FUEL CELL CONTROL LAB

Automatic Control of Electrolyzers for Green Hydrogen Production

Optimizing Green Hydrogen Production with Advanced Control Systems

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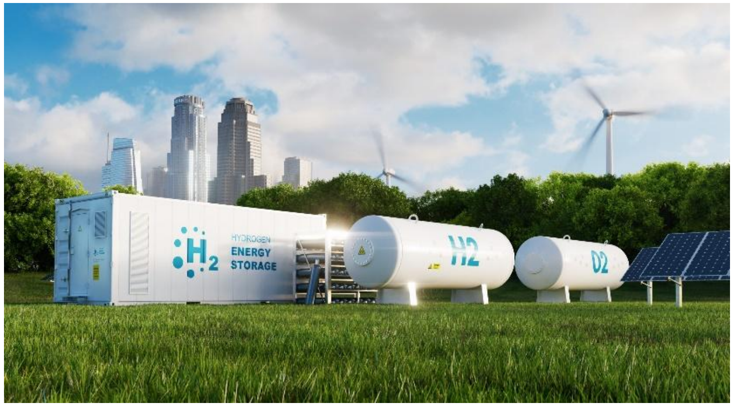
Abstract & Outline

This talk presents an overview of the fundamentals of **automatic control of electrolyzers**, addressing the main control issues and proposing control techniques for temperature control and integration with RES

1. Introduction
2. Control objectives, variables and loops
3. Temperature control. Disturbances
4. Integration with renewable generation
5. Concluding remarks

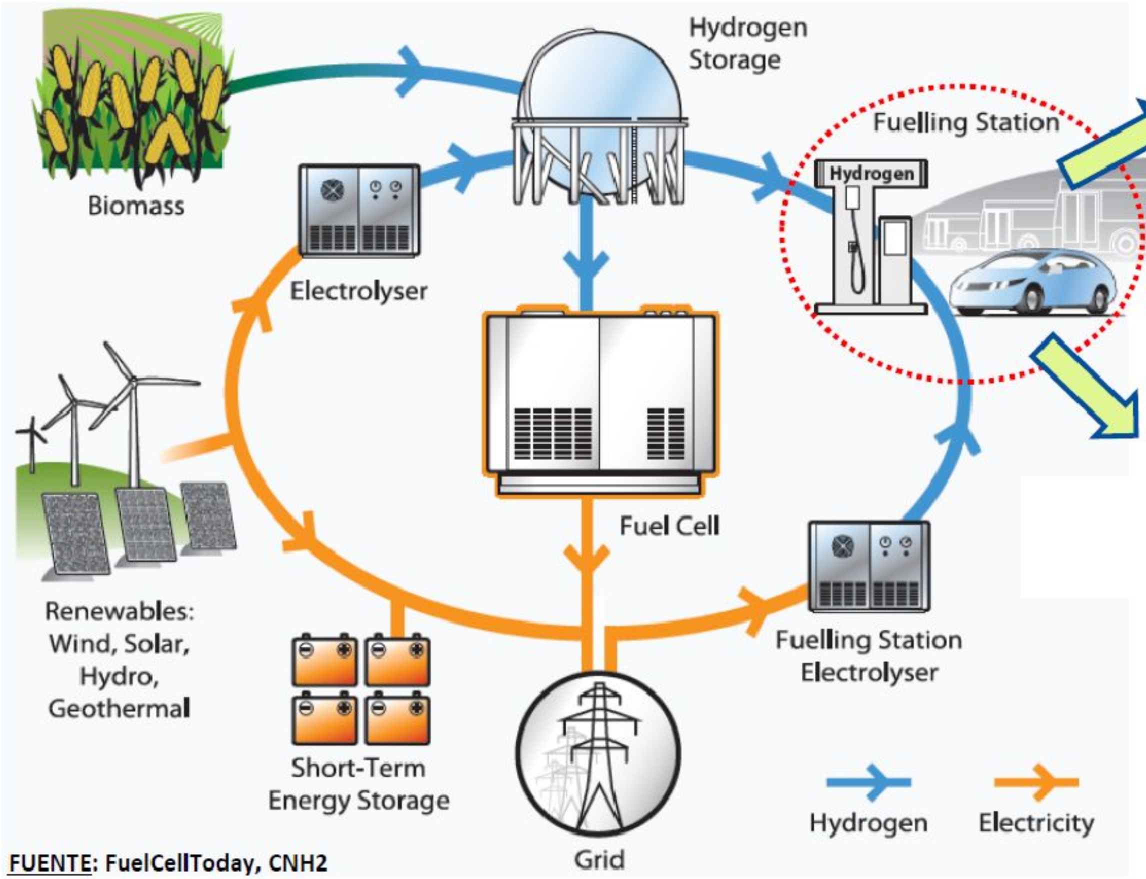
1. Introduction

- Green hydrogen involves using renewable electricity, such as solar or wind, to power electrolyzers, which split water into hydrogen and oxygen.
- The produced hydrogen can be stored and used as a clean fuel, either in fuel cells (electricity) or as a direct energy source for industrial applications.
- The efficiency of this process depends heavily on the automatic control of the electrolyzers.



This talk explores the principles, techniques, and technologies used to automate electrolyzers for optimized green hydrogen production.

Green Hydrogen



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1. Introduction

Three main types of low-temperature electrolyzers:

- Proton Exchange Membrane (PEM) Electrolyzers: Fast response. Expensive materials.
- Alkaline Electrolyzers: Mature technology, low cost, slow response.
- Anion Exchange Membrane (AEM): low-cost materials and fast dynamics. Great potential.

PEM electrolyzers can perform better in dynamic-current scenarios than alkaline technology. This is an important advantage when integrating hydrogen in microgrids, where RES are **intermittent** and depend on **meteorological conditions**

Outline

1. Introduction
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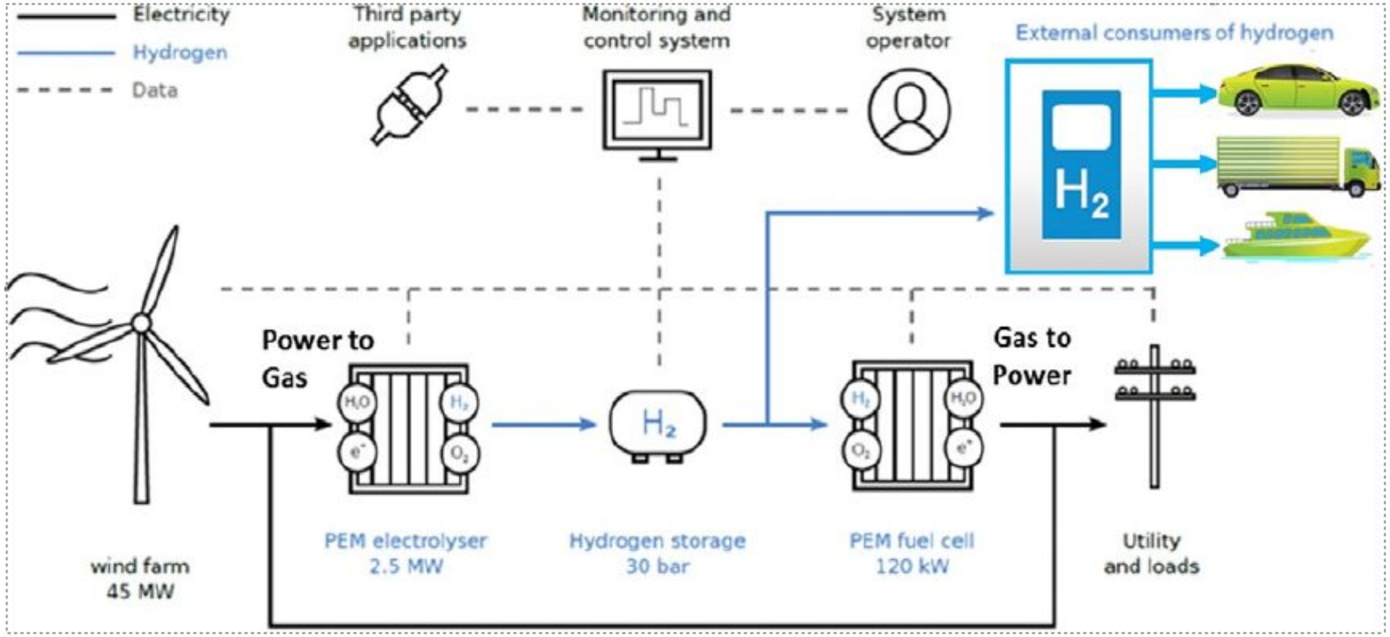
2. Control Objectives

Key control objectives in electrolyzer automation:

- **Maximizing Efficiency**: Ensuring that the electrolyzer operates at its optimal efficiency point, minimizing energy losses and maximizing hydrogen output
- **Load Balancing**: Balancing the load between energy input (renewable energy sources) and hydrogen production to account for fluctuations in energy supply.
- **Safety**: Ensuring safe operation by continuously monitoring temperature, pressure, and gas flow to prevent hazardous conditions.
- **Durability**: Prolonging the lifespan of the electrolyzer by avoiding operational stress such as high current densities or temperature extremes.

Hierarchical control structure:

- Low-level control: temperature, pressure, flow, etc. Usually supplied by the manufacturer
- High-level: a complete microgrid with electrolyzers and other elements. Manage the demand, regulating the flow of energy and the production or consumption of hydrogen.



