A Novel Low-THDi Rectifier for Electrolysis: Controller Optimization using C-HIL Simulations

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***Abstract*—This paper discusses developing and optimizing a novel low-total harmonic distortion rectifier to run an electrolyzer. As the demand for renewable energy and high-power rectification increases, power quality challenges arise due to non-linear current waveforms caused by rectifiers. Through Controller Hardware-In-the-Loop (C-HIL) simulations, we validate the innovative rectifier's performance and compare it to a conventional 12-pulse thyristor rectifier. The optimization process minimizes total harmonic distortion (THDi) across various operating points, highlighting the importance of tuning some key meta-parameters of the controller as a function of the electrolyzer's setpoint and age.**

***Index Terms*—Power Converter, Power Quality, Hardware-In-the-Loop, Electrolysis, Active Filter.**

I. Introduction

In recent years, the urgent need for a carbon-neutral society has driven the energy transition towards renewable energies and increased use of electric power. The number of electric appliances containing power electronics devices has grown considerably at every level of the power systems, from HVDC transmission and renewable electricity generation to laptop power supply or a simple dimmer switch. However, power electronics devices are intrinsically non-linear; their current or voltage waveforms are not perfectly sinusoidal and contain harmonics. Increasing their penetration is thus likely to cause power quality problems. This is a significant concern for power systems as they can lead them to instability and damage electrical devices [1], [2], especially when they drive high-power processes such as green hydrogen production plants. Green hydrogen, i.e., hydrogen produced by electrolysis of water using "low-carbon" electricity, is considered a crucial energy vector for achieving decarbonization of the industrial and transport sectors. In 2020, less than 3% of the global production of hydrogen was made through electrolysis [3]. Recent technological improvements and European policy have created a certain enthusiasm toward large-scale green hydrogen production. In the 2030 horizon, ENTSO-E predicts an efficiency of around 70% for the best large-scale electrolyzer technologies (Alkaline, PEM, and SOEC) and facilities operating at 100 MW [4]. Therefore, the development of high-power rectifiers, i.e., above 1 MW, is rising for industrial hydrogen production applications. A DC load, like an electrolyzer, draws choppy current waves on the AC side through rectifiers, generating harmonics in the network. The deployment of high-power hydrogen production units therefore represents a challenge in terms of compliance with power quality standards, since the extent of distortion is proportional to the consumed power.

This paper presents a validation and optimization method using Controller Hardware-In-the-Loop (C-HIL) simulations for a novel low-THDi rectifier in development. This innovative rectifier is designed to power a 5 MW electrolyzer. The benefits of the novel design are first introduced, and their performance in terms of total harmonic distortion of the current (THDi) is compared with a 12-pulse thyristors rectifier, a typical solution at this power level. Then, the practical implementation of the control algorithm inside a digital controller is validated. Finally, the controller is optimized by minimizing the THDi for all rectifier operating points by choosing the best control parameters. Section II describes the two rectifier architectures under study and introduces the electrical behavior of an electrolyzer load. Section III briefly explains the developed control principle for the low THDi converter. Section IV presents the C-HIL test bench, the validation process, and the optimization results obtained by relevant parameter sweeping.

II. High Power Rectifier Architecture

A. Electrolysis Constraints

Electrolyzers are electrochemical devices composed of stacked cells that use DC electricity to break down water into

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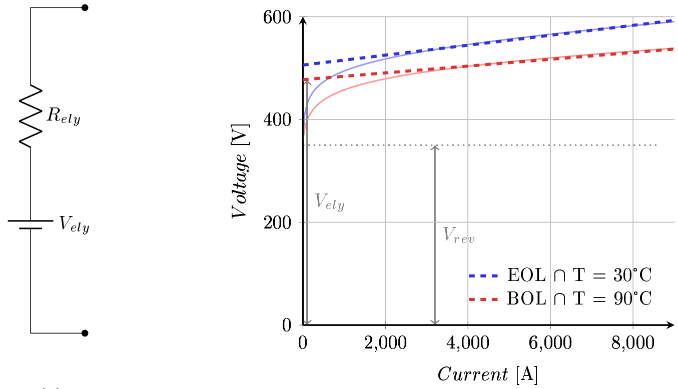

(a)

(b)

Fig. 1: Electrolyzer Model and Characteristics. (a) Equivalent Circuit. (b) V-I Curve of a 5 MW Proton Exchange Membrane (PEM) Electrolyzer.

