Distribution-Connected Electrolyzers with Partial Loading Limit and Power Response Characteristics

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1. Introduction

- The global power and energy sector is rapidly transitioning toward **decarbonization**, driven by net-zero targets and long-term sustainability objectives.
- High share of inverter-based resources (IBRs) **reduces power system inertia**, increasing **frequency and voltage stability challenges** in modern power systems.
- Hydrogen electrolyzers (HEs) can operate as **fast, flexible loads**, providing frequency and reactive power support in addition to their hydrogen production.
- Electrolyzer operation is constrained by certain **stack constraints** such as partial loading limitation imposed for safety and efficiency considerations.
- This work investigates distribution-connected electrolyzers with a **single-stage AC–DC converter** and evaluates their grid-support capability considering partial load limit and response characteristics.
- A detailed **dynamic modeling and control framework** is developed and validated through **EMT simulation studies**, demonstrating frequency and voltage support.

2. Dynamic Modeling of Distribution-Connected Hydrogen Electrolyzers

Electrolysis Plant Dynamic Model

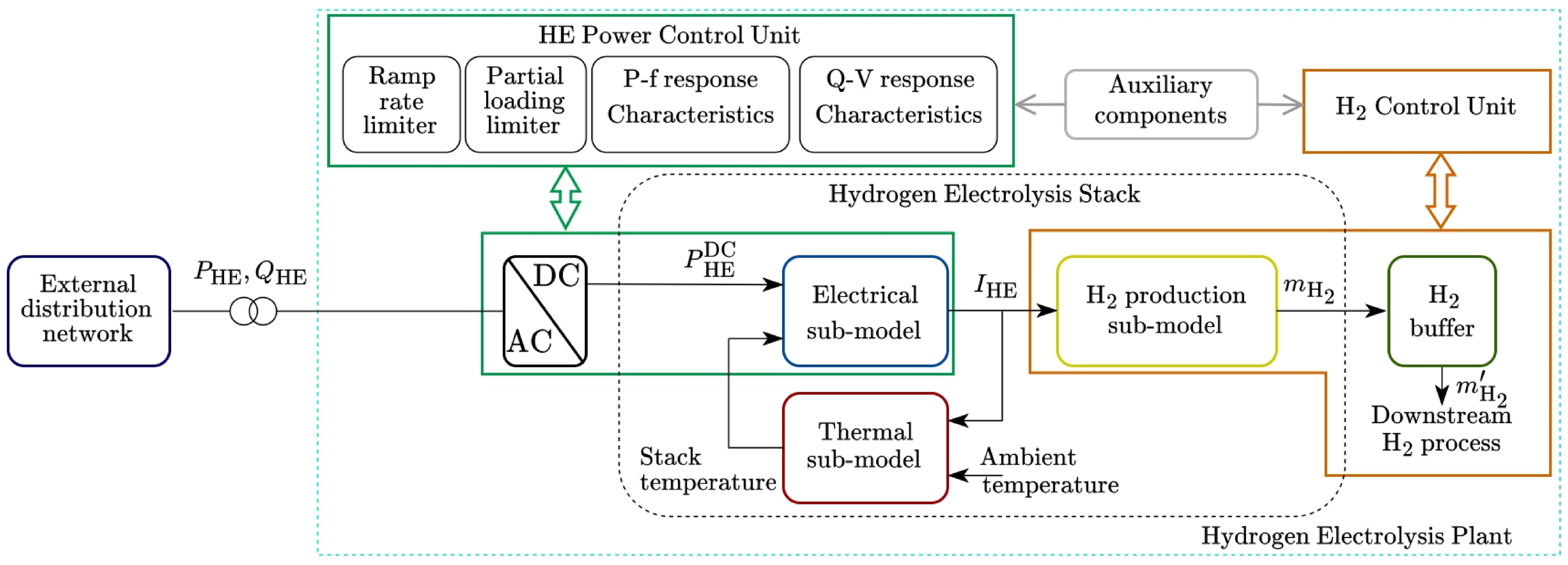

Figure 1: Detailed electrolysis plant model with H_2 control unit and power control unit.