Low level: key variables to control

- **Current Density**: Controls the rate of electrolysis. Higher current densities increase hydrogen production but may reduce efficiency and cause wear on the system. **Cannot be manipulated when connected directly to a renewable source**
- **Temperature**: Ensuring the electrolyzer operates within optimal temperature ranges for performance and longevity
- **Pressure**: Managing the pressure of both hydrogen and oxygen to ensure safety and proper operation.
- **Water Feed Rate**: Controlling the flow of water to maintain a continuous supply for electrolysis.
- **Level**: water tank and water-gas separators level
- **Input water**: conductivity and supply pressure
- **Gas Purity:** Monitoring the purity of hydrogen and oxygen to ensure the quality of the output gases.
- **Voltage:** Regulating the applied voltage to maintain high efficiency while avoiding degradation of the electrolyzer components.

Simple controllers, usually ON/OFF

Electronic power converter

S. Dahbi, R. Aboutni, A. Aziz, N. Benazzi, M. Elhafyani and K. Kassmi, "Optimised hydrogen production by a photovoltaic-electrolysis system DC/DC converter and water flow controller," *International Journal of Hydrogen Energy,* vol. 41, no. 45, pp. 20858-20866, 2016.

J.J. Caparrós, F. Segura, J. M. Andújar, F. J. Vivas and A. J. Calderón, "An Optimized Balance of Plant for a Medium-Size PEM Electrolyzer: Design, Control and Physical Implementation," Electronics, vol. 9, no. 5, pp. 871-895, 2020

Outline

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3. Temperature control

- Main control issue.
- Electrolyzers work at an operating point which involves an operating temperature (assuming it constant along the electrolyzer)
- An increasing in temperature improves electrolyzer **performance** and an increasing in pressure implies worse performance [*]
- However, there are two important phenomena which accelerate membrane **degradation**: stack temperature and input current density [**]
- The effect of high temperature is of greater importance. It accelerates membrane degradation by thermal and chemical reasons
- **Trade-off** between performance (high temperature) and degradation (upper limit temperature)
- The control system must ensure that deviations in electrolyzer temperature are within a tight range.

[*] B. Han, S. M. Steen III, J. Mo and F. Zhang, "Electrochemical performance modeling of a proton exchange membrane electrolyzer cell for hydrogen energy," International Journal of Hydrogen Energy, vol. 40, no. 22, pp. 7006-7016, 2015.
[**]M. E. Lebbal and S. Lecœuche, "Identification and monitoring of a PEM electrolyser based on dynamical modelling," International Journal of Hydrogen Energy, vol. 34, no. 14, pp. 5992-5999, 2009.

Temperature control. Common Techniques

- PID* controller with a hysteresis band for activation: maintain the cooling system deactivated until a nominal temperature is reached and then start the regulation [1]
- The manipulated variable is the water flowrate entering the electrolyzer (via input pump with PWM or valve) and the output variable is the difference between outlet and inlet water temperature [2]
- Adaptive PID controller which is based on look-up tables in order to adapt the PID parameters to different operating scenarios [3]
- Fault detection. Model-based residual deviations calculations using electrical and thermal models and measured variables to decide whether the system is healthy or not. In this way, membrane degradation, can be reduced [4]

*Proportional-Integrative-Derivative Controller

[1] B. Flamm, C. Peter, F. N. Büchi and J. Lygeros, "Electrolyzer modeling and real-time control for optimized production of hydrogen gas," Applied Energy, vol. 281, pp. 116031-116041, 2021.

[2] G. S. Ogumerem and E. N. Pistikopoulos, "Parametric optimization and control for a smart Proton Exchange Membrane Water Electrolysis (PEMWE) system," Journal of Process Control, vol. 91, pp. 37-49, 2020.

[3] R. Keller, E. Rauls, M. Hehemann, M. Müller and M. Carmo, "An adaptive model-based feedforward temperature control of a 100 kW PEM electrolyzer," Control Engineering Practice, vol. 120, pp. 104992-105001, 2021.

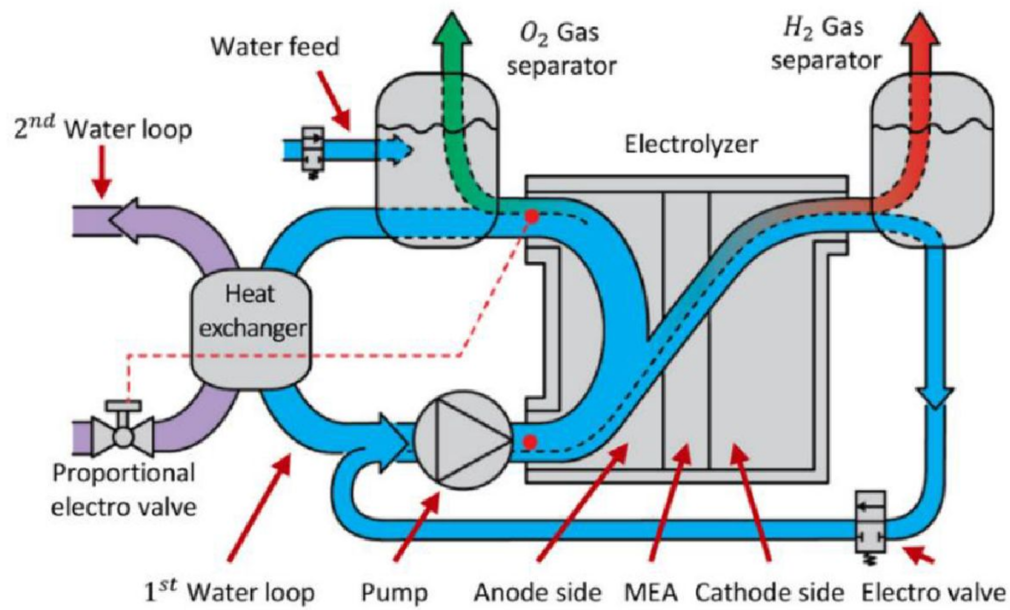
[4] M. E. Lebbal and S. Lecœuche, "Identification and monitoring of a PEM electrolyser based on dynamical modelling," International Journal of Hydrogen Energy, vol. 34, no. 14, pp. 5992-5999, 2009.

Temperature control. Cooling system

The cooling system is usually composed by water/air-based heat exchangers in which electrolyzer recirculation water removes some excess heat before entering the anode again.

Manipulated variable:
- Electrovalve/Pump
- Fan (air-cooled)

Can be continuous (PWM) or ON/OFF



Thermal dynamics is "slow"

Temperature control. Experiments

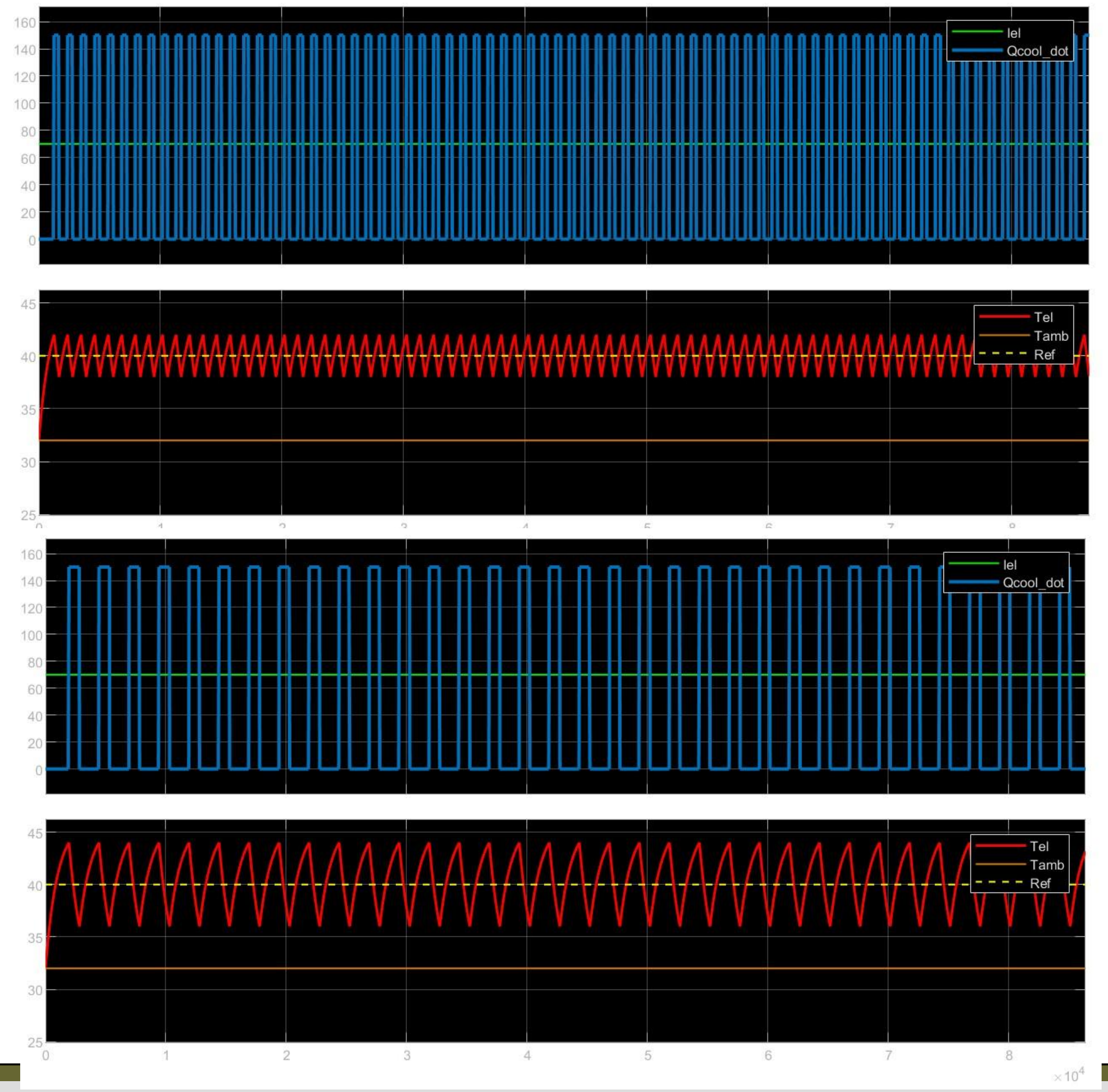
- Simulations performed on the nonlinear model of a 1 kW Hamilton-STD SPE-HG PEM Electrolyzer: 0.23 Nm3/h, $n_c = 6$ and thermal parameters $C_t = 9540 J/K$ and $R_t = 0.11 K/W$.
- Simulations during one day of operation

