23rd June 2025

Green Hydrogen Electrolysers in forming future grids – Power Electronics Perspectives

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AGENDA

- Introduction
- Challenges in the electrolysers power chain control
- Proposed power converters and control approaches
- PHIL validation tests
- Future work
- Conclusions

GRID CODES UPDATES

ACER European Union Agency for the Cooperation of Energy Regulators

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20.12.2024

ACER proposes electricity Grid Connection Network Code amendments to the European Commission

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ACER
European Union Agency for the Cooperation of Energy Regulators

RECOMMENDATION No 01/2024
OF THE EUROPEAN UNION AGENCY
FOR THE COOPERATION OF ENERGY REGULATORS

of 19 December 2024

on reasoned proposals for amendments to Commission Regulation (EU) 2016/1447 of 26 August 2016 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules

(21) More specifically, ACER proposes the frequency stability requirements, reactive power and voltage requirements to apply to asynchronously connected power park modules, asynchronously connected demand facilities, asynchronously connected power-to-gas demand units and asynchronously connected electricity storage modules. ACER also proposes the introduction of new articles on fault-ride-through capability and overvoltage ride through capability of power-to-gas demand units and grid forming capability of asynchronously connected PPMs and asynchronously connected electricity storage modules. ACER proposes amendments to control requirements, network characteristics, protection requirements, power quality and general system management requirements applicable to asynchronously connected power park modules, asynchronously connected electricity storage modules and asynchronously connected demand facilities. ACER also proposes amendments to frequency stability requirements, reactive power and voltage requirements, network characteristics and power quality for remote-end HVDC converter stations.

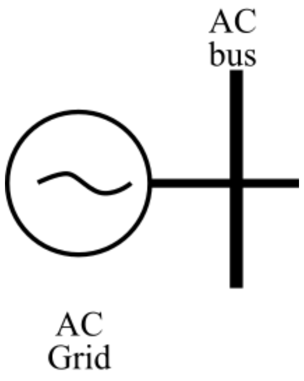
ACER website (2024, Dec. 20).“RECOMMENDATION No 01/2024 OF THE EUROPEAN UNION AGENCY FOR THE COOPERATION OF ENERGY REGULATORS,” www.acer.europa.eu, 2024. https://www.acer.europa.eu/news-and-events/news/acer-proposeselectricity- grid-connection-network-code-amendments-europeancommission (accessed Dec. 27, 2024).

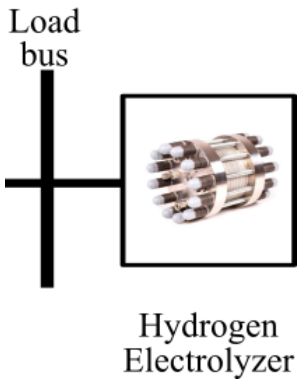
<u>Hydrogen Electrolyzers models are complex and dependent on:</u>

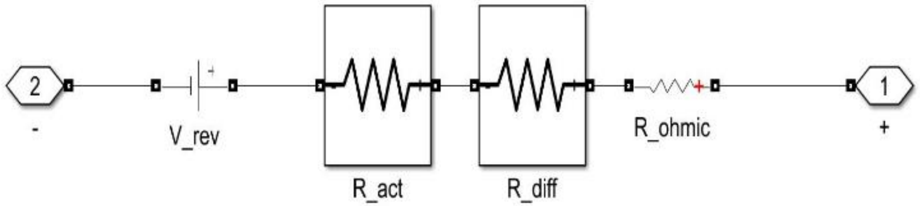
- Temperature
- Pressure
- Geometry
- Chemical solutions concentration
- Several other constants

+ Operating point

- **Behavior changes at every operating point**
- **Operation is sensitive to current**
- **Typical controllers aren’t suitable**
- **Typical Diode/Thyristor power converters aren’t suitable**







Electrolyzer electric equivalent at steady state

$$V_{act} = \frac{RT}{nF\alpha}\ln\left(\frac{I}{I_0}\right)$$

int of view:

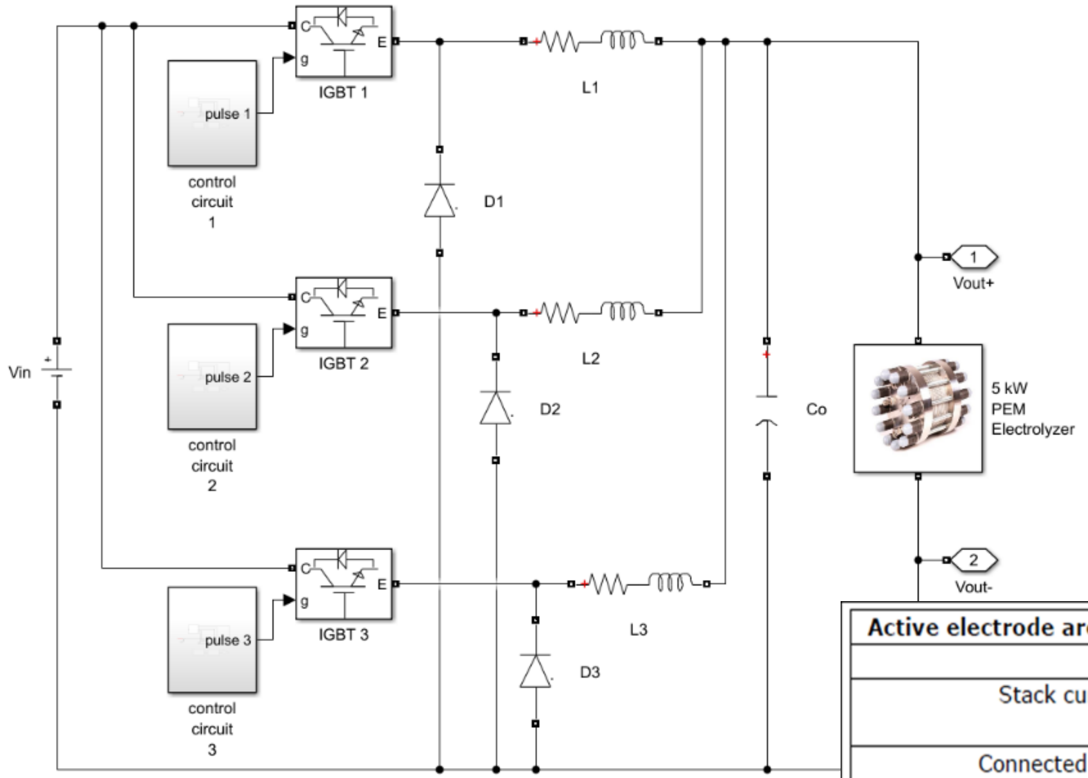
$$V_{diff} = \frac{RT}{nF\beta}\ln\left(1 + \frac{I}{I_{lim}}\right)$$

V] / A] $= 0.2235\ [\Omega]$

$$V_{rev} = V_0 + \frac{RT}{2F}\ln\left(\frac{P_{H_2}\sqrt{P_{O_2}}}{a_{H_2O}}\right)$$

170 [V] / A] $= 3.6765\ [\Omega]$

$$V_{ohm} = \frac{l_m}{A_m * (0.005139\lambda + 0.00326) * \exp\left(1276\left(\frac{1}{303} - \frac{1}{T}\right)\right)} * I$$



Active electrode area: 67.9 cm² (ø 93 mm)
Number of cells: 15
Stack current @ 40 bar @ 70 °C: 6.8 - 149.4 A (DC)
Connected load @ 40 bar @ 70 °C: approx. 0.17 - 4.99 kW @ BOL

$$H(s) = \frac{\Delta I_L}{\Delta D} = \frac{V_{in}}{L} * \frac{\left(s + {}^{1}/_{RC}\right)}{\left(s^2 + {}^{1}/_{RC}\, s + {}^{1}/_{LC}\right)}$$