Electrolysis Stack Electrical Sub-model

1. Relationship between the applied **voltage** and the resulting **current** flow during H_2 production.

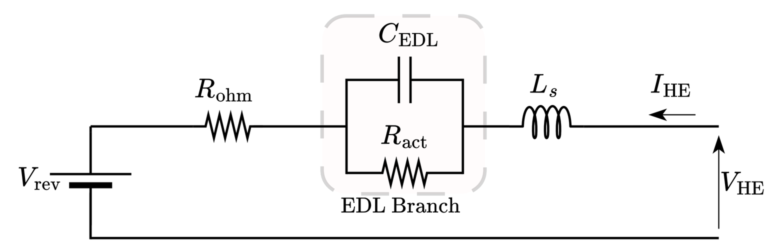

Figure 2: Unified HE electrical equivalent circuit.

Electrolysis Partial Loading Limit

At low current densities,

i. Increased energy losses reduce hydrogen production efficiency.

ii. Reduces transferring hydrogen molecules to the cathode side.

Table 1: Partial Loading Limits on Electrolysis Technologies by Different Manufacturers.

HE Manufacturer	Type	Partial loading limit (%)
Cummins (AEL)	HySTAT	40
NEL (AEL)	A	15
Cummins (PEM)	HyLYZER	5
NEL (PEM)	PSM	10

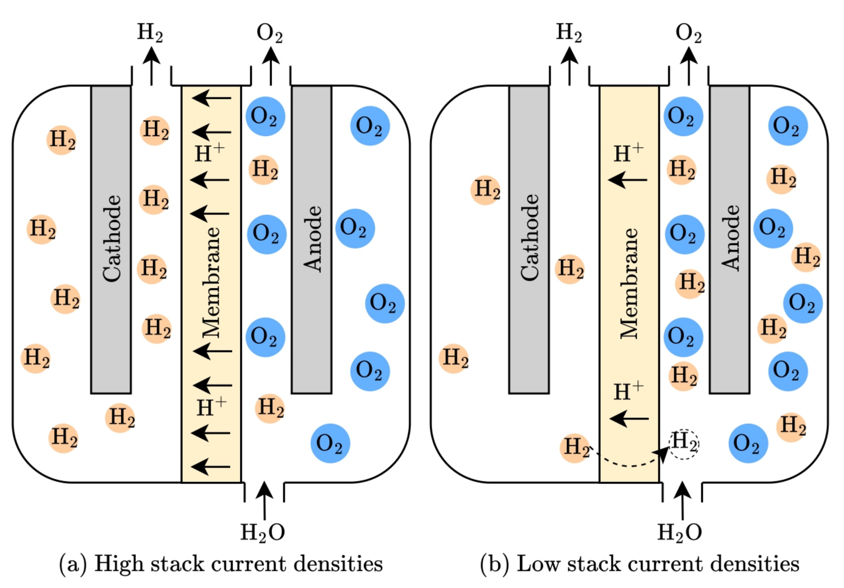

Figure 3: Cross-sectional diagram of electrolysis stack operating at (a) high stack current density and (b) low stack current density.