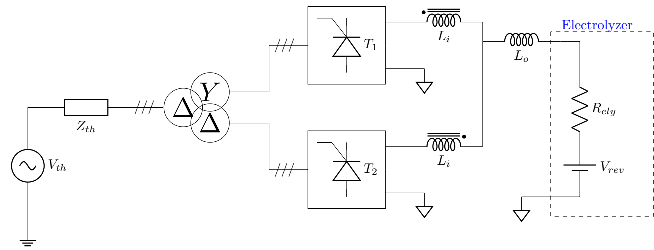

Fig. 2: Conventional 12-pulse Thyristors Rectifier Topology for H_2 production.

hydrogen and oxygen.

Electrolyzers follow the Voltage-Current (V-I) characteristics, illustrated by continuous lines in Figure 1b, derived from thermodynamics laws and chemical equations [5]. This curve shows a non-linear voltage-dependent DC load behavior, which is not practical for electrical simulation. The V-I characteristics are also influenced by the age of the electrolyzer and the operating temperature.

To be complete, an electrolyzer includes electrochemical and thermal dynamics. These dynamics are generally very slow, compared to those of the converter under study [5]. They are therefore omitted from this study. This assumption allows us to model an electrolyzer with a fixed resistance and a constant DC voltage, as shown in Figure 1a [6], [7]. This approximation, represented in dashed lines in Figure 1b, is used in our numerical experiments. This equivalent circuit model is similar to the one of a battery. The DC voltage is designated as V_{ely}, not to be confused with the reversible or Nernst voltage noted V_{rev} which is the minimum electrical potential required to start the hydrogen production process. The power developed by the current flowing through this constant V_{rev} is the useful power for hydrogen production. The remaining additional power is considered a loss. Furthermore, the shape of the V-I curve changes over time as the device ages. Losses increase with time, increasing the series resistance. Figure 1b illustrates the two extreme cases used in this study: a model for an electrolyzer at the beginning of life (BOL) operating at 90°C, and a model for an electrolyzer at the end of life (EOL) operating at 30°C.

B. 12-pulse Thyristors Rectifier

Diode or thyristor rectifiers are the two main families of converters commonly used for electrolyzers. These two families of rectifier solutions are compared for industrial high-power applications in [8]–[10], in terms of efficiency, power quality, and reliability. As hydrogen production is modulated by the current flowing through the electrolyzer and, by extension, by the voltage at its terminals, diode rectifiers have to be combined with DC/DC choppers or IGBT bridges [8], [9]. Unlike diode-based solutions, thyristor or PWM rectifiers enable a simple and direct solution [9]. While the chopper rectifiers offer low THDi and power factor correction features, thyristors exhibit attractive properties due to their efficiency, reliability, and power density for high-current applications, which makes them suitable for hydrogen production on the megawatt scale. Therefore, the thyristor solution appears to be the simplest and the most affordable. The main drawback of a single three-phase thyristor bridge is that it draws a staircase current from the AC side that contains many harmonics. In the past, active filters have already helped to smooth this current using harmonic selection control techniques [11], [12]. Another way to reduce this distortion is to use multiple bridges in series or parallel. These configurations are known as multipulse rectifiers and can have 6, 12, 24, or even more pulses [6], [13]. However, using too many bridges requires more transformers, which can be expensive components. Increasing the number of semiconductors reduces reliability, as it becomes more complicated to avoid their failure. Therefore, a reasonable configuration is the 12-pulse thyristor rectifier shown in Figure 2, the base building block of the novel low-THDi rectifier under study.