- Different control techniques:
  - ON/OFF
  - PID
  - MPC

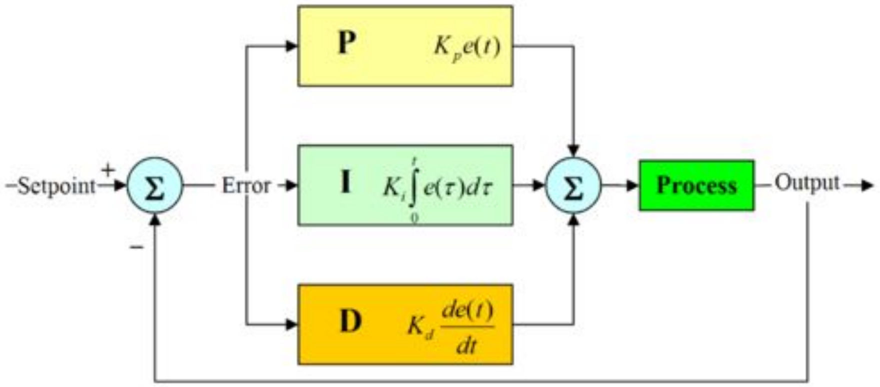
Simulink model (M.A. Ridao)

ON/OFF control

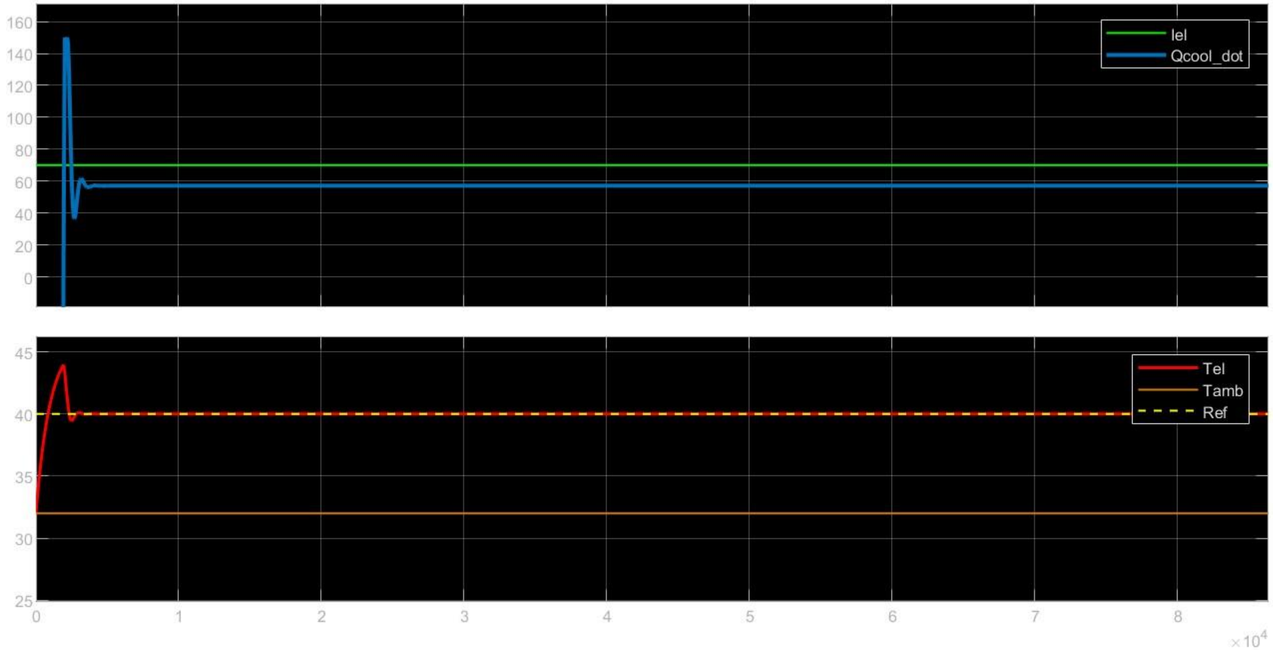
- Simplest technique:
- On/off with deadband
- Simulations with current and ambient temperature fixed
- Not precise setpoint tracking
- Switching can damage valve/pump/fan
- Increase deadband: less switching but worse setpoint tracking



PI(D) control



- Usually PI-type: offset free
- Derivative term may cause problems with noisy measurements



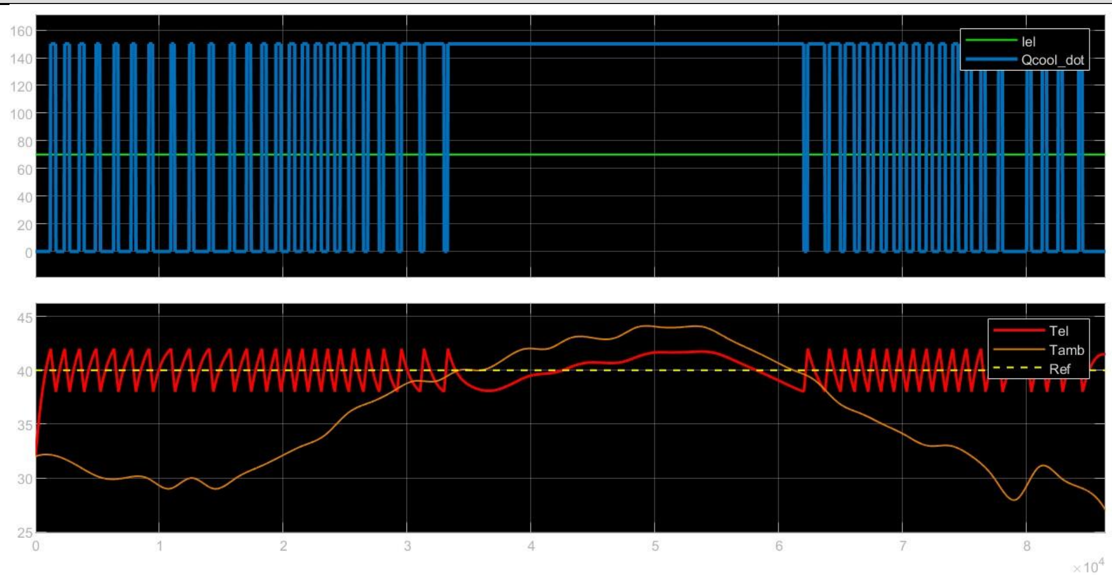
Everything seems easy and smooth, but…

Disturbances

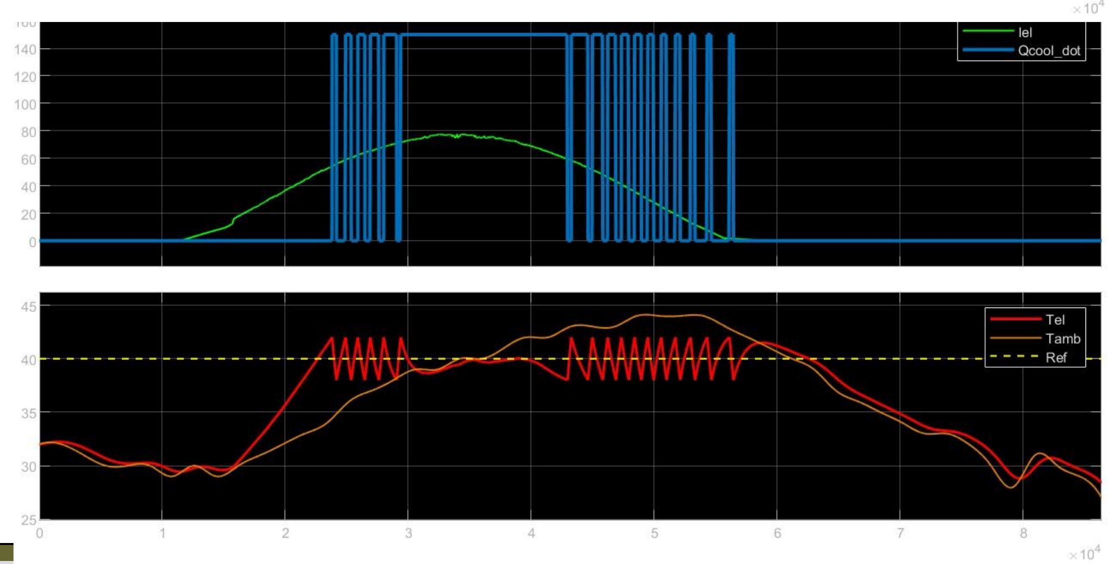
- Affect electrolyzer performance and hydrogen production
- Measurable disturbances:
  - Current (solar irradiance or wind). **Fast. The most important**
  - Ambient temperature & inlet water temperature. **Slow**
- Unmeasurable disturbances:
  - Intermittent changes in bus voltage (mainly produced by regulation with batteries)
  - Electrolyzer start-up phases

