



# A Power Converter Hardware-in-the-Loop System for Energy-Domain AI Evaluation

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## 1 Introduction

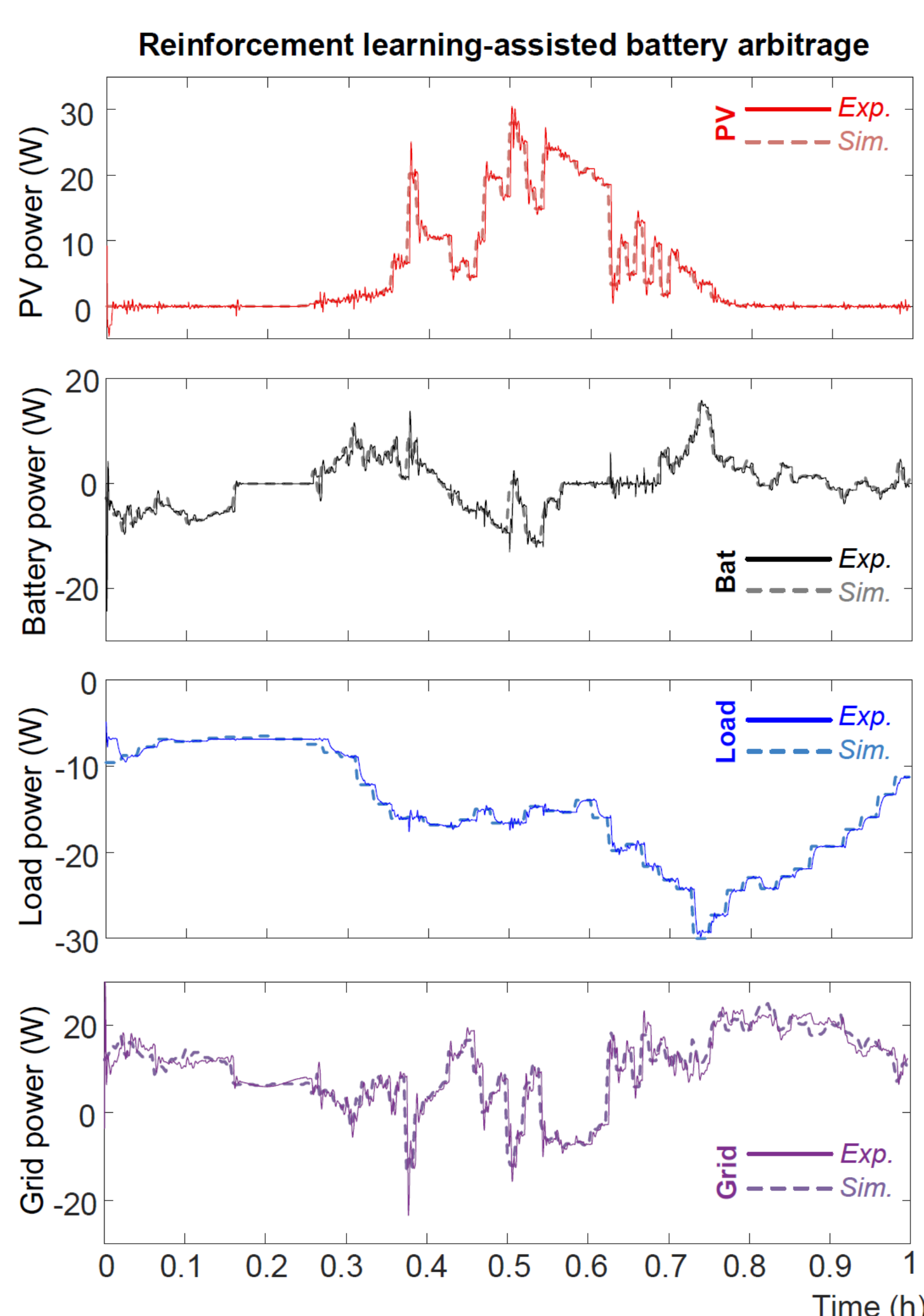
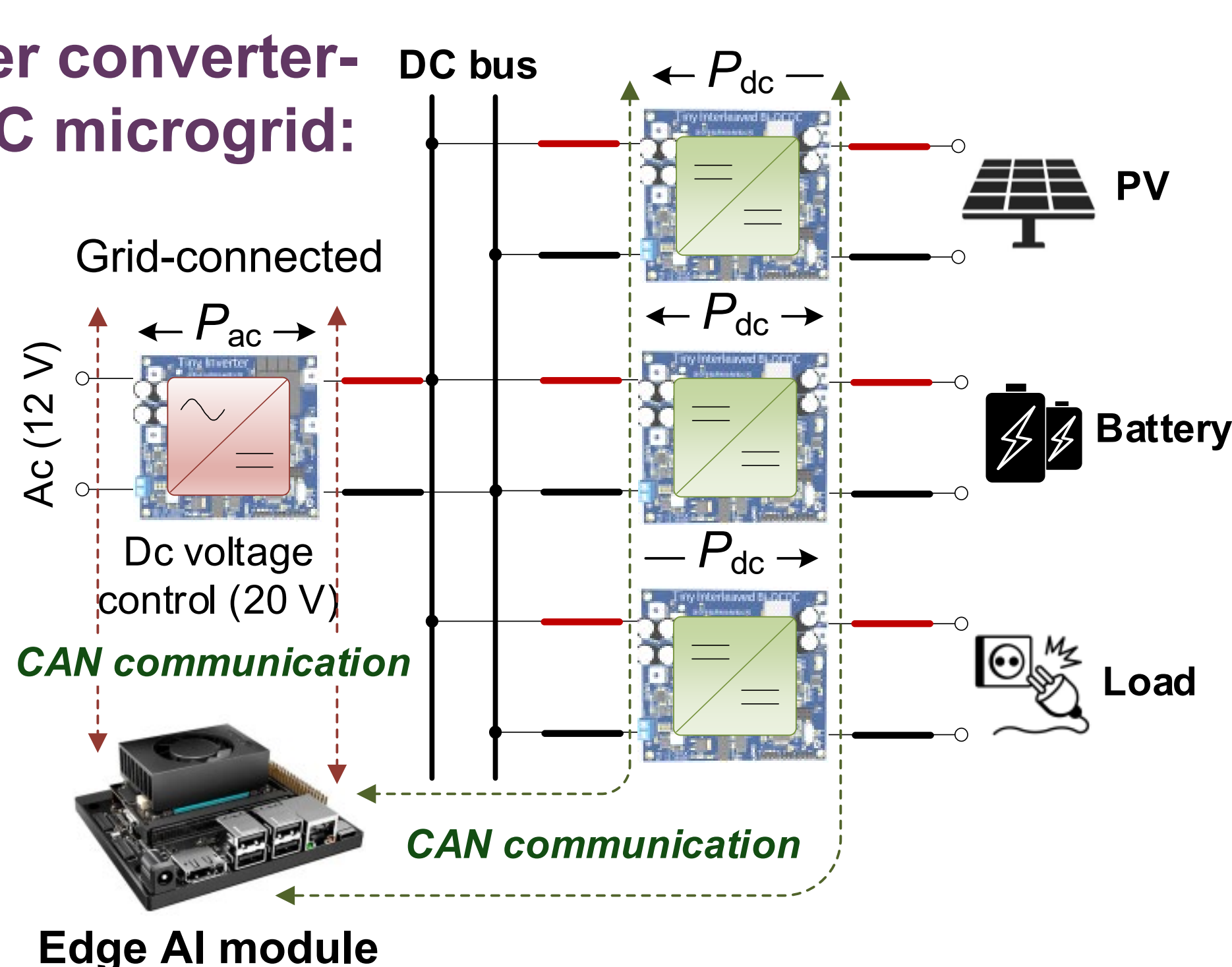
- Artificial intelligence (AI) algorithms often face a significant verification gap when moving from idealized simulations to real physical systems, as simulation models may fail to fully capture highly nonlinear behaviours, network delays, stochastic operational disturbances, and the computational complexity associated with real-time deployment.
- Existing commercial hardware-in-the-loop (HiL) platforms are developed with a focus on conventional power electronic applications, such as power converter testing and controller validation.
- These HiL platforms face challenges in accommodating real-time AI inference, distributed intelligence, and coordinated operation across multiple devices, limiting the practical translation of advanced AI solutions into energy system applications.

