process.




(a)




(b)

Fig. 10. Model validation over a span of (a) 1 hr and (b) 5 months of operation

Unfortunately, in the present research, we are only able to validate the model for the low-load (20%) scenario over a span of 5 months of electrolyzer operation as well as the one hour operation scenario as shown in Figures 10a and 10b, respectively. We couldn't validate the power quality-operation time relation at a nominal load condition (100%). This limitation can be attributed to the missing of stable operation data for a long time period at this load level since in reality, vast fluctuations in load current occur over time, altering the degradation rate. System dynamics along with an appropriate control scheme can help further the validation of higher loads and hence increase the understanding of power quality variation with time under a wide range of conditions. At the same time, the model reaches its limits when the output voltage will be close to the nominal voltage. However, the transformer output voltage can be increased in order to compensate for the increment in internal resistance.

To the best of our knowledge, there are no records in the available literature that show the relation of power quality parameters over time at MW-scale stack units. Further, model validation with real power plant data is necessary to test the model fidelity at different time scales.

### 5) Conclusions and Future Work

A power electronics - PEM electrolyzer model with cell stack degradation was developed and validated with experimental data. The performed simulation provides a novel insight into how power quality parameters benefit from electrolyzer cell stack degradation for the 6-pulse thyristor topology. Potentially, this model can bring a new perspective on power quality management for large-scale water electrolyzers under varying power supply scenarios, converter topologies, and cell stack degradation effects.

The results presented in this work showed that power quality parameters improve with electrolyzer aging for the 6-pulse thyristor topology, a reduction in DC ripple, and THD is achieved over time while the power factor increases. Additionally, the higher cell stack degradation rate will provide more benefits in terms of power quality at the expense of higher stack energy consumption over time. On the other hand, IGBT presents a lower degradation rate than the 6-pulse thyristor, even if a decrease of power quality was observed at high load.

The current model is limited to handling static loads, meaning that though it was used to predict the power quality performance over time, the conclusions drawn cannot be generalized to a dynamic power scenario. Previous research showed that the degradation rate can be significant at higher loads under steady-state conditions as compared to a dynamic load condition [15, 17]. Thus, it remains unclear how the introduction of dynamic loads affects the performance of the power quality parameters. Furthermore, the representation of the PEM electrolyzer cell as a linear resistance model is simplistic and does not resemble the real physics of all the resistances encountered during the process. The implementation of a physics-based module PEM electrolyzer into the current model can help identify what specific impact the DC ripple has over the cell overpotentials.

Moreover, in the current model and in the available literature, no considerations have been made with respect to the degradation of the power electronic components, it is clear that these components are rated to withstand dynamic conditions and are designed for the end-of-life of the electrolyzer. However, it remains unknown how the degradation of power electronic rectifiers impacts the performance of the overall electrolysis process.

## 6) Acknowledgment

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## 7) References

[1] IEA. 2022. The Future of Hydrogen – Analysis - IEA. [online] Available at: <https://www.iea.org/reports/the-future-of-hydrogen> [Accessed 3 May 2022].

[2] IEA. 2022. Hydrogen Projects Database - Data product - IEA. [online] Available at: <https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database> [Accessed 3 May 2022].

[3] vdocuments.net. 2022. Gigawatt green hydrogen plant - ISPT - [PDF Document]. [online] Available at: <https://vdocuments.net/gigawatt-green-hydrogen-plant-ispt.html> [Accessed 3 May 2022].

[4] Koponen, J., Ruuskanen, V., Kosonen, A., Niemela, M. and Ahola, J., 2019. Effect of Converter Topology on the Specific Energy Consumption of Alkaline Water Electrolyzers. IEEE Transactions on Power Electronics, 34(7), pp.6171-6182.

[5] Keddar, M., Zhang, Z., Periasamy, C. and Doumbia, M., 2021. Comparative analysis of thyristor-based and transistor-based rectifiers for PEM water electrolysis. 2021 12th International Renewable Energy Congress (IREC).

[6] Koponen, J., Poluektov, A., Ruuskanen, V., Kosonen, A., Niemelä, M. and Ahola, J., 2021. Comparison of thyristor and insulated-gate bipolar transistor -based power supply topologies in industrial water electrolysis applications. Journal of Power Sources, 491, p.229443.

[7] Koponen, J., Ruuskanen, V., Hehemann, M., Rauls, E., Kosonen, A., Ahola, J. and Stolten, D., 2020. Effect of power quality on the design of proton exchange membrane water electrolysis systems. Applied Energy, 279, p.115791.

[8] Buitendach, H., Gouws, R., Martinson, C., Minnaar, C. and Bessarabov, D., 2021. Effect of a ripple current on the efficiency of a PEM electrolyser. Results in Engineering, 10, p.100216.

[9] Chen, M., Chou, S., Blaabjerg, F. and Davari, P., 2022. Overview of Power Electronic Converter Topologies Enabling Large-Scale Hydrogen Production via Water Electrolysis. Applied Sciences, 12(4), p.1906.

[10] Rakousky, C., Reimer, U., Wippermann, K., Carmo, M., Lueke, W. and Stolten, D., 2016. An analysis of degradation phenomena in polymer electrolyte membrane water electrolysis. Journal of Power Sources, 326, pp.120-128.

[11] HPEM2GAS. 2022. Technical Highlight - HPEM2GAS. [online] Available at: <https://hpem2gas.eu/itm-power-technical-highlight/> [Accessed 3 May 2022].

[12] Bernt, M., 2022. Analysis of Voltage Losses and Degradation Phenomena in PEM Water Electrolyzers. Ph.D. Technische Universität München.

[13] Fch.europa.eu. 2022. [online] Available at: <https://www.fch.europa.eu/sites/default/files/FCH%202%20JU%20MAWP-%20final%20%28ID%204221004%29.pdf> [Accessed 3 May 2022].

[14] Sun, S., Shao, Z., Yu, H., Li, G. and Yi, B., 2014. Investigations on degradation of the long-term proton exchange membrane water electrolysis stack. Journal of Power Sources, 267, pp.515-520.

[15] Papakonstantinou, G., Algara-Siller, G., Teschner, D., Vidaković-Koch, T., Schlögl, R. and Sundmacher, K., 2020. Degradation study of a proton exchange membrane water electrolyzer under dynamic operation conditions. Applied Energy, 280, p.115911.

[16] Irena.org. 2022. [online] Available at: <https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf> [Accessed 3 May 2022].

[17] Rakousky, C., Reimer, U., Wippermann, K., Kuhri, S., Carmo, M., Lueke, W. and Stolten, D., 2017. Polymer electrolyte membrane water electrolysis: Restraining degradation in the presence of fluctuating power. Journal of Power Sources, 342, pp.38-47.