ON-OFF. Disturbances

Simulation with varying ambient temperature and fixed current

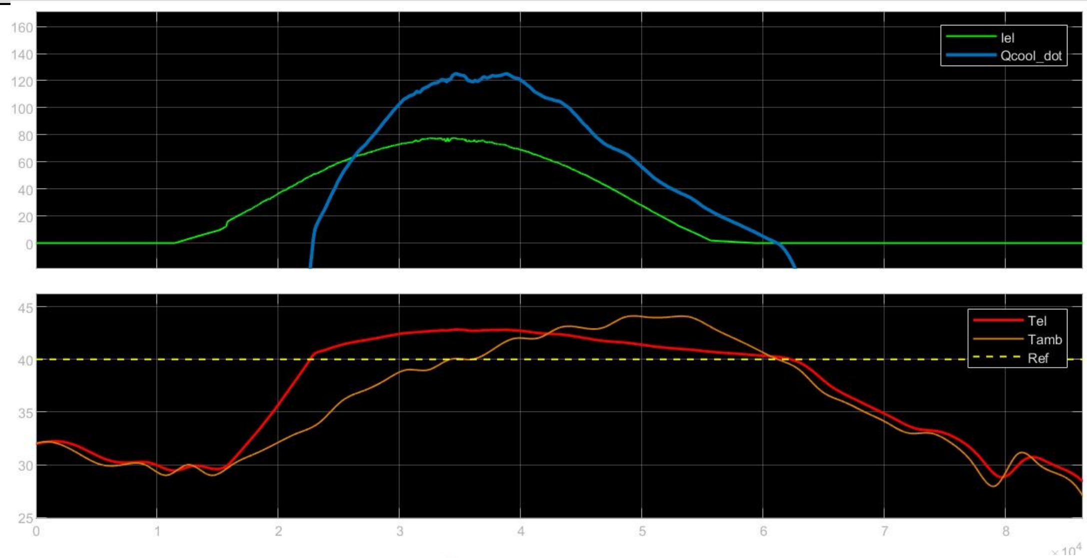


Varying current & temperature

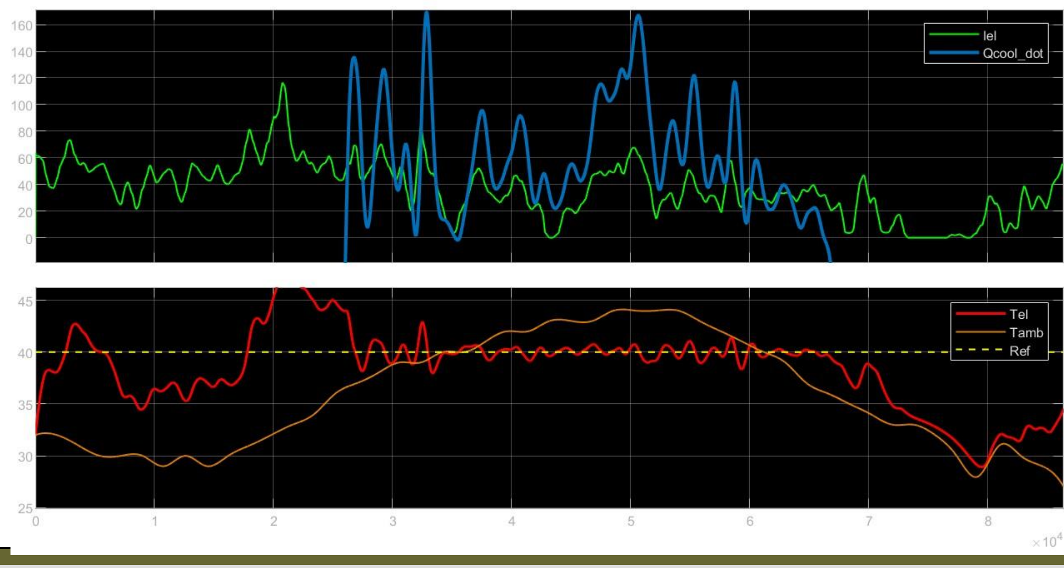


PID. Disturbances

- Sunny day



- Wind

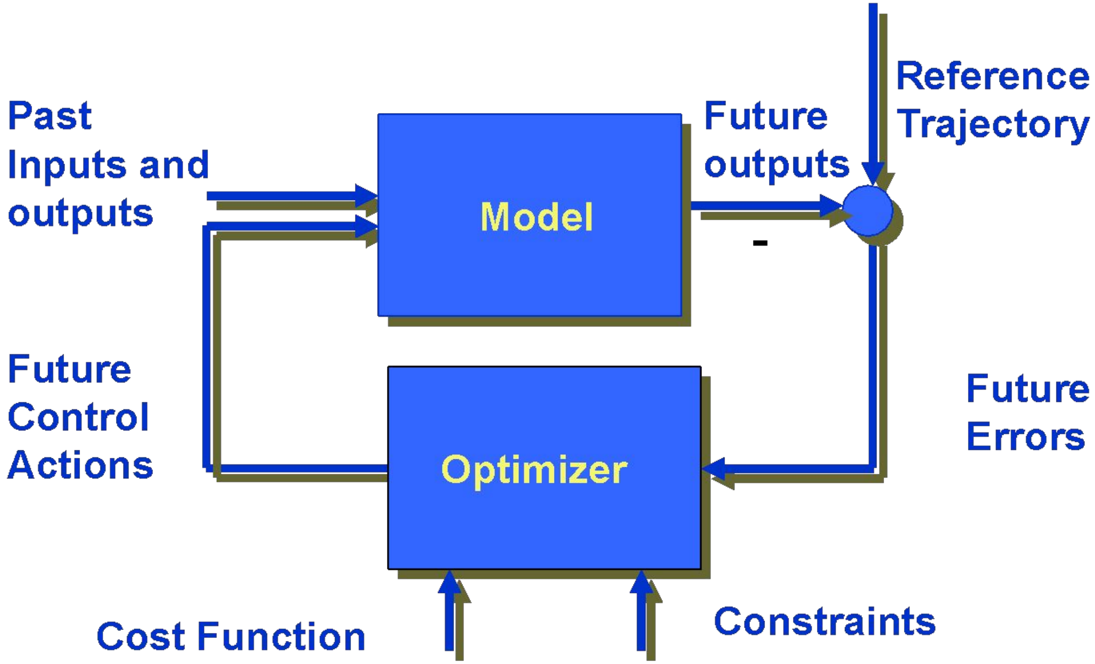


Not so good

Temperature control based on MPC

- Model Predictive Control for improved performance
- Not only SP tracking. Can include constraints and future disturbances

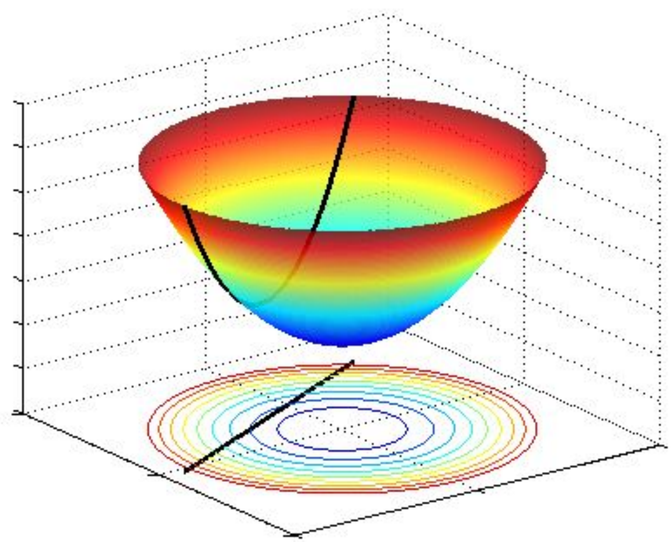
MPC: Optimization over a future receding horizon using a dynamic model of the plant



Controller development

- Cost function. Can consider several objectives. Not only Setpoint tracking. Can include constraints

- Control effort (minimize cooling effort)
- Constraints (operational limits, slew-rate)



- Unconstrained:

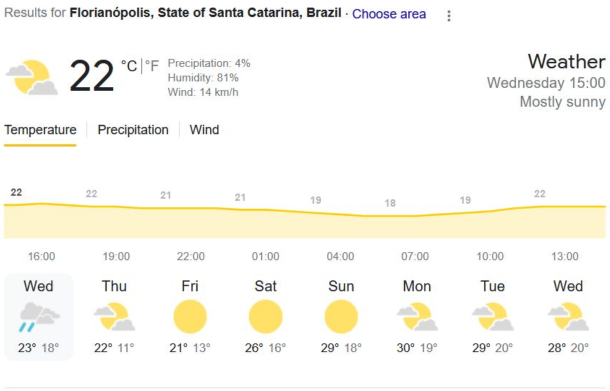
  Explicit solution $\frac{\partial J}{\partial u} = 0$