$$= \frac{V_{in}}{L} * \frac{(s+z_1)}{(s+p_1)(s+p_2)},$$

Where, $$s_{1,2} = \frac{-L \pm \sqrt{L(L-4CR^2)}}{2LCR}$$

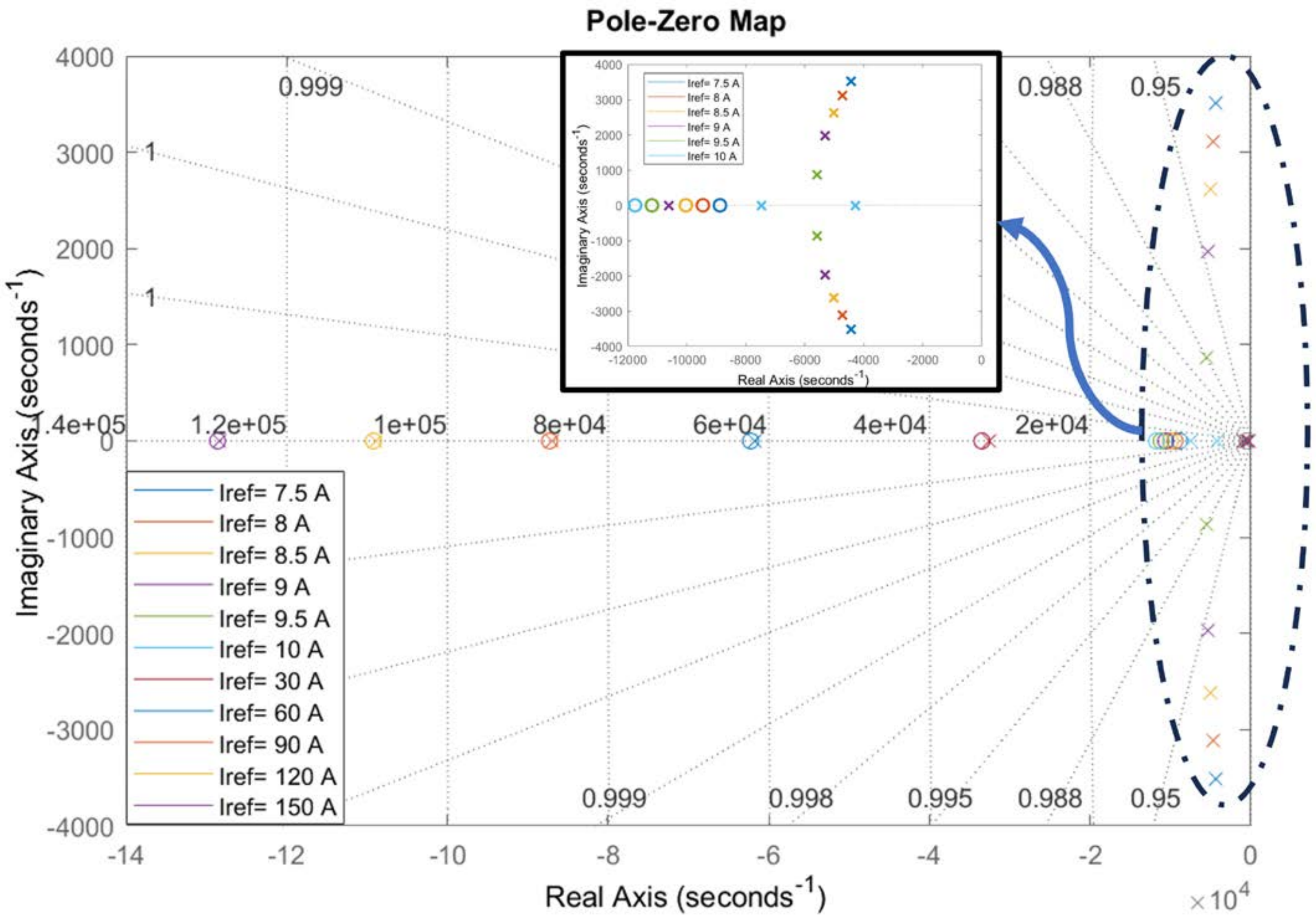
Y. Zhao, W. Qiao and D. Ha, "A Sliding-Mode Duty-Ratio Controller for DC/DC Buck Converters With Constant Power Loads," in IEEE Transactions on Industry Applications, vol. 50, no. 2, pp. 1448-1458, March-April 2014, doi: 10.1109/TIA.2013.2273751

MODELS OF PEM ELECTROLYSER AND BUCK CONVERTER- 2

TABLE I
PARAMETERS TABLE PER CONVERTER

Parameter	V_{in}	ΔI_L	ΔV_{out}	L	C	$F_{switching}$
Value	150 V	0.3 A	0.1 V	2.5 mH	$12.5\mu F$	20 kHz

- ❖ Typical PI controllers aren’t suitable and pose limitations
- ❖ Typical Diode/Thyristor power converters aren’t suitable



PROPOSED CONTROL SCHEME - LEAD LAG

$$C(s)_{lead} = K_{lead} * \frac{(s + \dots}{(s + \dots p_c}$$

$$C(s)_{lag} = \frac{(s + z_{lag})}{(s + p_{lag})}$$

$$K = \frac{\prod L_p}{\prod L_z} = \frac{L_{p1} * \dots}{L_{z1} * L_{z_{lead}}} \dots L_{z1}$$

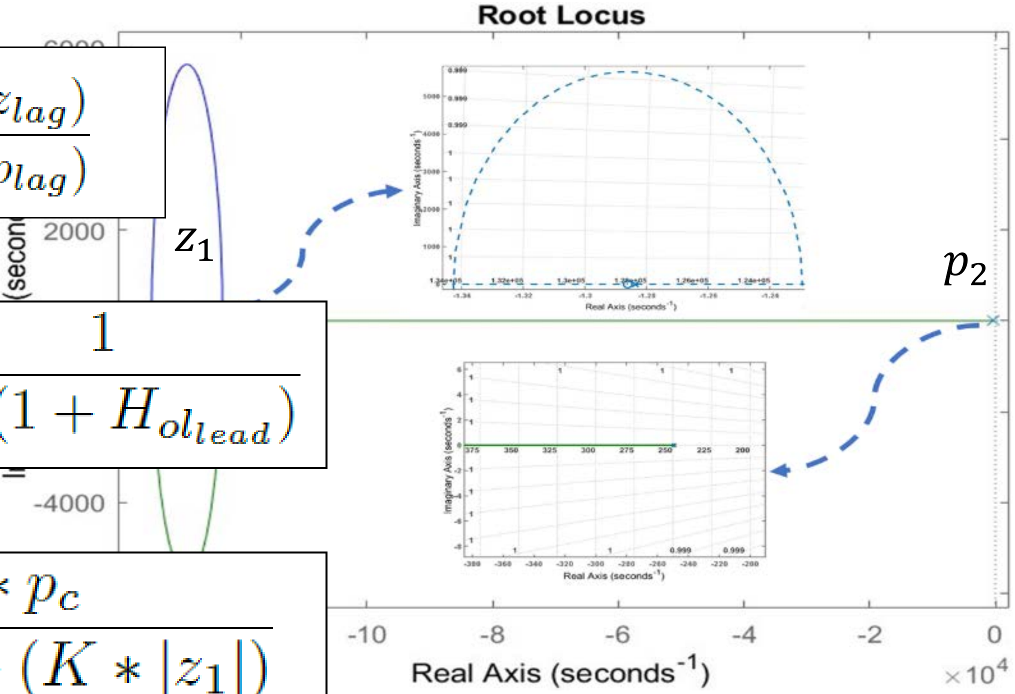
$$E_{ss} = \lim_{s \to 0} s * \frac{1}{s * (1 + H_{ol_{lead}})}$$

$$E_{ss} = \frac{p_1 * p_c}{(p_1 * p_c) + (K * |z_1|)}$$

$$K = K_{lead} * \frac{V_{in}}{L} = \sqrt{(|(P_1| - |Re(P_1)|)^2 + (|Im(P_1)|)^2 \dots}$$