C. Novel Low-THDi Rectifier

The idea behind the design of the novel rectifier architecture is to combine the advantages of thyristor bridges with those of IGBT bridges. This means transmitting a high amount of power while controlling the power factor and enabling low harmonic distortion.

To achieve this goal, the well-known solution is to add passive or active filters in shunt or series with the non-linear appliance that disturbs the network [7], [14]. Active filters are typically IGBT-based converters connected to an energy buffer, which can be a capacitor or reactor. They are controlled to generate a current or voltage that will dynamically compensate for the harmonics and phase shift. The innovation in the converter under development is that the active filter is fully encapsulated in the power supply. Firstly, this allows active power to be transferred through the active filter parts, which can improve the efficiency of the overall power supply. Secondly, it enables the implementation of more advanced and powerful control algorithms, as the same controller manages

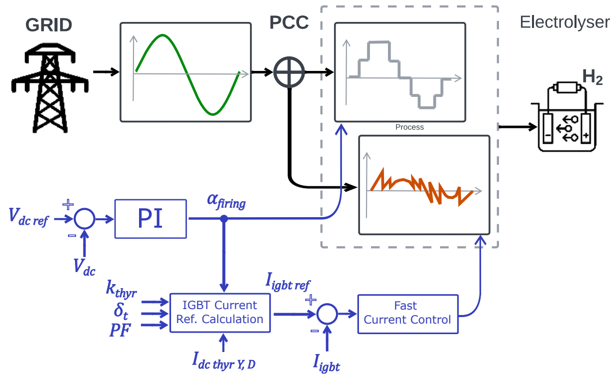

Fig. 3: Conceptual Schematic of the 5 MW power supply designed for hydrogen production, showing current waveforms and main control blocks.

the entire system. Figure 3 illustrates the concept of this novel rectifier solution for high-power hydrogen production.

III. Controller Principle

The control algorithm comprises two main control loops: the control of the electrolyzer voltage and the rapid control of the alternating current flowing through the active filter. Voltage control is performed by a PI controller, which adjusts the firing angle of the 12-pulse thyristor bridge to modulate the output voltage. This creates a stable DC voltage at the output, enabling the IGBT (VSC configuration) bridge to control the compensation current correctly. The principle of the second control loop is, therefore, similar to that of a grid-connected inverter, which computes a current reference for the AC side and attempts to reach it.

To compute this AC reference for the IGBT inverter, the controller first uses measurements and computations to estimate the current drawn by the thyristor bridges at the point of connection to the grid. The controller then computes the desired sinusoidal current according to the desired power factor and a parameter named k_{thyr}. The estimation of the thyristor current is then subtracted from this desired sinusoidal current, noted $I_{grid\,ref}$, to obtain the current reference for the IGBT inverter, noted $I_{igbt\,ref}$.

The k_{thyr} parameter fixes the amplitude, noted $I_{m\,Grid}$, of the desired sinusoidal current, relative to the peak value of the thyristors' staircase current :

$$I_m(t) = \frac{1}{k_{thyr}}(n_Y I_{dc\,thyr\,Y}(t) + n_D I_{dc\,thyr\,D}(t)) \quad (1)$$

$$I_{grid\,ref}(t) = I_m(t) sin(\omega t) \quad (2)$$

with $I_{dc\,thyr\,Y}$, $I_{dc\,thyr\,D}$ the filtered current measured in each branch of the interphase reactor, and n_Y, n_D the corresponding transformer ratio of the 12-pulse thyristors part.