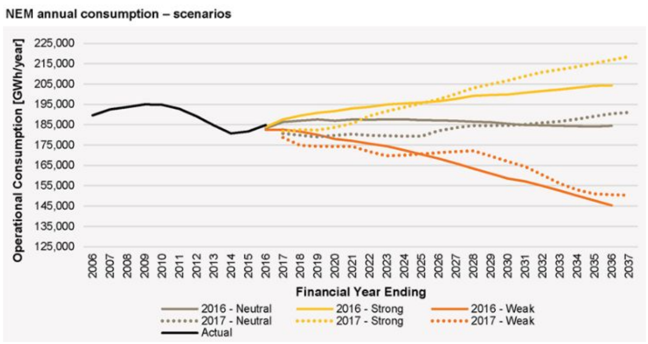
- Constrained:

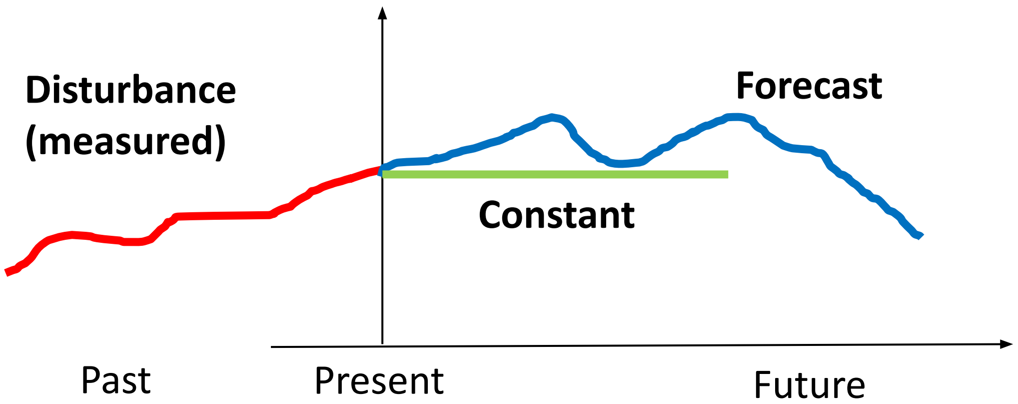
  Quadratic/Linear Programming (QP/LP)

Include forecasting

- Make use of the prediction capabilities of MPC. Feedforward effect
- Include forecasting of renewable **generation** and ambient **temperature**
- Feedback mechanism always reduces the effect of disturbances but, besides, MPC can **anticipate** if forecasting is available.

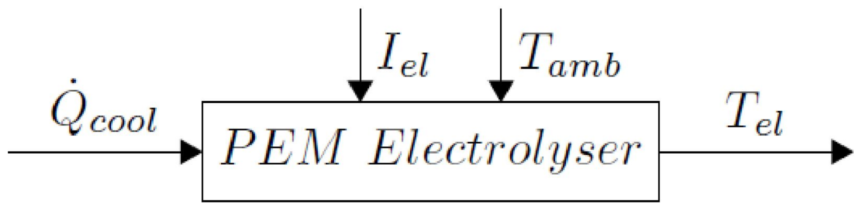






Dynamic model

A control-oriented Dynamic model is needed



Disturbances are included in the model

Dynamic model: $$\frac{dT_{el}}{dt} = \frac{1}{C_t}[n_c I_{el}(V_{el} - V_{tn}) - \frac{1}{R_t}(T_{el} - T_{amb}) - \dot{Q}_{cool}].$$

Discretized low-order linearized model: $$x(k+1) = a_d x(k) + b_d u(k) + m_{1d} d_1(k) + m_{2d} d_2(k).$$

Simplified low-order linearized model. Around I = 40 A

$$x(k+1) = 0{,}9077x(k) - 0{,}01u(k) + 0{,}022d_1(k) + 0{,}0908d_2(k).$$

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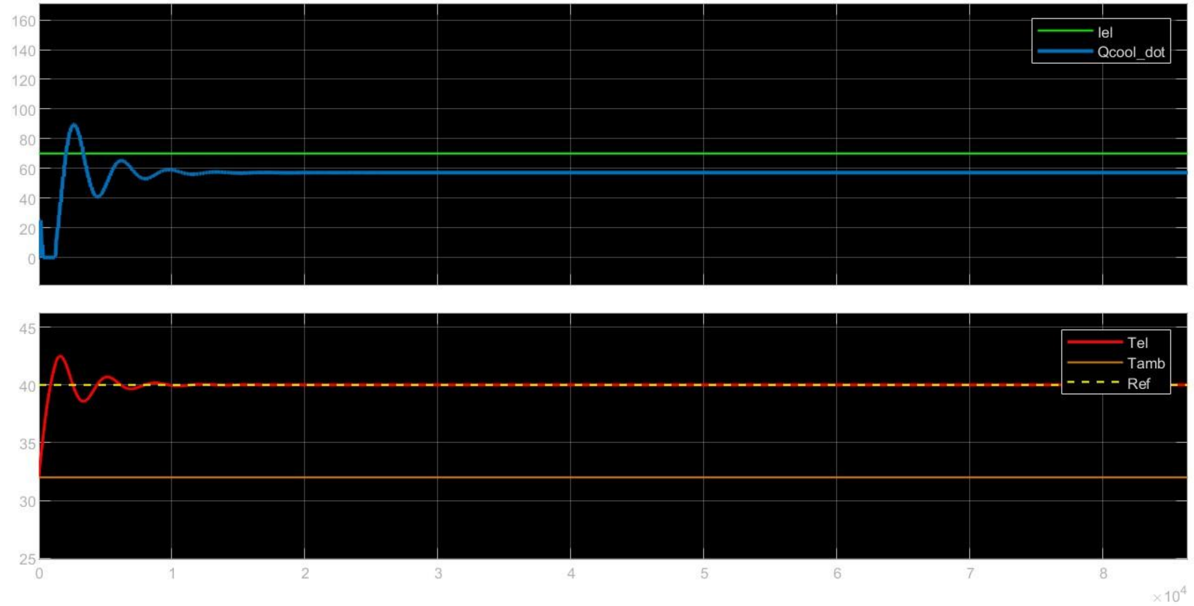
Temperature control for a PEM electrolyser powered by a renewable source. Barros-Queiroz, J. S., Torrico, B. C., Nogueira, F. G, Bordons, C., Ridao, M. A. Jornadas de Automática, Málaga, 2024

MPC Simulations (1/2)