$$\frac{|P_{lag}|}{|z_{lag}|} = \frac{0.99 * (P_c * P_1)}{0.01 * K * |z_1|}$$

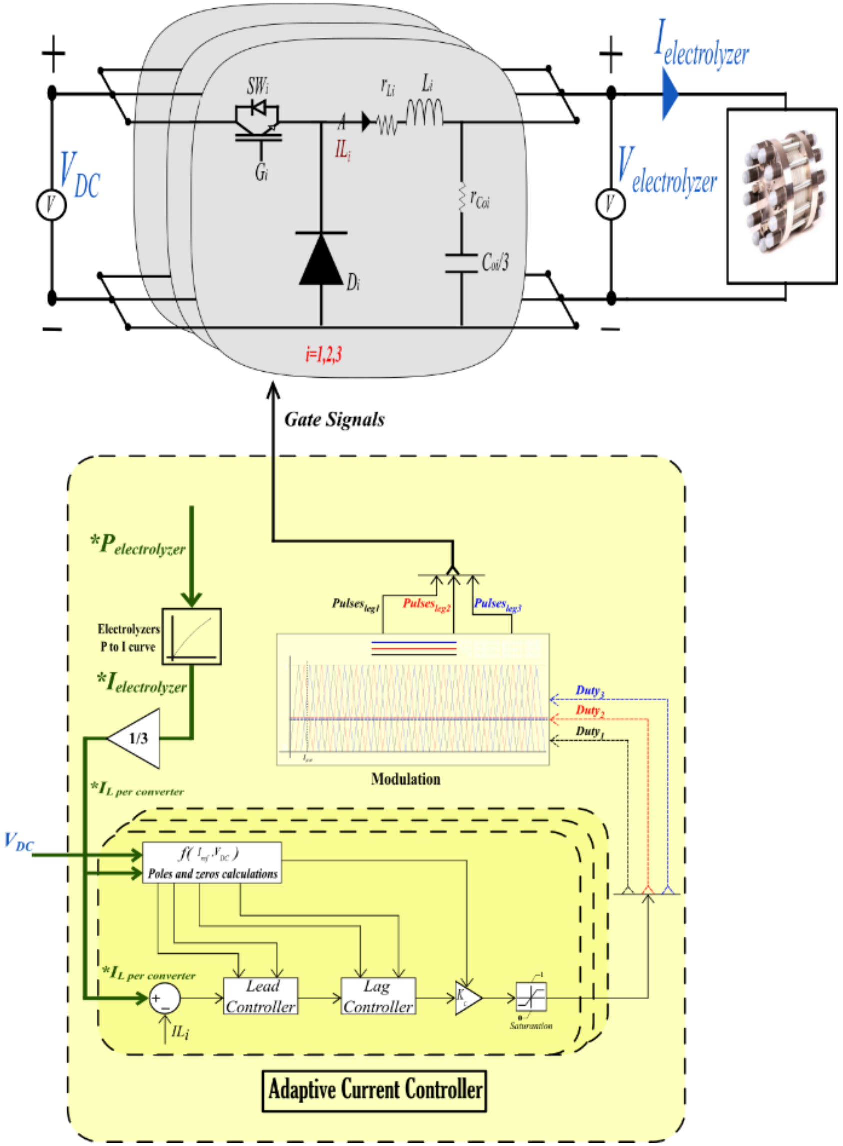
$$H_{ol_{lead}} = \frac{V_{in}}{L} * K_{lead} * \frac{(s + z_1)}{(s + p_1)(s + p_c)}$$



Steady state error $(E_{ss}) = 1\%$

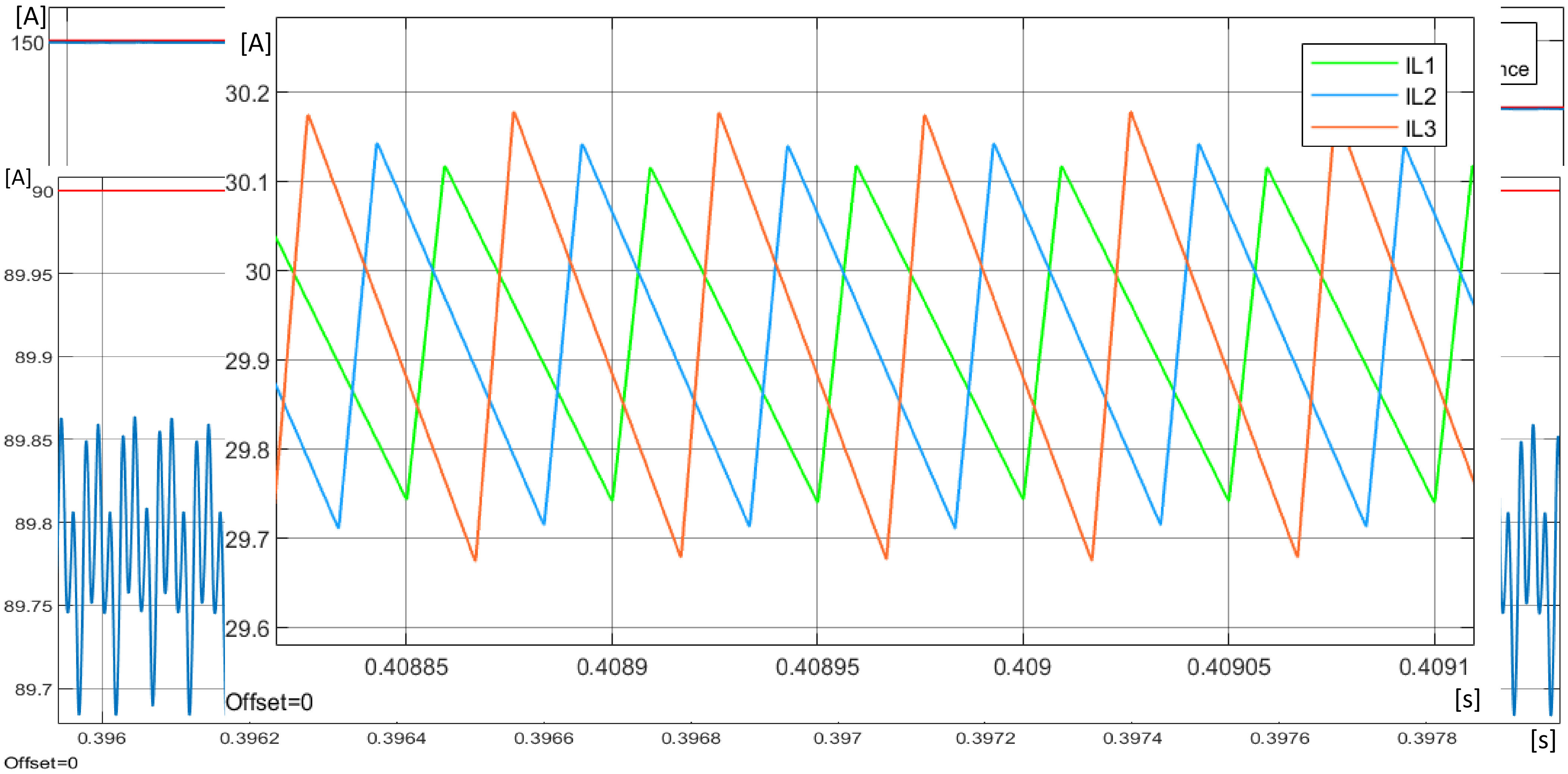
ADAPTIVE LEAD LAG CURRENT CONTROLLER

- ✓ Calculate the operating I_{ref} based on P_{ref} using the polarisation curve
- ✓ Calculate system poles and zeros using the $V_{Dc\ in}$, I_{ref} , and circuit passive components
- ✓ Based on the calculated poles and zeros, the gain and coefficients of the lead controller are computed to cancel the system's ones and introduce the intended control pole
- ✓ The lag controller coefficients are calculated in a similar manner to achieve the required steady-state error
- ✓ Modulation for each leg with 120 degrees phase shift for ripples cancelation



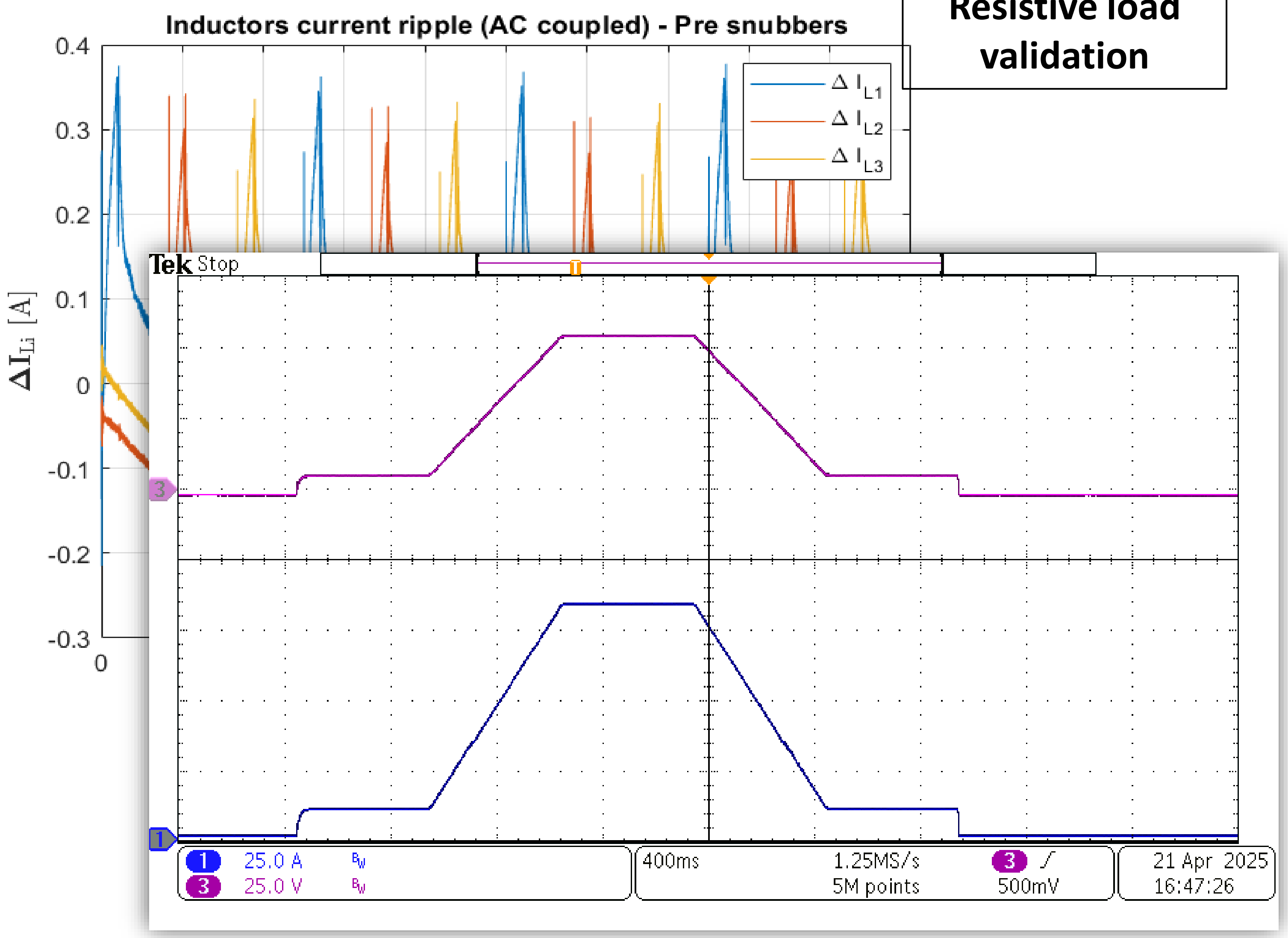
A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "A New Adaptive Lead-Lag Control Scheme for High Current PEM Hydrogen Electrolyzers," 2023 IEEE Vehicle Power and Propulsion Conference (VPPC), Milan, Italy, 2023, pp. 1-6, doi: 10.1109/VPPC60535.2023.10403130.