3. AC-DC Power Electronic Interface Control Strategy

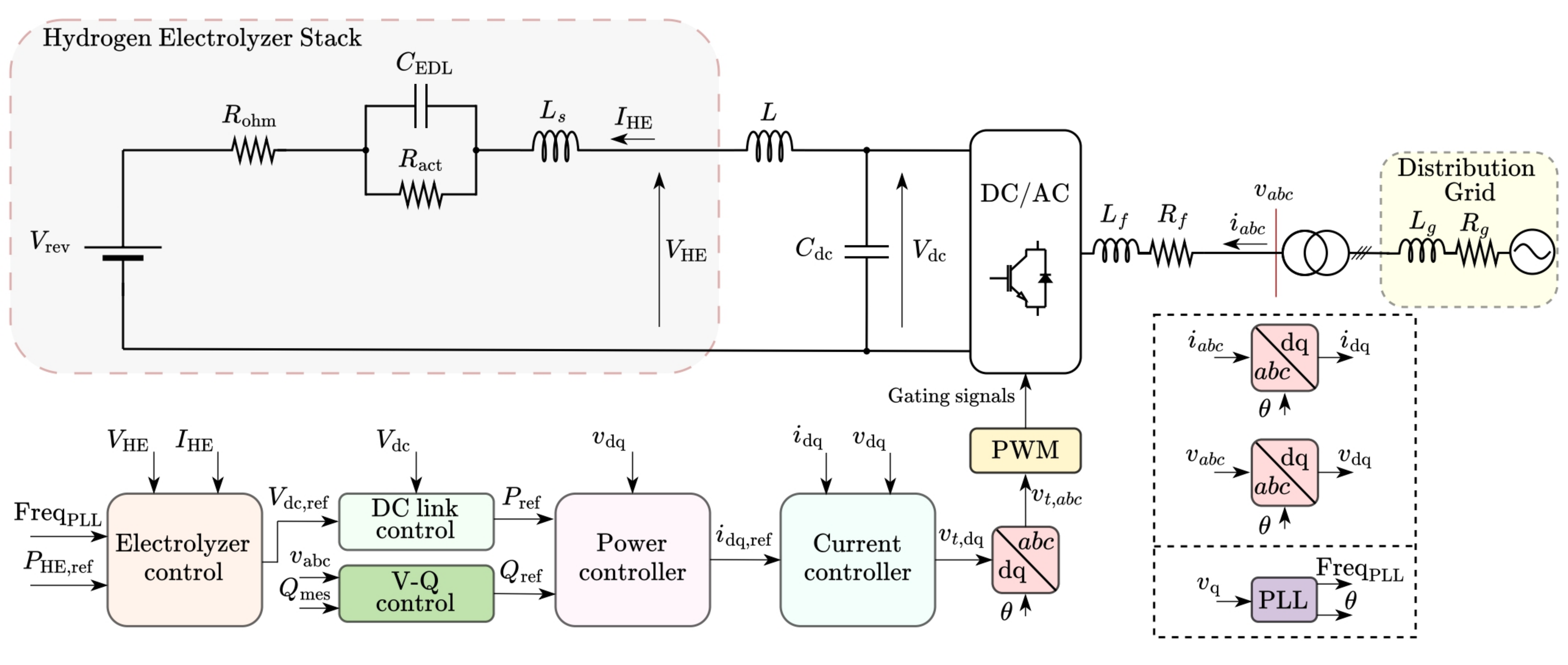

Figure 4: Block diagram of the proposed control strategy for distribution-connected HEs.