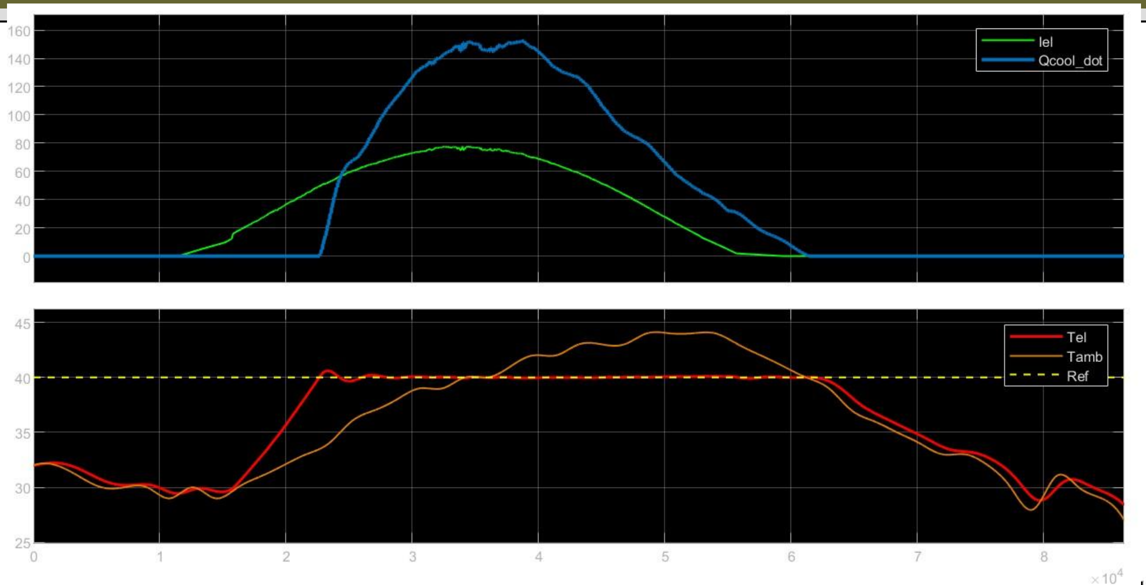
No disturbances: performs like a PID



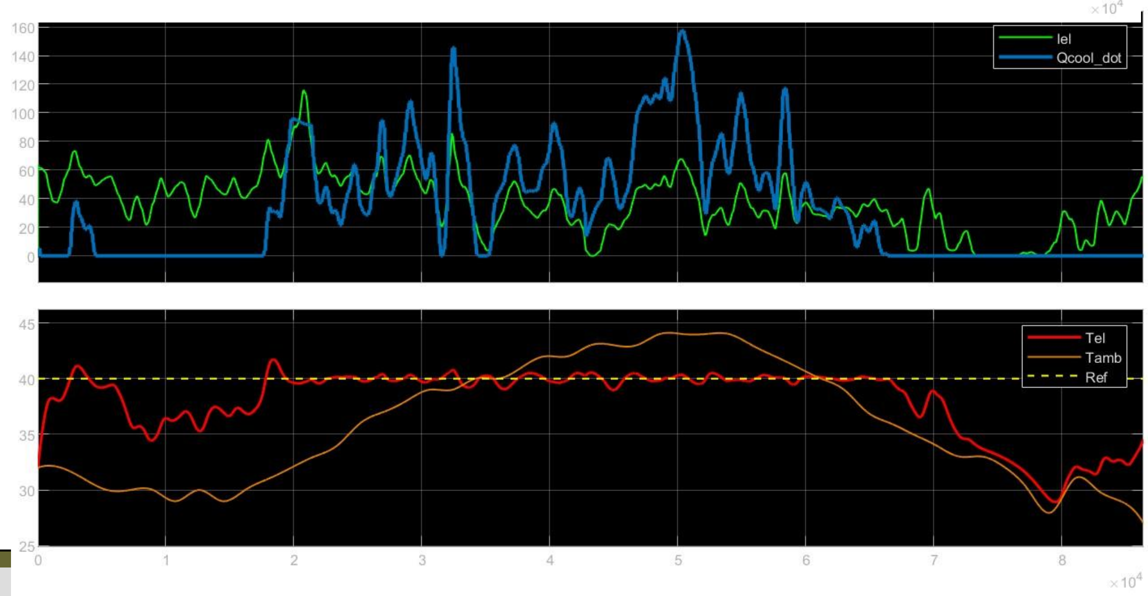
MPC Simulations (2/2)

Disturbances

- Irradiance



- Wind



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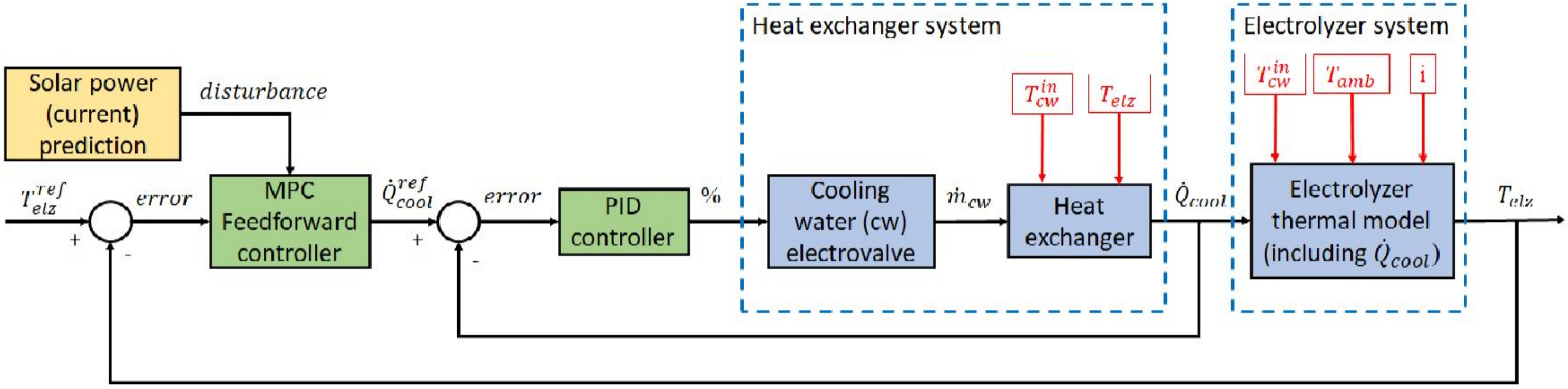
The complete solution

Most complete solution: MPC with cascade PID



Open issues in temperature control

- Which is the optimal reference temperature?
- Which temperature is representative? Big gradients between cells
- Multistack with only one controller?
- Calculation of the optimal current in case it can be manipulated (PV and battery in a microgrid)

Outline

4. Integration with RES

- Critical phenomena in electrolyzer performance and hydrogen production [*]:
  - Unexpected variations in produced renewable power
  - Intermittent changes in bus voltage
  - Electrolyzer start-up phases

- Objective: try to feed the ELZ with constant current. Avoid peaks, changing current values and startup/shutdowns

- Solution: integrate the ELZ with other sources and storage systems (batteries, ultracapacitors, etc.) in a **microgrid**

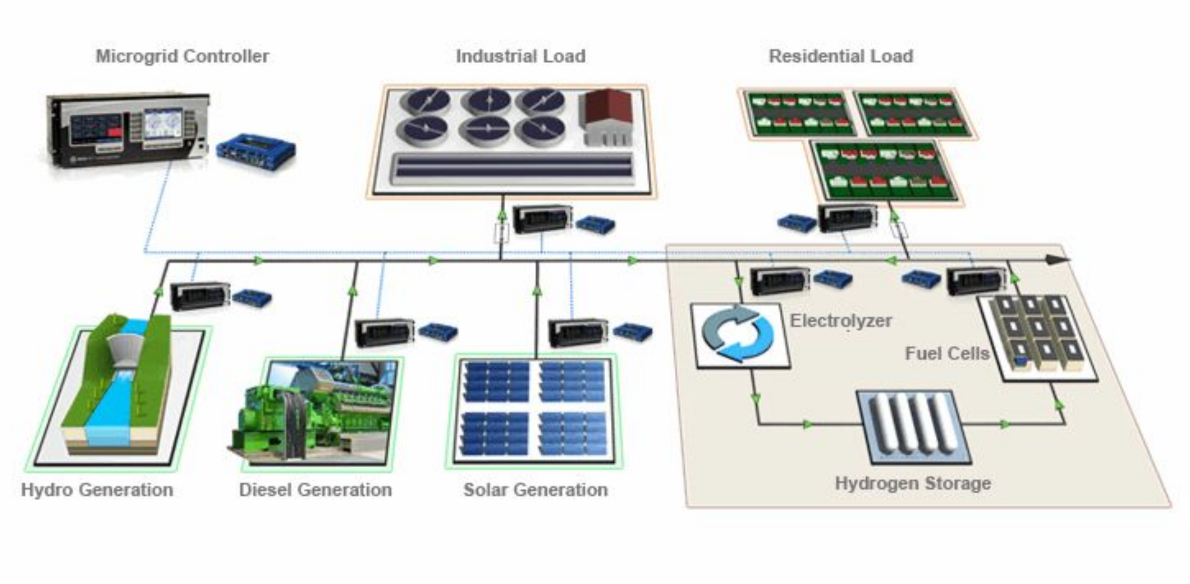
[*] A. Bergen, L. Pitt, A. Rowe, P. Wild and N. Djilali, "Transient electrolyser response in a renewable-regenerative energy system," *International Journal of Hydrogen Energy,* vol. 34, no. 1, pp. 64-70, 2008.

Integration: microgrid

Control systems help electrolyzers integrate with renewable energy by:

- Managing demand-side fluctuations.
- Optimizing energy storage.
- Providing grid stabilization through flexible load management

Concept of microgrid [*]

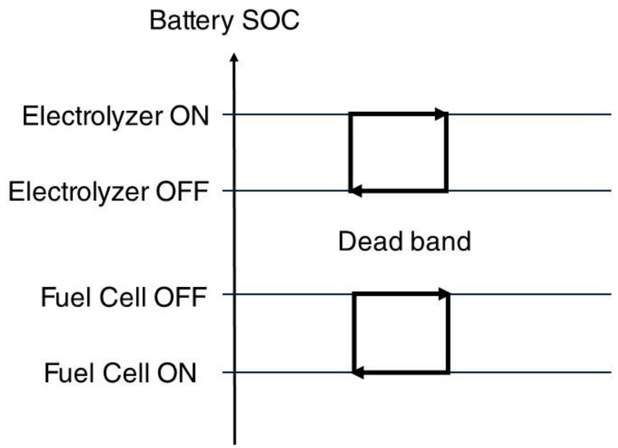


Lasseter, R. H. Microgrids. IEEE Power Eng Soc Transm Distrib Conf, 2002

*Optimal operation of hybrid power systems including renewable sources in the sugar cane industry. MM Morato, PRC Mendes, JE Normey-Rico, C. Bordons. IET Renewable Power Generation, 2017

Control techniques applied to microgrids

- Hysteresis Band Control (Ulleberg, 2003; Ghosh, 2003; Ipsakis, 2008)
- Neural Networks (López, 2007)
- Fuzzy Logic (Bilodeau, 2006; Stewart, 2009; Hajizadeh , 2009)
- Droop Control (Vasak, 2014)
- **Model Predictive Control** (Del Real, 2007; Baotic, 2014; Garcia-Torres, 2016; Parisio, 2016)



The use of MPC technique allows to **maximize the economical benefit** of the microgrid, **minimizing the degradation** causes of each storage system, fulfilling the different system **constraints**