SW RESULTS: NON-IDEAL COMPONENTS CASE



A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "A New Adaptive Lead-Lag Control Scheme for High Current PEM Hydrogen Electrolyzers," 2023 IEEE Vehicle Power and Propulsion Conference (VPPC), Milan, Italy, 2023, pp. 1-6, doi: 10.1109/VPPC60535.2023.10403130.

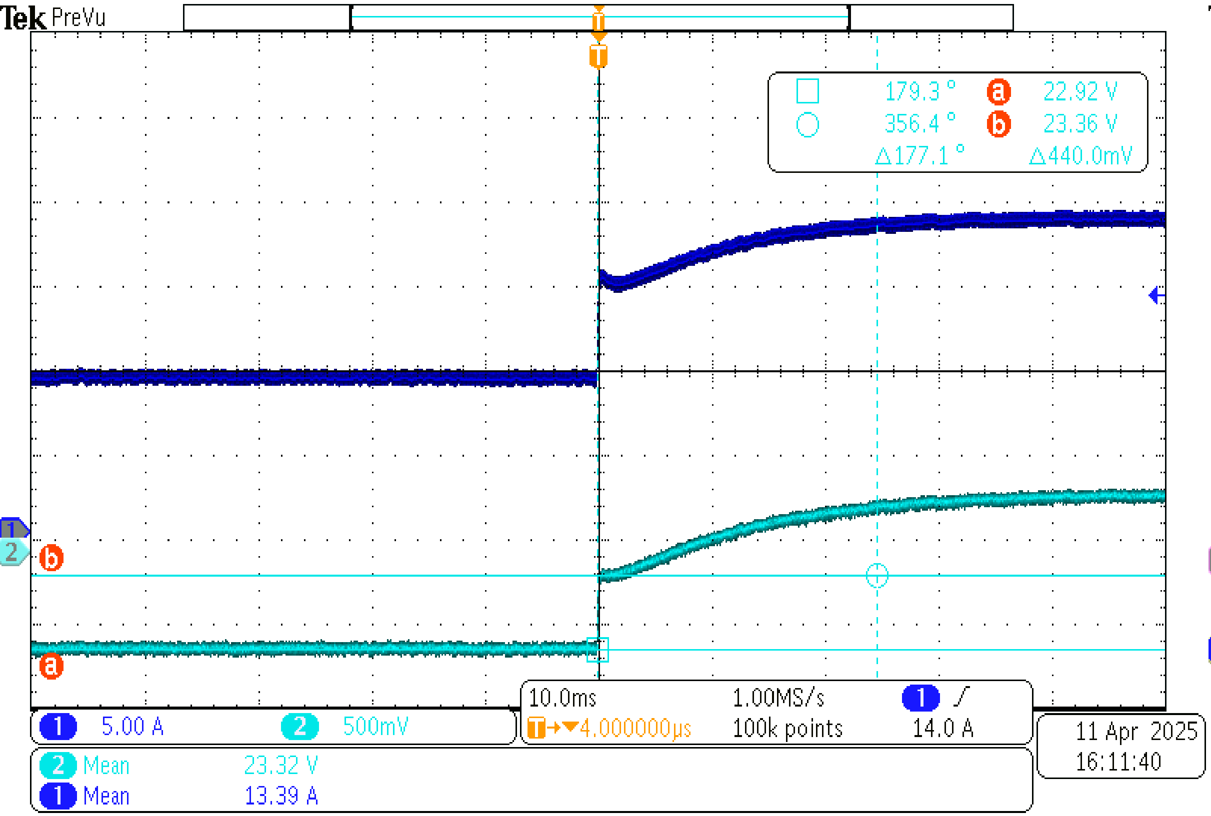
HW RESULTS - 1

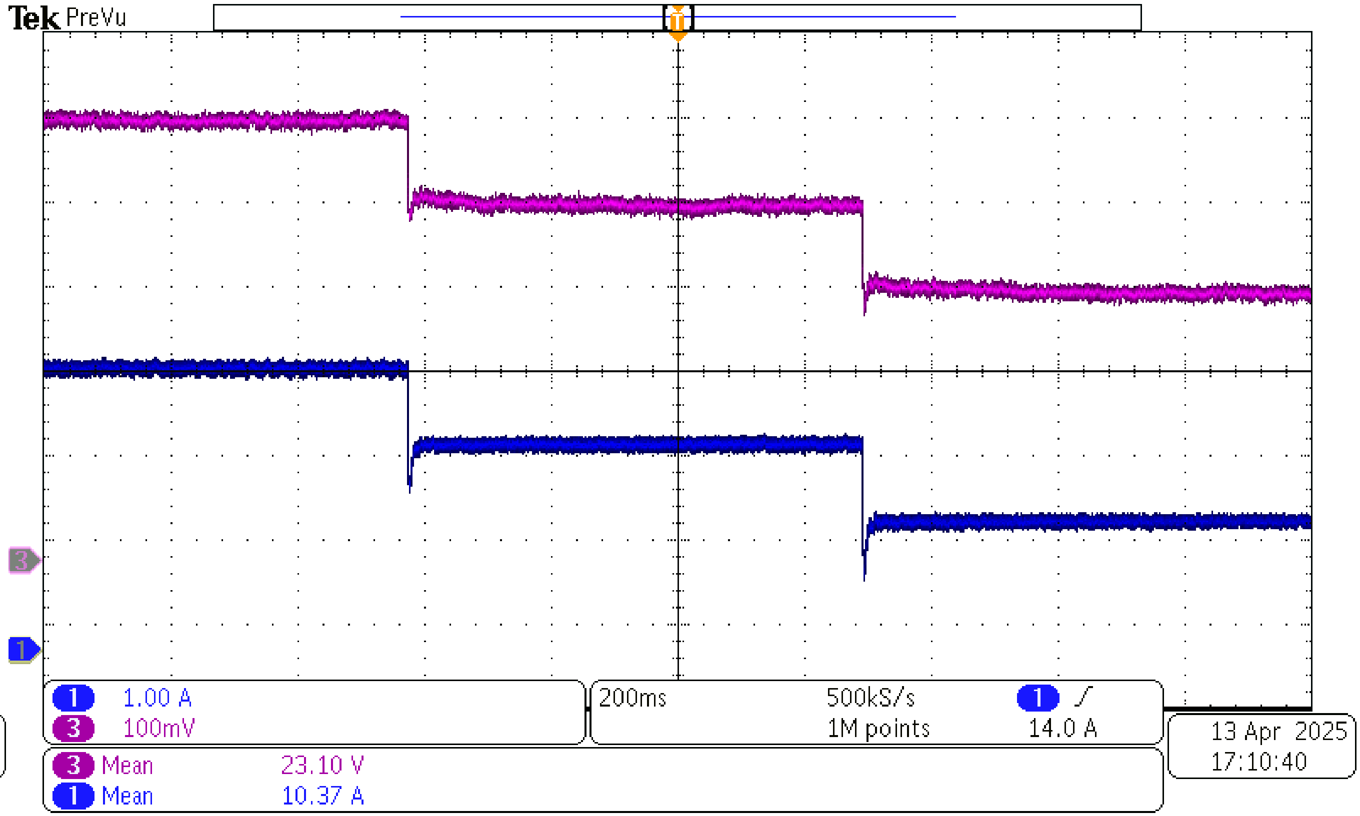