The purpose of this parameter is to control the active power repartition between the thyristors and the IGBTs parts. If k_{thyr} is maximum, all the active power is transmitted via the thyristor bridges while the IGBT inverter performs only harmonic compensation and power factor correction. For smaller values of k_{thyr}, the inverter transmits a share of the desired active power to the load. This parameter has been designed primarily to control and optimize the converter's efficiency according to load conditions. The maximum value of k_{thyr} varies according to the phase shift between the two current waveforms. It is hence related to the resulting firing angle of the load and the power factor setpoint. The lower limit of the possible value of k_{thyr} depends on the thermal limit of the IGBTs, which depends on the current flowing through them. By extension, this k_{thyr} limit is also influenced by the power setpoint.

One of the challenging parts of this control algorithm lies in the current control of $I_{igbt\,ref}$. Indeed, the waveform of the current to be reached varies greatly over time, with sometimes very steep edges, as illustrated by the red curve in Figure 3, requiring the controller to react very quickly. This is particularly challenging given that the switching frequency of IGBTs is around 9 kHz, which is relatively low.

The challenge was achieved using an FPGA-based controller and an algorithm similar to the current control of hysteresis. Although the digital controller is high-speed (two execution rates of 50 µs and 1 µs), it still has to anticipate steep edges as there remains a non-negligible settling time when the reference changes. Therefore, another essential control parameter is the time shift δ_t that quantifies how much we anticipate. This parameter requires tuning as the settling time depends on the system's dynamics. The inductive characteristics of both parts mainly influence the dynamics. The overlap effect occurring during thyristors' commutation also influences the slope of these edges.

The following section shows the advantages of C-HIL simulation for the development of complex power converters and highlights its value for optimal controller tuning regarding these two parameters, i.e. k_{thyr}, and δ_t.

IV. C-HIL Simulations

The C-HIL platform is a real-time digital simulator with a hardware interface for exchanging analog and digital signals

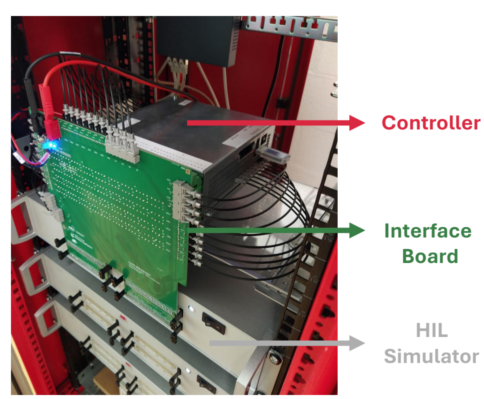

Fig. 4: C-HIL hardware setup for the validation of the active filter and rectifier controller.

with real controllers. This platform has already been used to speed up the validation process of other power supplies or motor drives under development [15], [16]. The platform's principle is as follows: a specialized simulator device emulates the system's plant, i.e. the electrolyzer and power converters stay in a virtual environment, and the intended controller is implemented on the real digital commercial controller. This enables quick controller prototyping by providing the flexibility of a conventional simulation, allowing the system to be adjusted when required while getting close to the accuracy of a laboratory experiment without requiring the manipulation of high-power currents. Figure 4 shows the C-HIL setup realized for the study.

This type of tool offers two main advantages for power electronics validation. Firstly, it emulates all hazardous voltage or current levels, ensuring no material damage during testing. Secondly, power converters are complex, non-linear systems. Conventional electromagnetic transient (EMT) simulators sometimes require computations 100 to 1000 times longer than the simulated period. HIL simulators guarantee real-time operation, which means that one second of simulation is equivalent to one second of computation. These features make it the ideal tool for studying power converters at all possible operating points. The data generated by C-HIL simulation can be used, among other things, to optimize controller design or tuning, as we will demonstrate below.

A. Validation

The rectifier and its controller should be validated for all possible load and network conditions. For the sake of brevity, we will illustrate the correct operation of our system with a test at 100% loading in the BOL electrolyzer case. The test is performed with the controller's parameters fixed at power factor $PF = 1$, $\delta_t = 100$ µs, and $k_{thyr} = 0.9$.