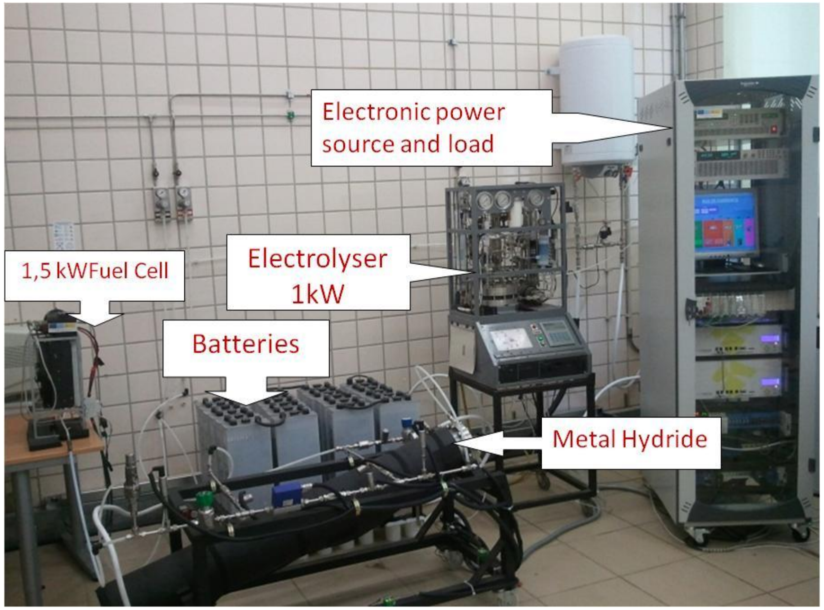
Experience has demonstrated that system performance is highly subject to the control strategy. MPC has shown >30% reduction in operational costs*

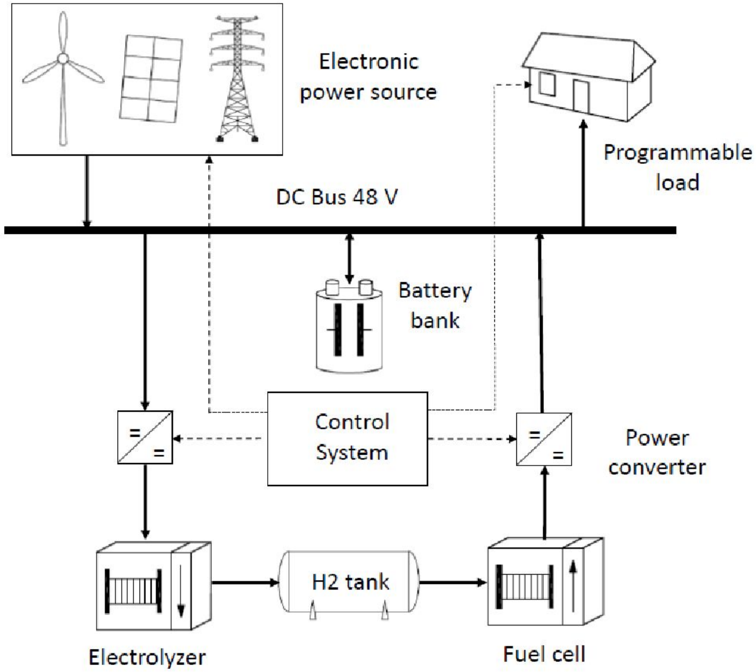
*Integration of Fuel Cell Technologies in Renewable-Energy-Based Microgrids Optimizing Operational Costs and Durability. L. Valverde, C. Bordons, F. Rosa. IEEE Trans on Industrial Electronics, 2016.

ELZ in a lab-scale microgrid

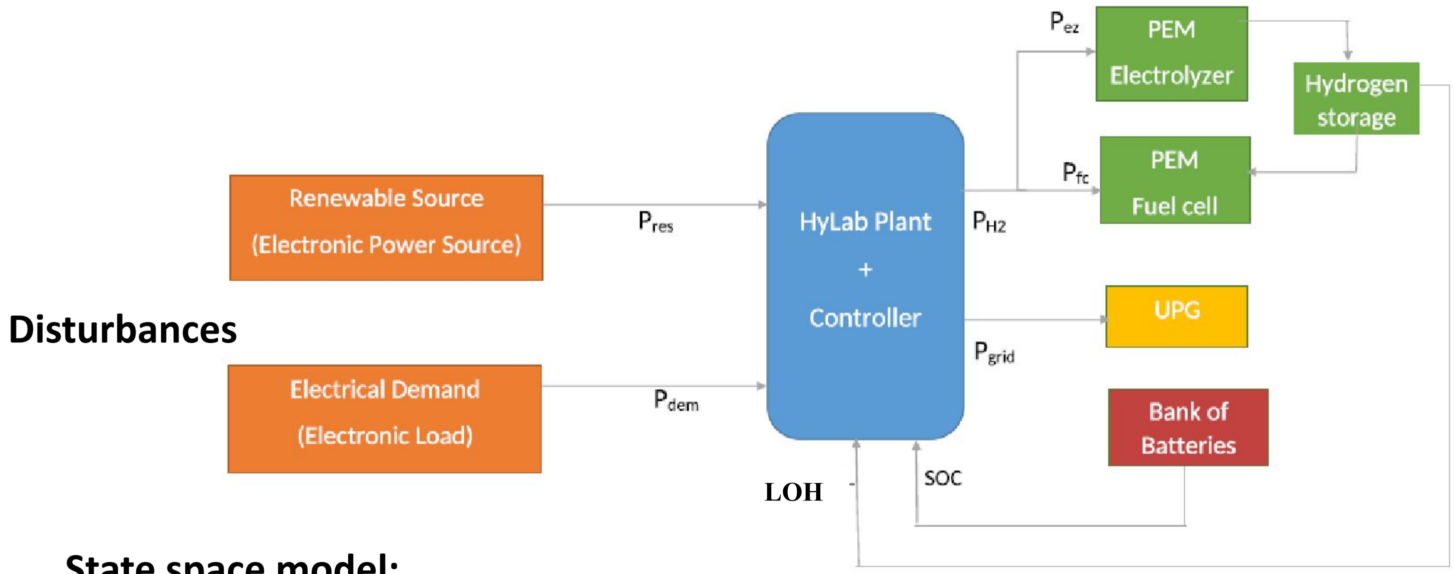
DC microgrid (Hylab)

Hydrogen is used only for storage, (no sell to market)





Microgrid Scheme



State space model:

$$SOC(t+1) = SOC(t) - \frac{\eta_{bat} T_s}{C_{\max}} P_{bat}(t)$$

$$LOH(t+1) = LOH(t) + \frac{\eta_{elz} T_s}{V_{\max}} P_{elz}(t) - \frac{T_s}{\eta_{fc} V_{\max}} P_{fc}(t)$$

Power in the battery bank (balance):

$$P_{bat}(t) = P_{load}(t) + P_{elz}(t) - P_{fc}(t) - P_{grid}(t) - P_{gen}(t)$$

MPC Cost function

3 weighted objectives

- Minimize the use of grid
- Protect equipment from sudden changes
- Keep storage levels (H_2 and electricity)

$$J = \sum_{k=1}^{N_c} \alpha_1 P_{fc}^2(t+k) + \alpha_2 P_{elz}^2(t+k) + \alpha_3 P_{grid}^2(t+k) + \alpha_4 P_{bat}^2(t+k) +$$

$$+\beta_1 \Delta P_{fc}^2(t+k) + \beta_2 \Delta P_{elz}^2(t+k) + \beta_3 \Delta P_{grid}^2(t+k) + \beta_4 \Delta P_{bat}^2(t+k) +$$

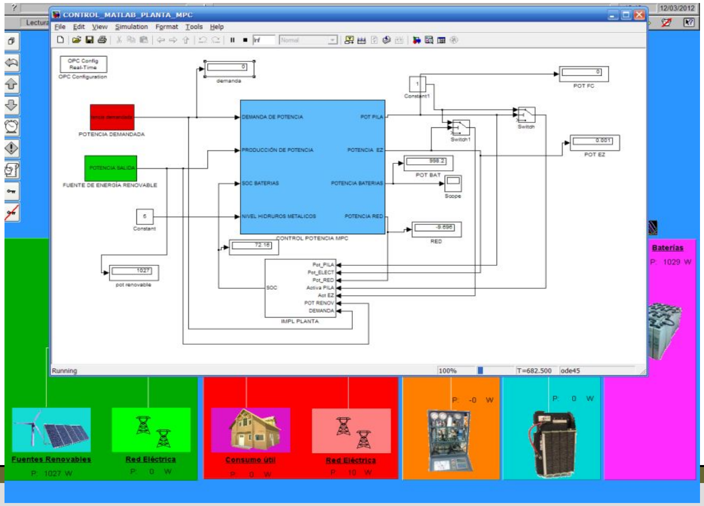
$$+ \sum_{k=1}^{N_p} \gamma_1 (SOC(t+k) - SOC_{ref})^2 + \gamma_2 (LOH(t+k) - LOH_{ref})^2$$

And operational constraints (power slope)