Resistive load validation

HW RESULTS- 2

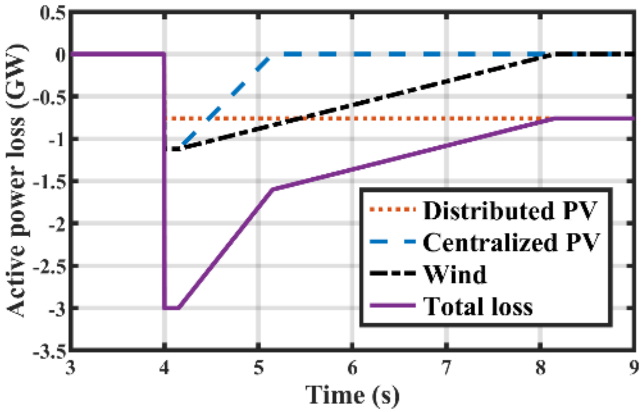
Electrolyser validation

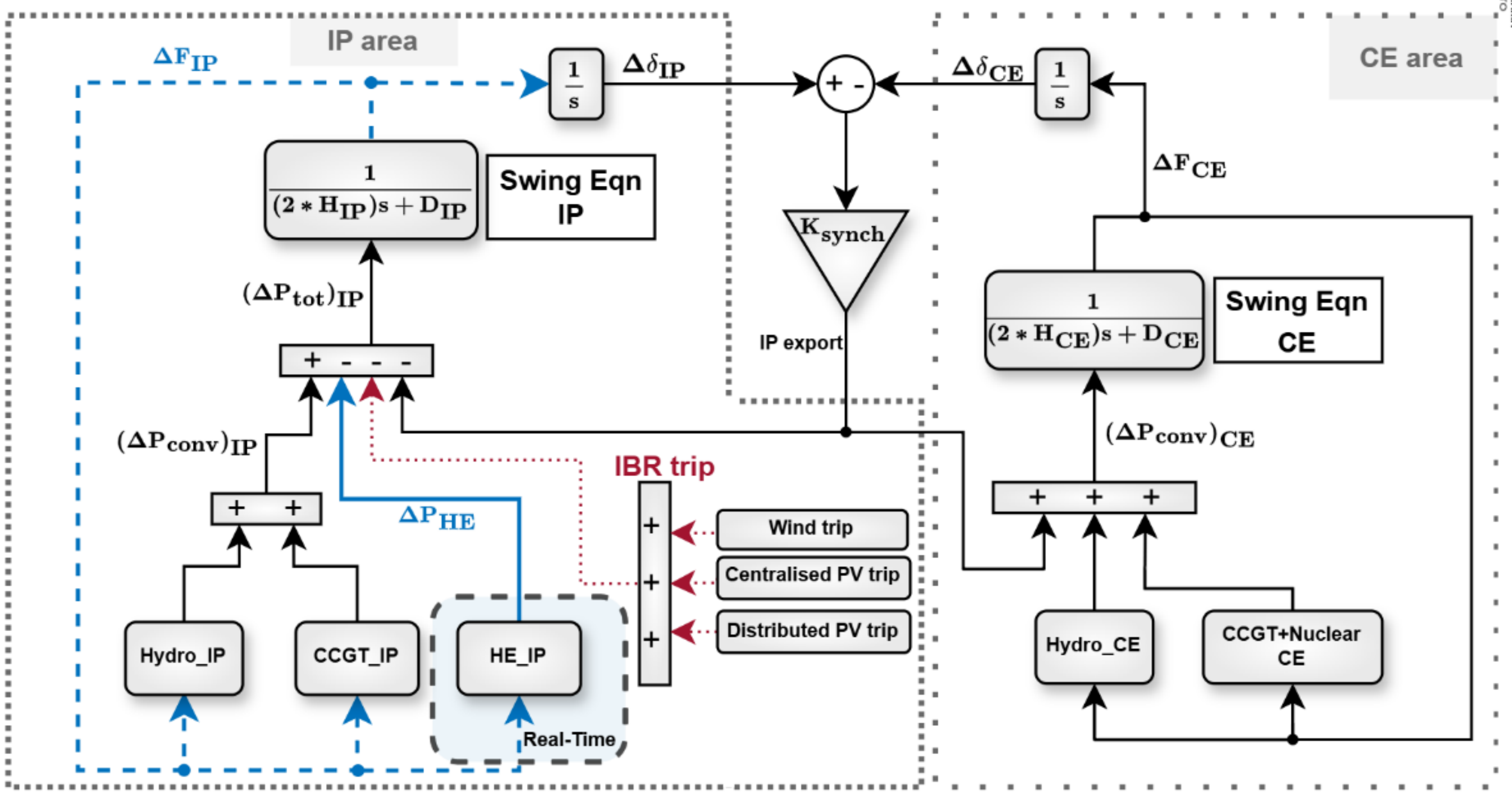




APPLICATION: 2-BUS EQUIVALENT MODEL, PHIL VALIDATION

- Simple HE were used in [1], just ramp limiters
- FCR capabilities were investigated at 3 GW IBR generation loss





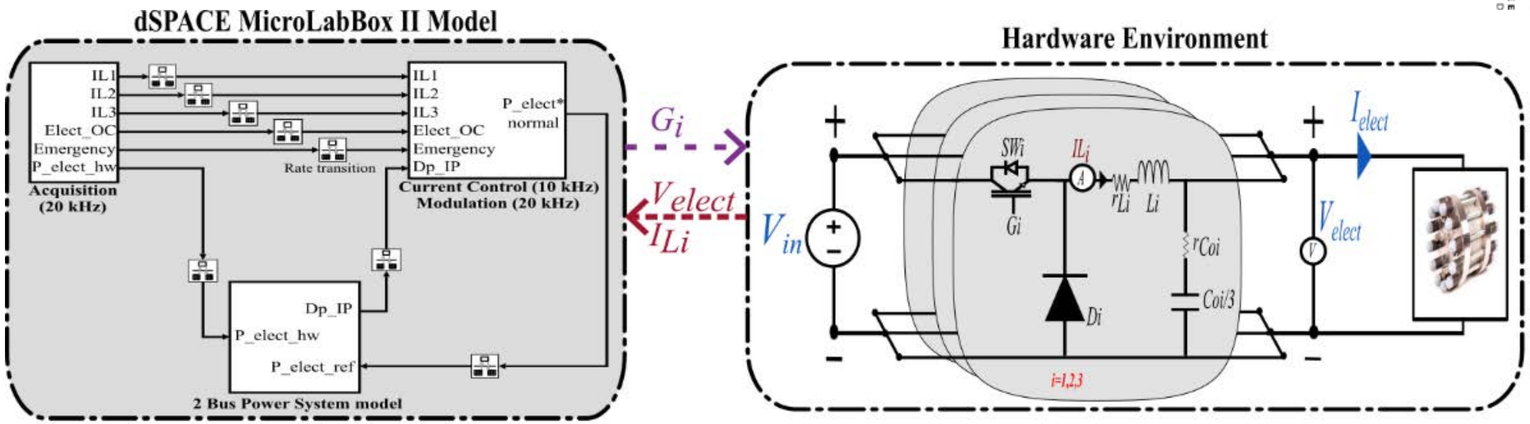
Will a real PEM hydrogen electrolyzer provide the same response?