4. Power Response Characteristics and Operational Constraints

Active Power- Frequency Control with Partial Loading Constraint

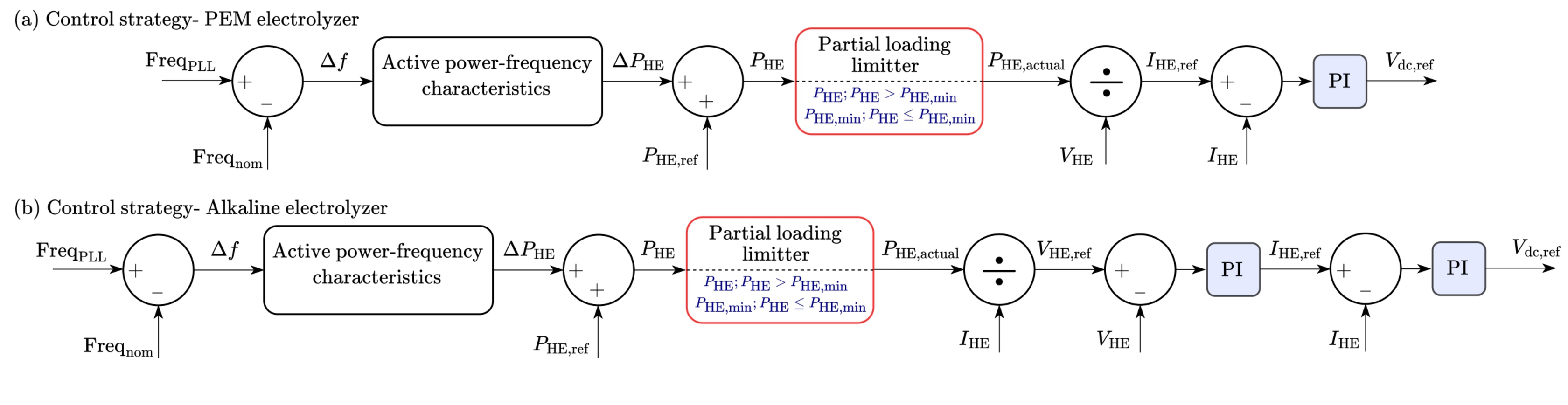

Figure 5: Active power reference generation strategy for (a) PEM HE and (b) AEL electrolyzers.

Reactive Power- Voltage Control

i. Q Mode: Reactive power follows an **external reference** for power factor and voltage regulation.

ii. $Q-V$ Droop Mode: The HE power electronic converter adjusts reactive power in response to voltage deviations based on a predefined **droop** characteristic.

5. Simulation Case Studies

Case I. Fast Frequency Response (FFR) from Electrolyzers

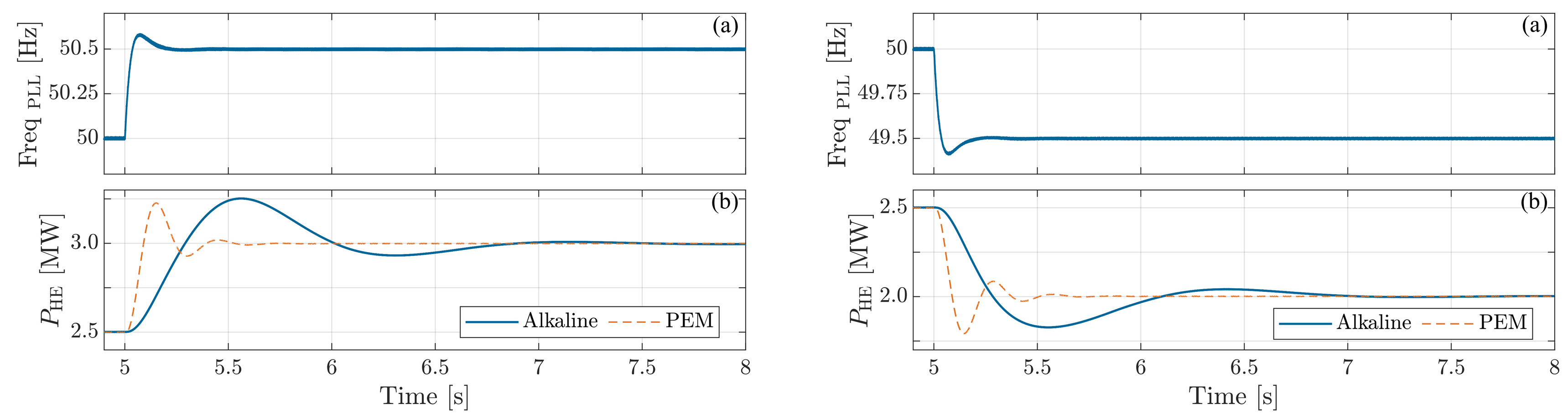

Figure 6: Dynamic response of PEM and alkaline electrolyzers to 1% frequency increase and decrease at $t = 5$ s: (a) frequency and (b) active power output.