The results are expressed in per-unit form, with $P_b = 5$ MW, $I_b = 9000$ A, $V_b = \frac{P_b}{I_b} = 555$ V, and $R_b = \frac{P_b}{I_b^2} = 62$ mΩ serving as the base power, current, voltage, and resistance for the DC part, respectively. Figure 1b illustrates the electrolyzer model in dashed red with $V_{ely} = 0.85$ pu and $R_{ely} = 0.11$ pu. The AC grid side variables are normalized using $S_b = 5$ MVA, $U_{bRMS} = 30$ kV, $I_{bRMS} = \frac{S_b}{\sqrt{3}U_bRMS}$ and $f_b = 50$ Hz.

Figure 5 shows the transition from conventional 12-pulse rectification to the new filtered rectification during a few network periods. Only one phase is shown for simplicity. All curves in the lower graph represent currents observed from the AC grid connection base: in gray, the estimated current drawn by the 12-pulse thyristor bridge I_{thyr}; in red, the measured current drawn by the IGBT section I_{igbt}; and in green, the total measured current drawn on the network I_{grid}. The stepped waveform is transformed into a smoother sinusoidal current. The THDi, measured according to the standard [17], drops from 11.8% to 2.5% when the IGBT bridge is activated at 0 ms. As desired, given the chosen value of k_{thyr} parameter, the peak of the total sinusoidal current is slightly higher than the current flowing through the thyristor. Some distortion still

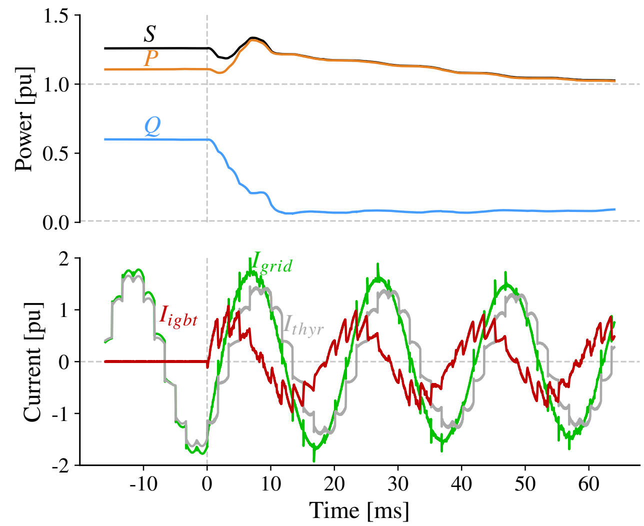

Fig. 5: C-HIL data capture of the grid current when it switches to the novel rectification mode, with the contribution of each converter part and the measured power sink from the grid.

occurs at each thyristor bridge pulse transition. This shows that control parameters, such as δ_t, need fine-tuning to minimize THDi. Finally, the peak value of the green curve undergoes a dynamic decrease in amplitude as a result of power control.

Indeed, DC voltage control maintains active power at 1 pu on the load side. In conventional 12-pulse rectification, the modulation of active power creates an inherent reactive power, linked to the firing angle, illustrated in the upper part of Figure 5. The active power at the grid connection, P, is measured above 1 pu before the start of the new mode. This indicates losses in the thyristor path. When the novel rectification mode starts, the control unit tries to compensate for the reactive power as the target PF is set to 1. This is observed by the decrease in Q. In addition, a decrease in active power losses is observed as P tends towards 1 pu. This shows that the novel rectifier architecture is also beneficial for conversion efficiency. However, this efficiency improvement, $> 5\%$, seems perhaps too optimistic compared to the typical efficiency of IGBT and thyristor bridges. This result could be mitigated by further analysis.

B. Control Optimization

The optimization aims to improve the performance of the rectifier and learn more about the system's characteristics. Indeed, such a complex converter with digital control can sometimes reveal unexpected behavior due to unforeseen system interaction. A grid-search method is therefore used. This method browses the operating space of simulation and control parameters, generates the data, and analyzes the different metrics of interest.