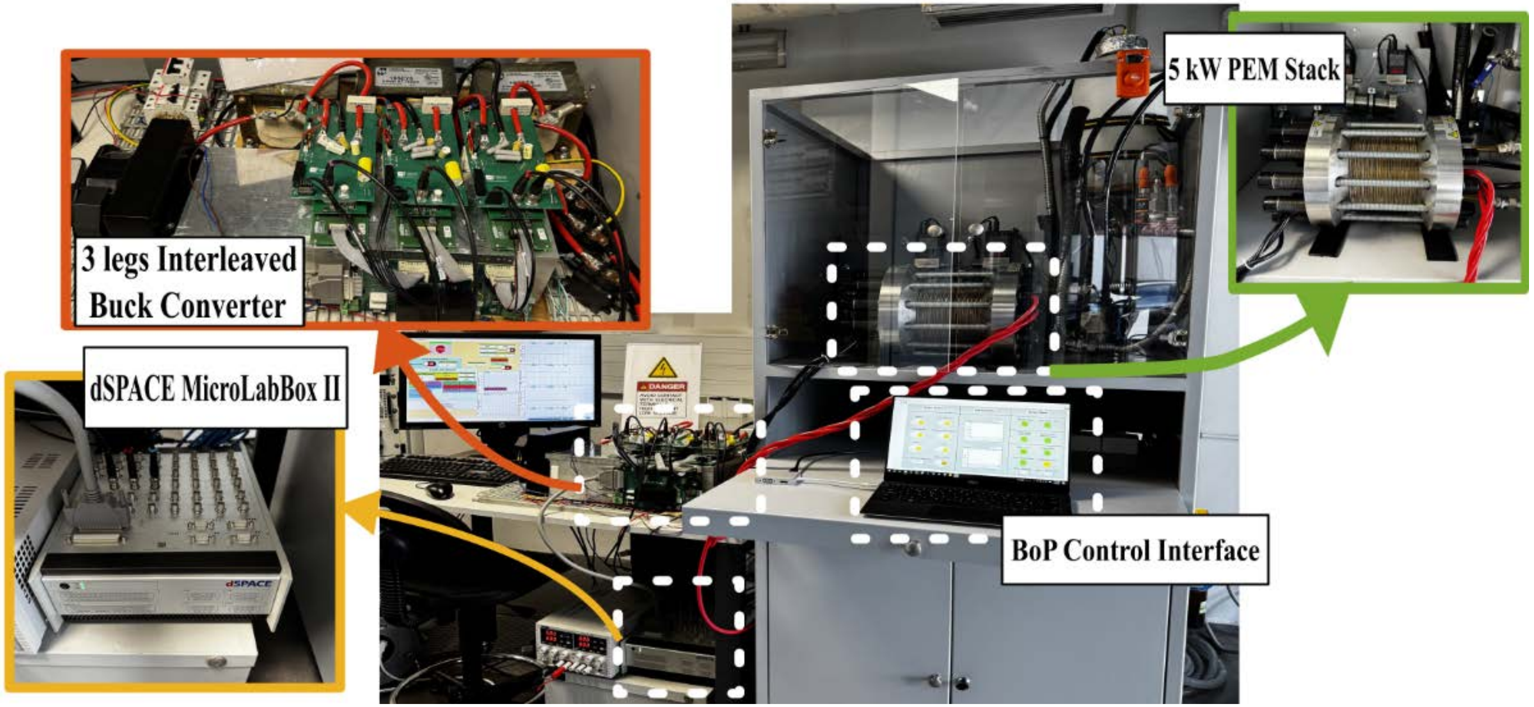
[1] F. J. Ribeiro, P. Lopes, F. S. Fernandes, F. J. Soares, A. G. Madureira, The role of hydrogen electrolysers in frequency related ancillary services: A case study in the iberian peninsula up to 2040, Sustainable Energy Grids and Networks 35 (2023) 101084. doi:10.1016/j.segan.2023.101

[2] A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "Frequency support from PEM hydrogen electrolysers using Power-Hardware-in-the-Loop validation," [under review]

POWER HARDWARE IN THE LOOP SETUP

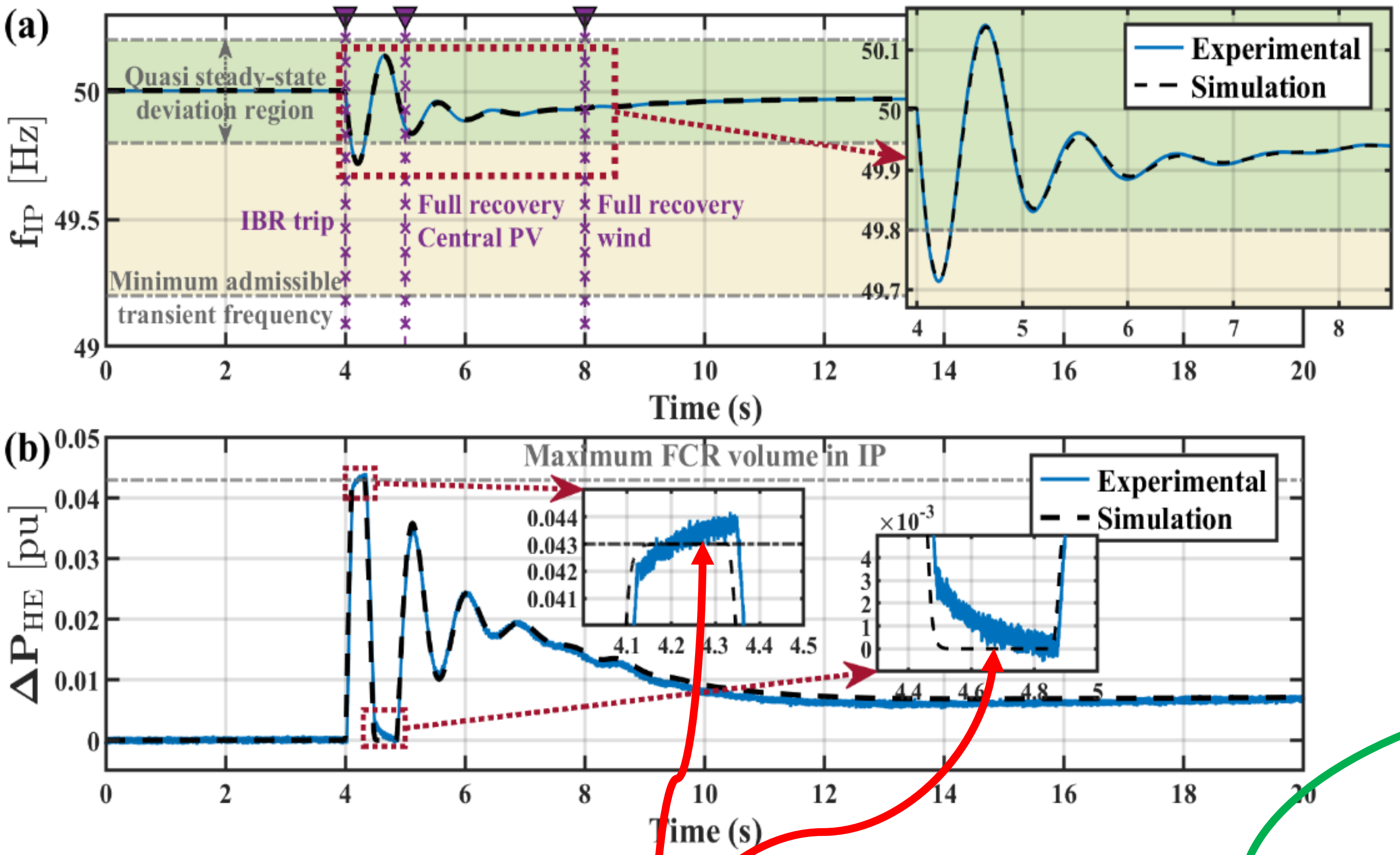
- 3-level interleaved buck converter with adaptive current controller [2] (handles high current densities with reduced ripple levels)
- Isolated control of BoP of PEM electrolyzer, ensure constant and safe operation for tests
- dSPACE MicroLabBox II to model the 2-bus system, droop control of PEM electrolyzer, and control loop of the converter
- DC power supply as interest is power set-point changes