Implementation

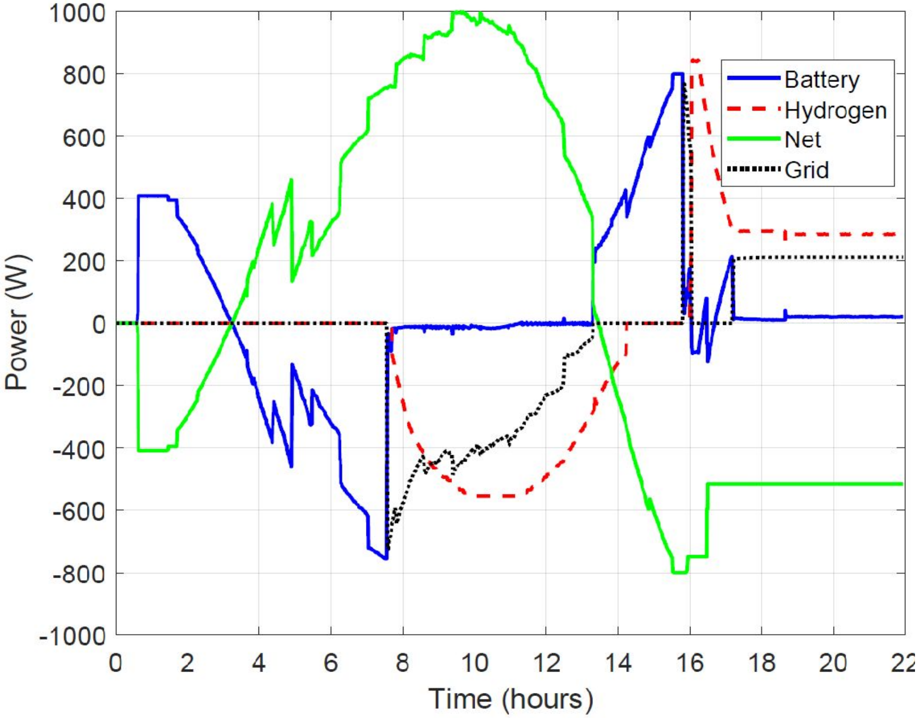
PLC for Real-Time control. Unity/Vijeo

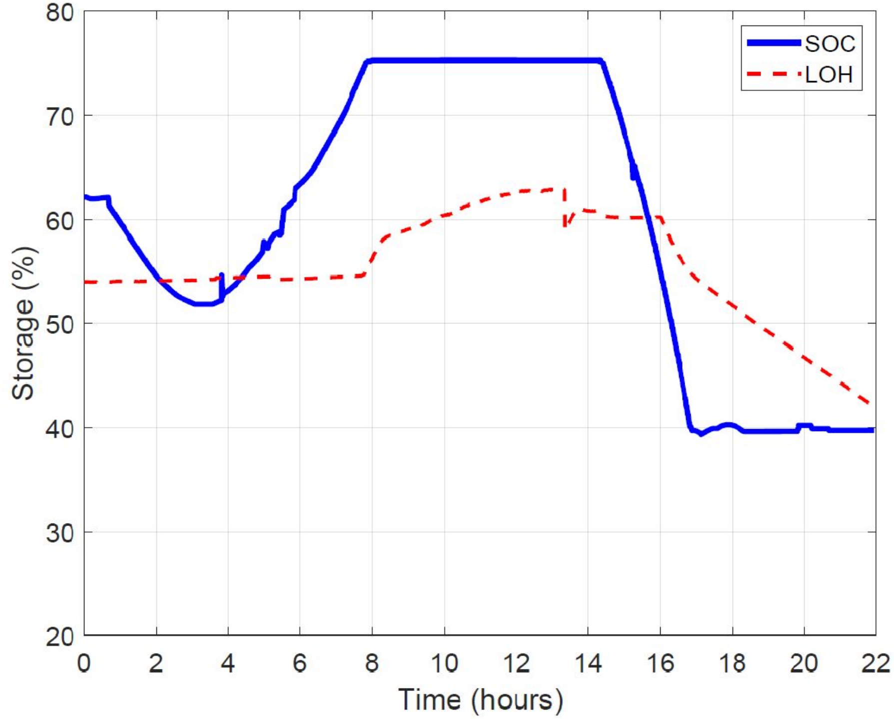
Matlab/Simulink□ Quadratic Programming



Model Predictive Control of Microgrids. Bordons, García-Torres and Ridao. Springer, 2020

Experimental results: Sunny day





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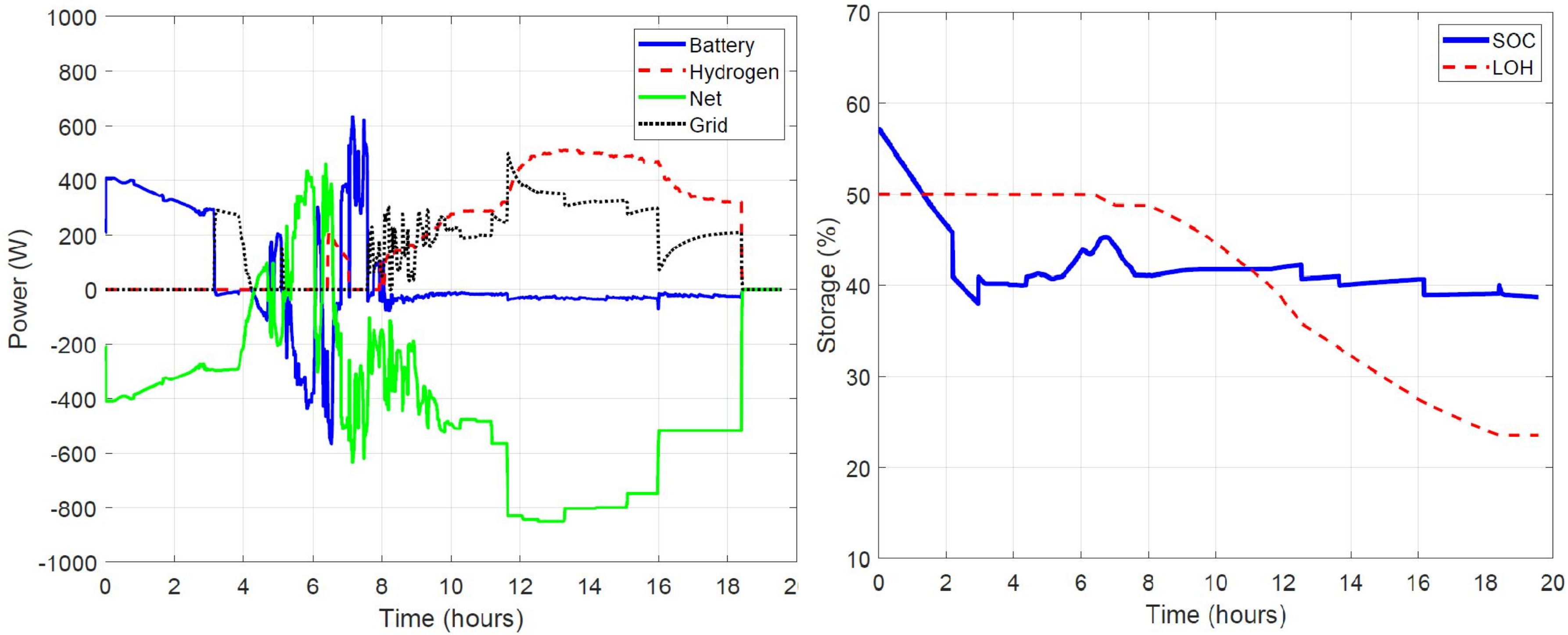
Experimental results: Cloudy day



Extended control objectives

- Durability and O&M costs
- Manufacturers of electrolyzers give the life a function of the number of working hours. **Start up and shut down cycles** and **fluctuating load** conditions can affect seriously to this devices
- Logical variables included: on/off states, startup and shutdown states

$$\sigma_j^{on}(t_k) = max(\delta_j(t_k) - \delta_j(t_{k-1}), 0)|_{j=elz,fc}$$
$$\sigma_j^{off}(t_k) = max(\delta_j(t_{k-1}) - \delta_j(t_k), 0)|_{j=elz,fc}$$

$$J_{elz}(h_i) = \left(\frac{\text{CC}_{elz}}{\text{Hours}_{elz}} + \text{Cost}_{o\&m,elz}\right)\delta_{elz}(h_i) + \text{Cost}_{startup,elz} \cdot \sigma_{elz}^{on}(h_i) + \text{Cost}_{shutdown,elz} \cdot \sigma_{elz}^{off}(h_i) + \text{Cost}_{degr,elz} \cdot \vartheta_{elz}^2(h_i)$$

- **Reduce the number of start-ups and shut-downs of ELZ**
- **Binary variable: transitions MIQP**

F. García and C. Bordons. Optimal Economic Dispatch for Renewable Energy Microgrids with Hybrid Storage using Model Predictive Control. IEEE IECON 2013.

Outline

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4. Integration with renewable generation
5. **Concluding remarks**

5. Conclusions

- Advantages of automated control in electrolyzers:
  - Enhanced efficiency
  - Lower operational costs
  - Improved safety through real-time monitoring
  - Flexibility in adapting to renewable energy fluctuations
- The integration of ELZ in RES can be improved with the concept of microgrid and advanced energy management system
- With advanced control strategies electrolyzers can become more efficient, adaptable, and safer, playing a crucial role in the clean energy transition.

Open issues

- Fault-tolerant control
- Degradation of FC & ELZ
- Demand side management
- Stochastic algorithms
- Digital twins of FC/ELZ and microgrids

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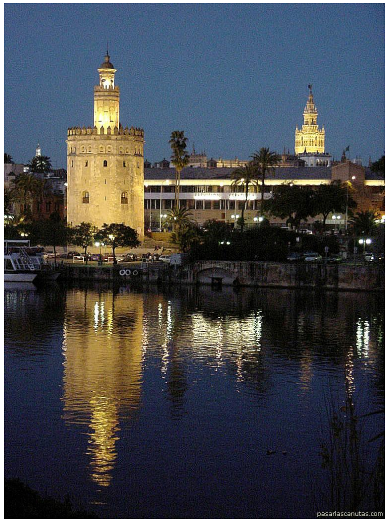

PhD students welcome to Sevilla!




Automatic Control of Electrolyzers for Green Hydrogen Production

Optimizing Green Hydrogen Production with Advanced Control Systems

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