The grid search is performed for the two electrolyzer cases EOL ($V_{ely} = 0.91$ pu and $R_{ely} = 0.16$ pu) and BOL ($V_{ely} = 0.85$ pu and $R_{ely} = 0.11$ pu) introduced in

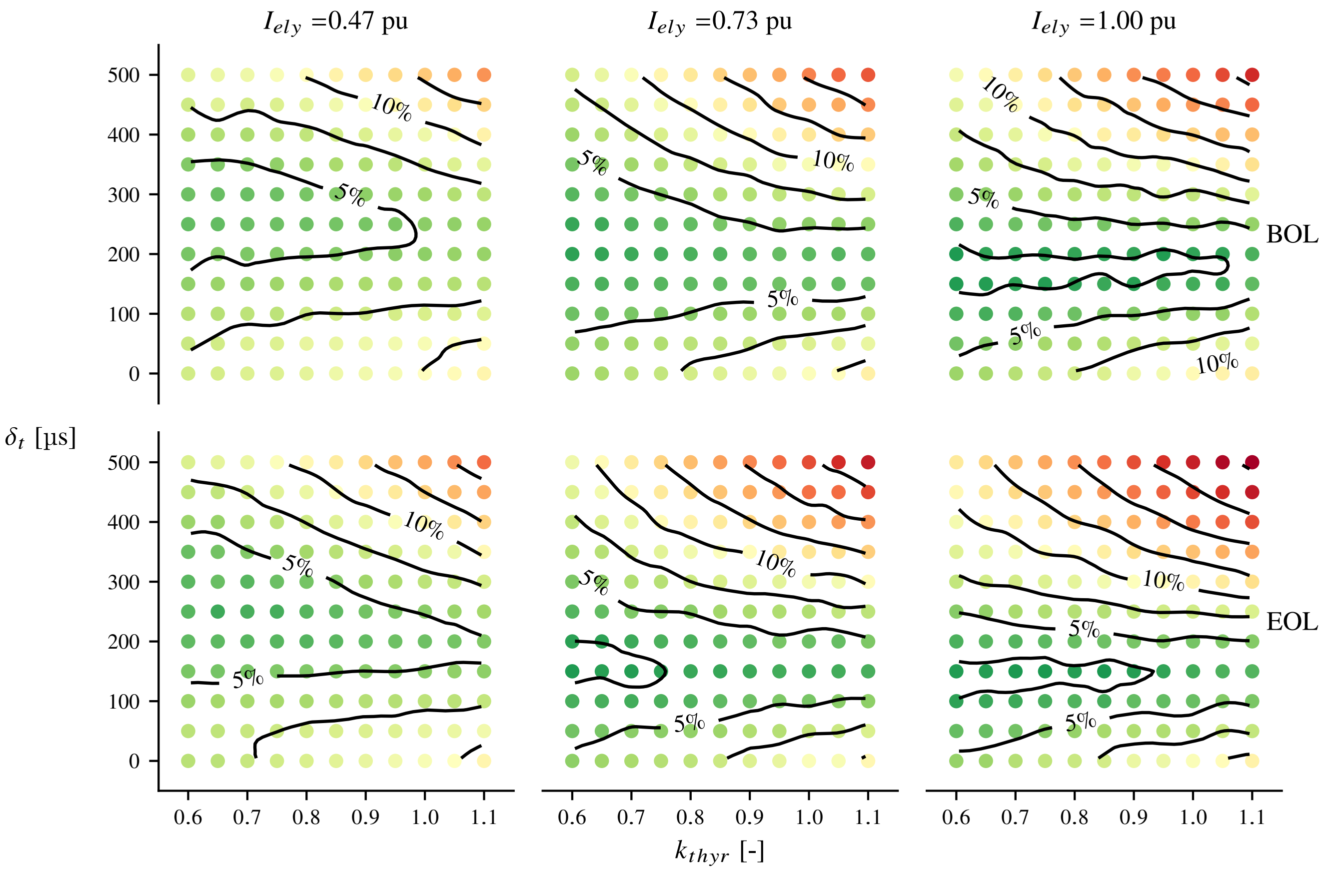

Fig. 6: Minimization of THDi as a function of control parameters k_{thyr} and δ_t for different BOL and EOL electrolyzer consumption. The greater the load, the greater the optimum in a deep valley, which means that at higher loads, this novel rectifier can reach THDi lower than 2.5%, provided it is properly tuned.