Case II. Voltage and Reactive Power Support from Electrolyzers

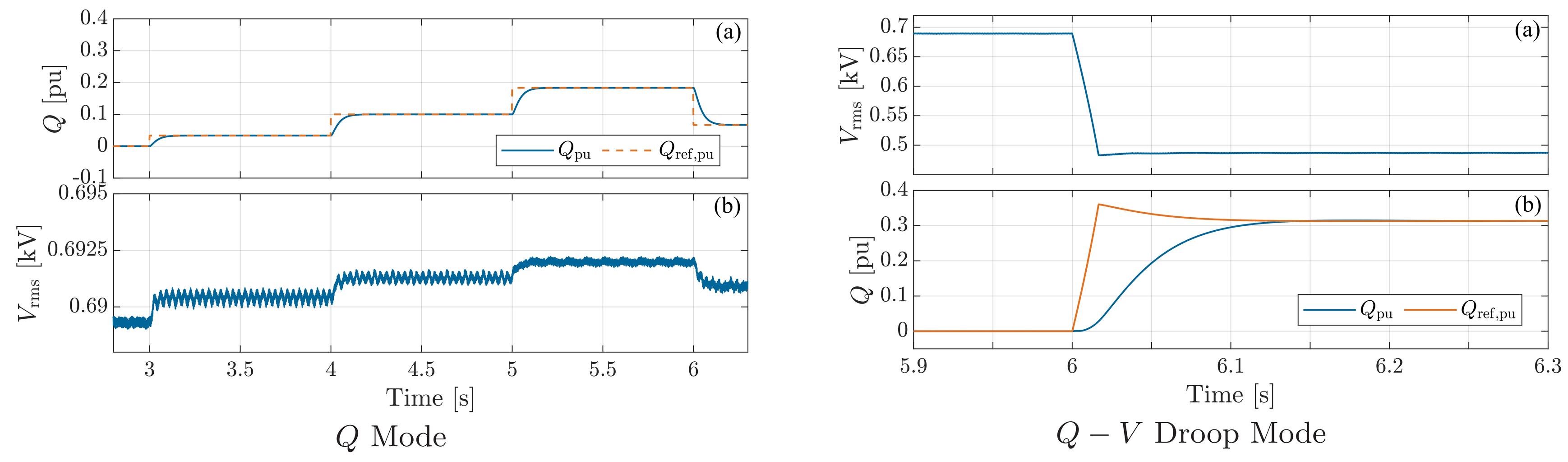

Figure 7: Reactive power and voltage response of the electrolyzer under Q mode and Q–V droop control

Case III. Impact of Partial Loading Limit on FFR Provision

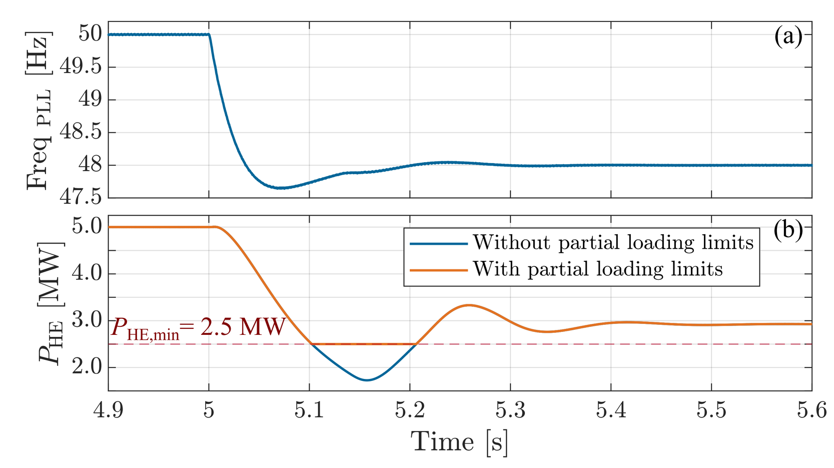

Figure 8: PEM electrolyzer response to a 4% frequency drop with and without the partial loading limit.

5. Conclusions

1. Distribution-connected hydrogen electrolyzers can effectively provide fast frequency and voltage support using a single-stage AC–DC interface.
2. Partial loading limitation significantly constrains available frequency support and must be explicitly considered in control design and system studies.
3. PEM electrolyzers exhibit faster dynamic response compared to alkaline electrolyzers, making them more suitable for fast frequency response.
4. The proposed dynamic modeling and control framework provides a realistic basis for integrating electrolyzers into active distribution networks and stability services.

References

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2. M. A. Torres, M. Zhang, L. Söder and Q. Xu, "Decentralized Dynamic Power Sharing Control for Frequency Regulation Using Hybrid Hydrogen Electrolyzer Systems," in IEEE Trans on Sustainable Energy, vol. 15, no. 3, July 2024.
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