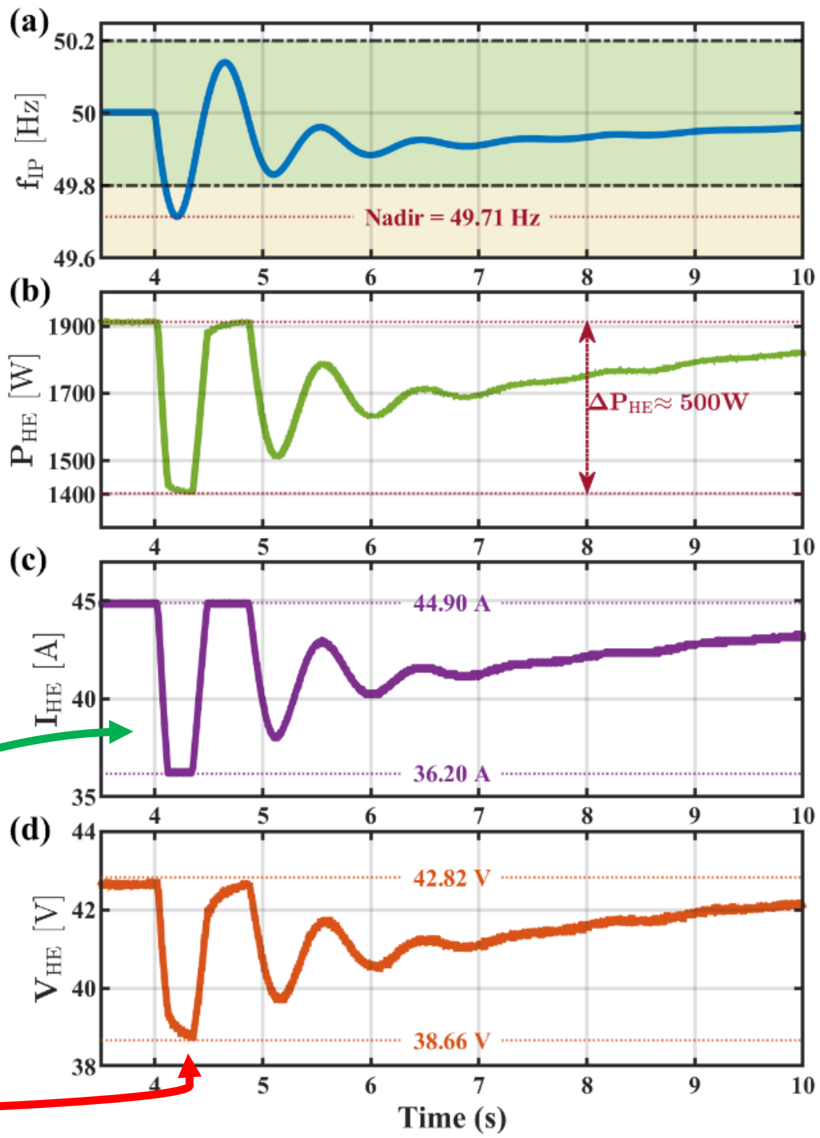




[1] A. M. Elhawash, R. E. Araújo, J. A. P. Lopes, A new adaptive lead-lag control scheme for high current pem hydrogen electrolyzers, in: Proc. IEEE Veh. Power Propuls. Conf. (VPPC), 2023, pp. 1–6. doi:10.1109/vppc60535.2023.10403130.
[2] A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "Frequency support from PEM hydrogen electrolysers using Power-Hardware-in-the-Loop validation," [under review]

VALIDATION OF HW WITH SW RESULT



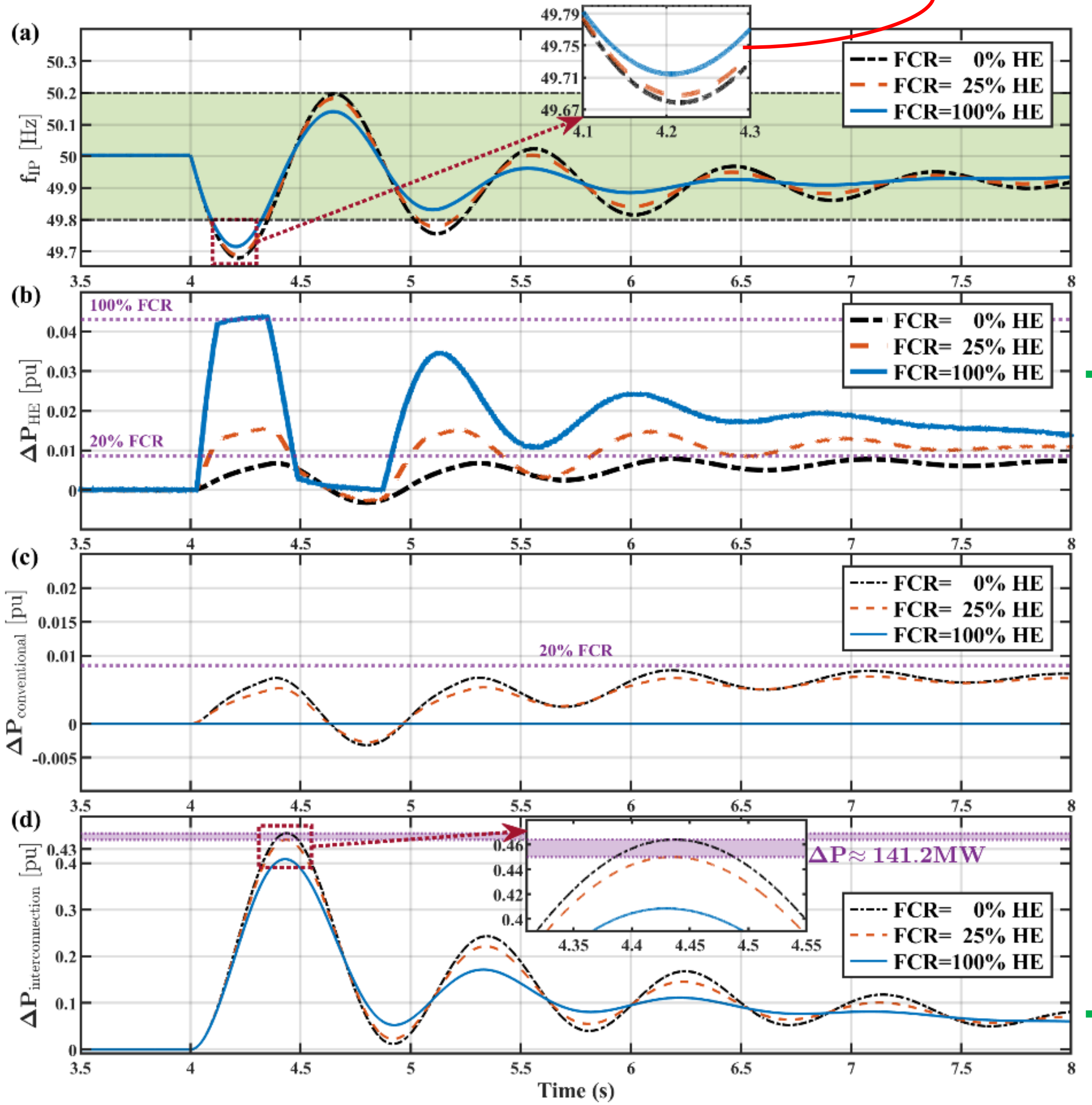


Adaptive current controller providing low ripple level at electrolyzer terminals

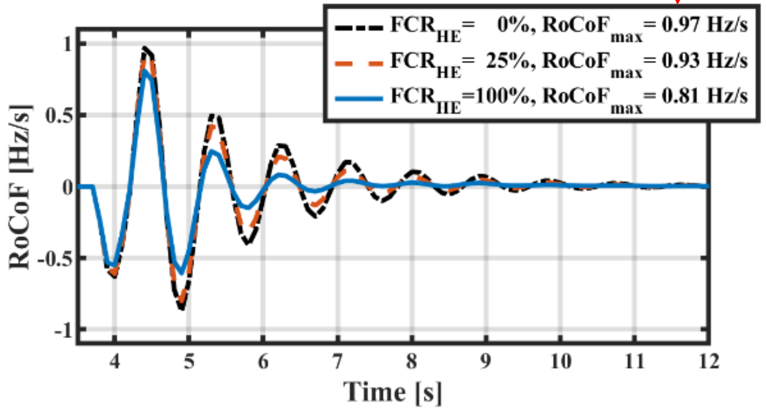
PEM dynamics due to double layer capacitance effect + internal resistance

[1] A. M. Elhawash, R. E. Araújo, J. A. P. Lopes, A new adaptive lead-lag control scheme for high current pem hydrogen electrolyzers, in: Proc. IEEE Veh. Power Propuls. Conf. (VPPC), 2023, pp. 1–6. doi:10.1109/vppc60535.2023.10403130.
[2] A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "Frequency support from PEM hydrogen electrolysers using Power-Hardware-in-the-Loop validation," [under review]

FCR RESULTS



Close nadir values, but RoCoF



- HE allows full deployment of FCR volume in IP, conventional only deploys ≈ 20%
- Accordingly, less power import from CE, less cost in secondary control (aFRR)

[1] A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "Frequency support from PEM hydrogen electrolysers using Power-Hardware-in-the-Loop validation," [under review]

FURTHER WORK – LOW VOLTAGE RIDE THROUGH

Active Rectifier to provide:

1- Power quality at the grid connection terminals (reactive power control)