Section II-A. The search has three dimensions. First, it browses the load conditions. The set point of the DC voltage is set to obtain 20%, 47%, 73%, and 100% of current flowing through the electrolyzer, noted I_{ely}, for both models, as hydrogen production is directly proportional to it. The parameters k_{thyr} and δ_t are browsed more finely, from 0.6 to 1.1 and from 0 μs to 500 μs, respectively, to obtain more information about their influence on the system performance. The Power Factor setpoint is fixed to 1.

Figure 6 shows several contour plots of THDi minimization, interpolated through the grid search results for the cases BOL and EOL. Furthermore, Table I summarizes all the optimal points found according to load conditions and reveals, as expected, that the novel rectifier largely outperforms the 12-pulse thyristor rectifier case. First, the comparison between BOL and EOL's best THDi scores shows that operating at higher DC Voltage, i.e. EOL, leads to a lower THDi. This probably implies that the control algorithm performs better when the firing angle of the 12-pulse thyristor bridge is lower as the output DC voltage is inversely proportional to the firing angle.

In terms of optimal controller settings, EOL required slightly smaller δ_t than BOL but similar k_{thyr}. Observing the contour plot gives interesting intuition about our control behavior. As expected, the THDi seems to be mostly sensitive to variation of δ_t under most load conditions. One other noticeable result is that, surprisingly, the k_{thyr} parameter also impacts the performance of THDi depending on the load conditions. At high load, the distortion is slightly influenced by the k_{thyr} variations, while at low load, the optimal value decreases. This means that transferring more power through the IGBT parts is beneficial for the current distortion on the grid at a lower load. The last observation is about the low load test. Although the test improves THDi compared to the 12-pulse Thyristor case, 7 to 8% is still relatively high. This observation can be mitigated by noting that a low-intensity current, even if highly distorted, will only generate minor voltage distortions through the grid. Nonetheless, the control algorithm can probably be improved for the low loading conditions, which is another key learning from this study.

V. Conclusion

The C-HIL is a powerful tool that has enabled the optimization of control parameters in a short time for a com-

TABLE I: Optimized parameters with a resolution of 0.05 and 50 µs, respectively for k_{thyr} and δ_t, and 12-pulse thyristor characteristics.

Load	**Optimal Values**						**12-Pulse Thyristor**			
	k_{thyr}		δ_t [µs]		THD [%]		THD [%]		PF	
	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL
0.20 pu I	0.7	0.7	300	300	7.9	7.1	12	12.2	0.67	0.71
0.47 pu I	0.7	0.65	300	250	4.1	3	9.7	9.9	0.75	0.82
0.73 pu I	0.6	0.6	200	150	2.6	2.1	10.8	11.4	0.81	0.89
1.00 pu I	0.95	0.85	200	150	2.2	2	11.8	12.8	0.87	0.97

plex converter. This methodology will be reused for future interesting analyses. Their objectives will be to test the performance and robustness of the developed controller in various grid conditions and to observe its behavior in case of grid faults. The efficiency of the converter should also be studied, taking into account the detailed characteristics of the various semiconductors, which have been deliberately abstracted in this work to emphasize the methodology. The final choice of the parameter k_{thyr} should take into account its contribution to lowering the harmonic distortion, but also its contribution to increasing the overall efficiency of the converter. Perspectives could also include the electrochemical and thermal dynamics of the electrolyzer by modifying its electrical circuit model, and analyzing how these dynamics influence the controller behavior. The results also confirm that the novel rectifier architecture can guarantee a low THDi for different electrolyzer loadings, which is promising for large-scale deployment of green hydrogen production.