2- DC bus voltage control

3- Droop control to adjust power set-point to electrolyzer

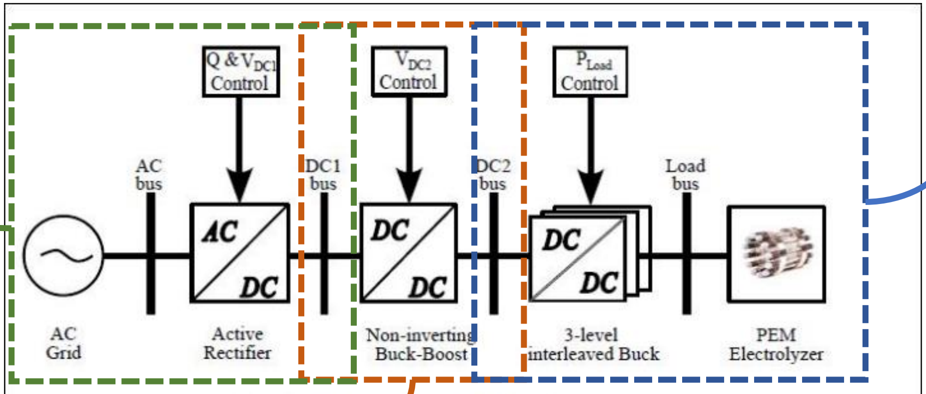
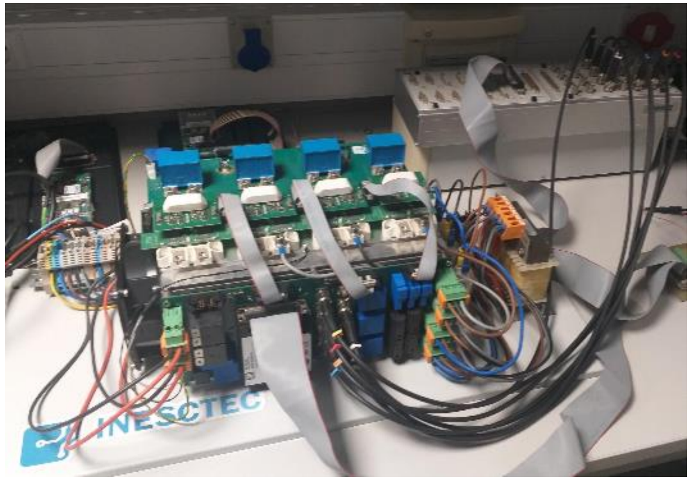


Fig. 1. Power chain block diagram.

New adaptive current controller to ensure:

1- Power quality at the terminals of the electrolyzer

2- Fast ramping up/down capabilities

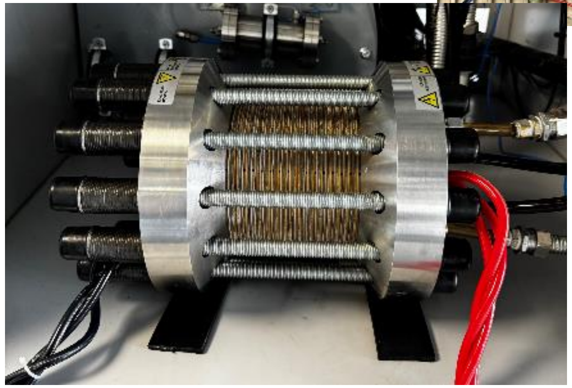


Buck-boost converter:

1- Control input DC voltage to electrolyzer

2- Enabling Fault ride through capabilities

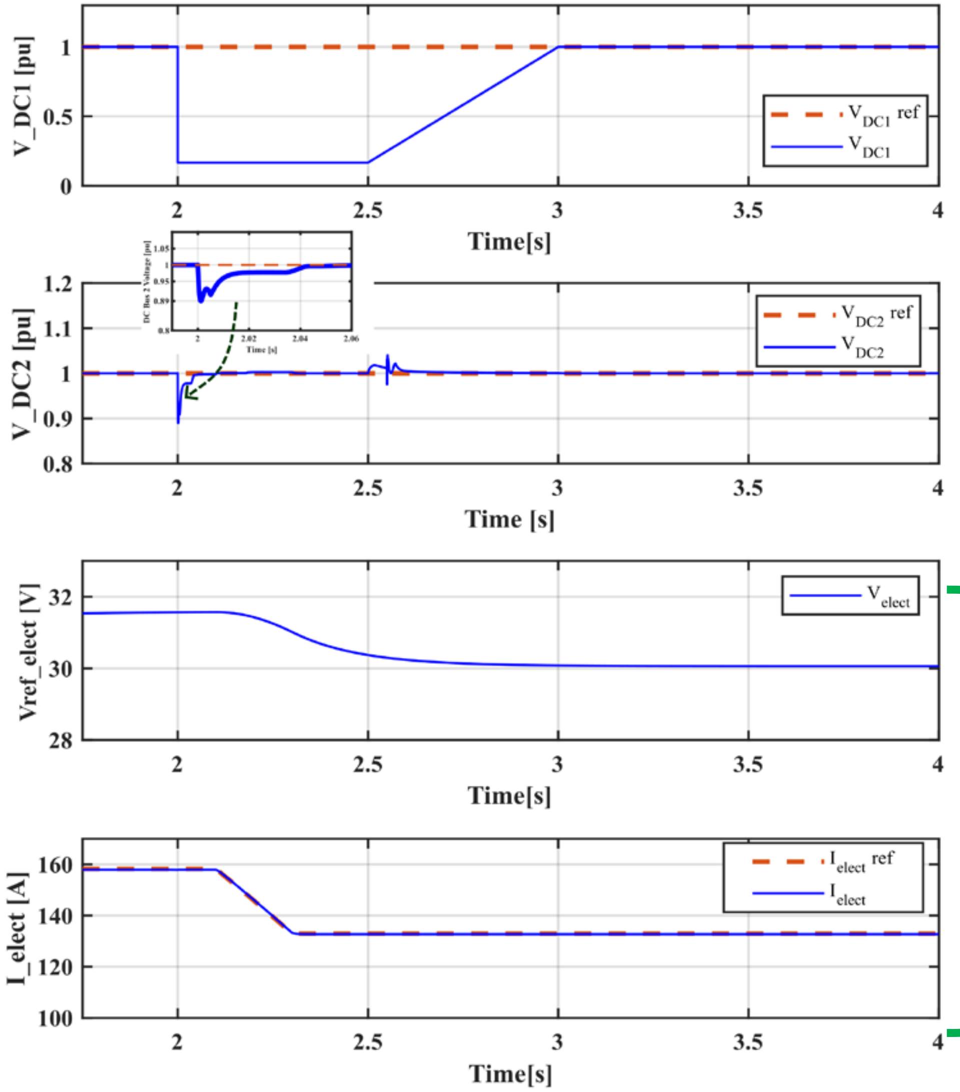
3- Acts as buffer between the grid and the electrolyzer, thus ensure a constant supply at the electrolyzer terminals

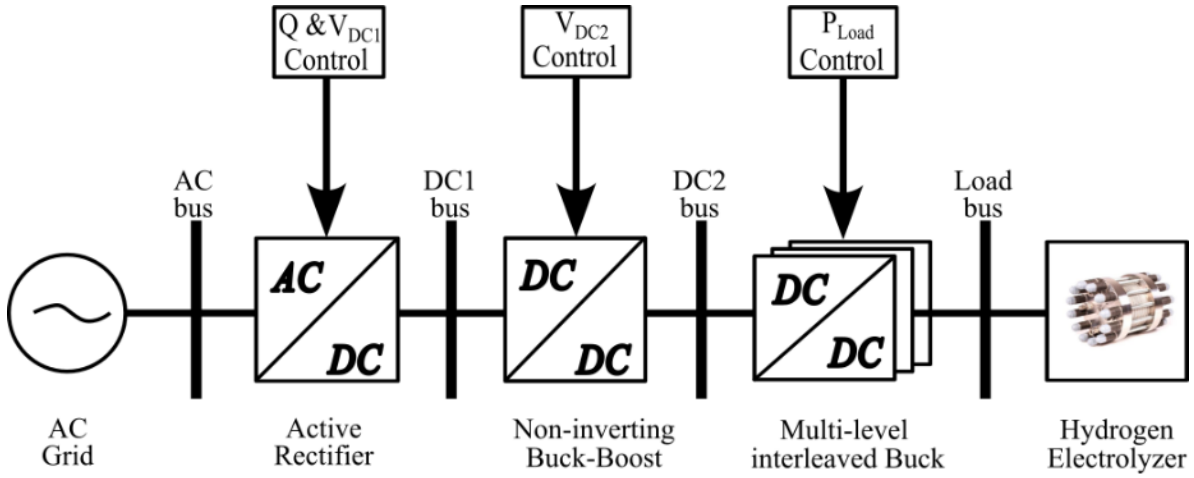


* The content of the slide is part of a patent application currently in preparation and evaluation, and the information should not be publicly disclosed without prior authorisation from the authors.

[1] A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "A New Design for an Electrolyzer Power Converter Architecture Capable of Fault Ride Through," 2025 IEEE Kiel PowerTech [accepted - awaiting presentation and publishing]

FURTHER WORK – LOW VOLTAGE RIDE THROUGH (SIMULATION RESULTS)





- No effect at the electrolyzer terminals
- The electrolyzer is able to change its consumption even during a fault

* The content of the slide is part of a patent application currently in preparation and evaluation, and the information should not be publicly disclosed without prior authorisation from the authors.

[1] A. M. Elhawash, R. E. Araújo and J. A. P. Lopes, "A New Design for an Electrolyzer Power Converter Architecture Capable of Fault Ride Through," 2025 IEEE Kiel PowerTech [accepted - awaiting presentation and publishing]

Thank You!

Questions?

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