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REFERENCES

[1] D. Li, T. Wang, W. Pan, X. Ding, and J. Gong, "A comprehensive review of improving power quality using active power filters," *Electric Power Systems Research*, vol. 199, p. 107389, 2021.

[2] L. Motta and N. Faundes, "Active/passive harmonic filters: Applications, challenges & trends," in *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*. IEEE, October 2016, pp. 657–662.

[3] Global CCS Institute, "Distribution of hydrogen production worldwide in 2020, by type," In Statista, December 10 2020, [Graph]. [Online]. Available: https://www.statista.com/statistics/1200503/global-hydrogen-production-share-by-type/

[4] F. E. L. ENTSO-E, "Potential of p2h2 technologies to provide system services," Tech. Rep., 2022. [Online]. Available: https://www.entsoe.eu/2022/06/28/entso-e-publishes-a-study-on-flexibility-from-power-to-hydrogen-p2h2/

[5] M. H. Nehrir and C. Wang, *Modeling and control of fuel cells: distributed generation applications*. John Wiley & Sons, 2009.

[6] S. Puteanus, S. Wettengel, M. Meißner, and S. Bernet, "Multipulse rectifiers for large scale water-electrolysis-reactive power and harmonics," in *2024 Energy Conversion Congress & Expo Europe (ECCE Europe)*. IEEE, 2024, pp. 1–8.

[7] J. Solanki, N. Fröhleke, J. Böcker, and P. Wallmeier, "Comparison of thyristor-rectifier with hybrid filter and chopper-rectifier for high-power, high-current application," in *Proc. PCIM Europe*, 2013, pp. 1391–1398.

[8] M. Chen, S. F. Chou, F. Blaabjerg, and P. Davari, "Overview of power electronic converter topologies enabling large-scale hydrogen production via water electrolysis," *Applied Sciences*, vol. 12, no. 4, p. 1906, 2022.

[9] B. Yodwong, D. Guilbert, M. Phattanasak, W. Kaewmanee, M. Hinaje, and G. Vitale, "Ac-dc converters for electrolyzer applications: State of the art and future challenges," *Electronics*, vol. 9, no. 6, p. 912, 2020.

[10] J. R. Rodríguez, J. Pontt, C. Silva, E. P. Wiechmann, P. W. Hammond, F. W. Santucci, R. Álvarez, R. Musalem, S. Kouro, and P. Lezana, "Large current rectifiers: State of the art and future trends," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 3, pp. 738–746, 2005.

[11] C. Lascu, L. Asiminoaei, I. Boldea, and F. Blaabjerg, "High performance current controller for selective harmonic compensation in active power filters," *IEEE Transactions on Power electronics*, vol. 22, no. 5, pp. 1826–1835, 2007.

[12] S. Buso, L. Malesani, and P. Mattavelli, "Comparison of current control techniques for active filter applications," *IEEE transactions on industrial electronics*, vol. 45, no. 5, pp. 722–729, 1998.

[13] B. Singh, S. Gairola, B. N. Singh, A. Chandra, and K. Al-Haddad, "Multipulse ac–dc converters for improving power quality: A review," *IEEE transactions on power electronics*, vol. 23, no. 1, pp. 260–281, 2008.

[14] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, 1999.

[15] A. Bouscayrol, "Different types of hardware-in-the-loop simulation for electric drives," in *2008 IEEE International Symposium on Industrial Electronics*. IEEE, 2008, pp. 2146–2151.

[16] D. Majstorovic, I. Celanovic, N. D. Teslic, N. Celanovic, and V. A. Katic, "Ultralow-latency hardware-in-the-loop platform for rapid validation of power electronics designs," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4708–4716, 2011.

[17] International Electrotechnical Commission, "IEC 61000-4-7: Testing and measurement techniques for harmonics and interharmonics," IEC, Tech. Rep., 2002.