This work develops a novel power converter HiL system for energy-domain AI algorithm implementation. This is a new HiL paradigm, integrating edge intelligence (using an Edge-AI developer kit) with power converter hardware (AC-DC and DC-DC) to form a closed loop with real-time deployment of AI algorithms.

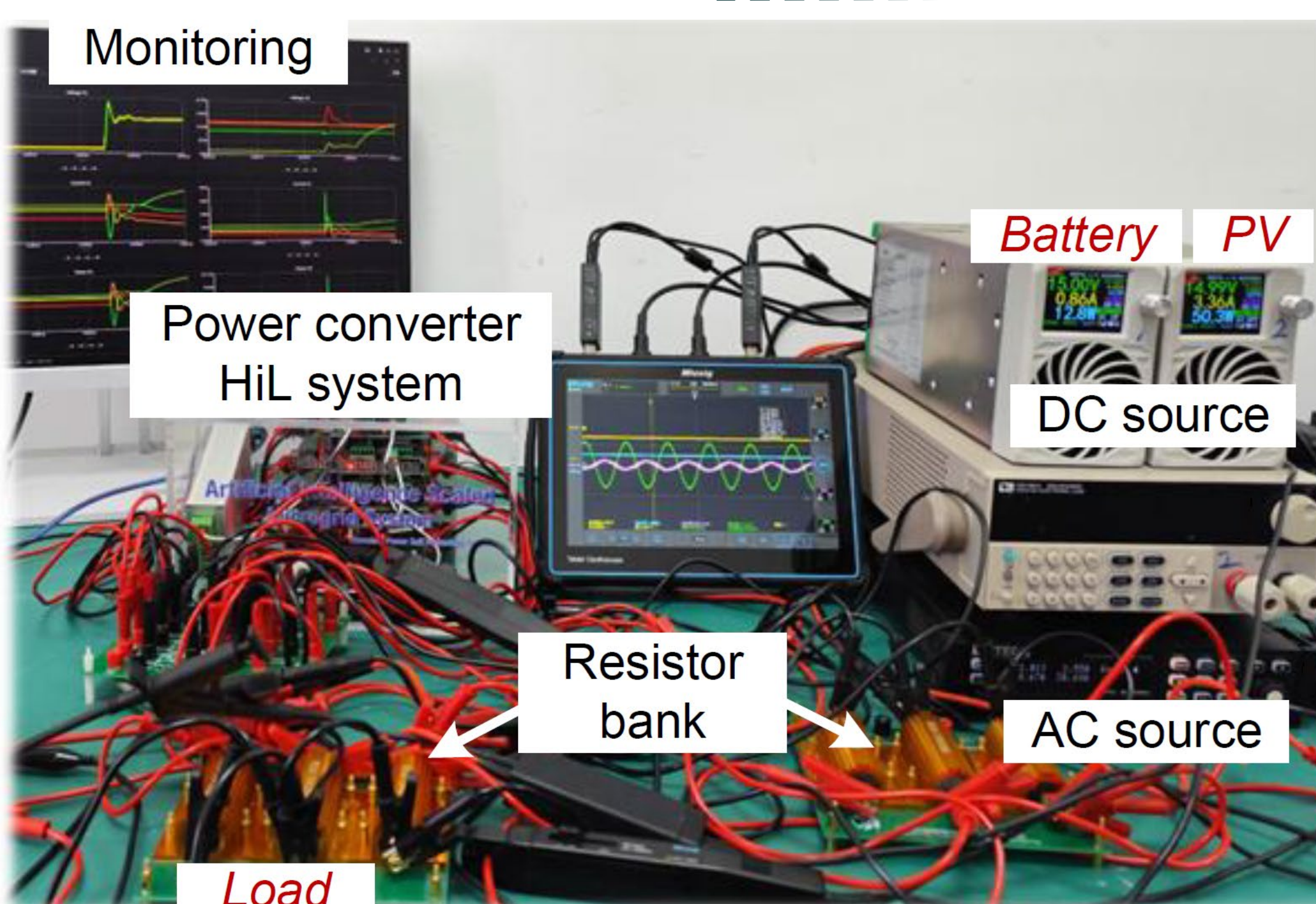
## 4 Verification (an RL-based case)

### Studied power converter-based DC microgrid:

A soft actor-critic (SAC) reinforcement learning (RL) agent is trained offline for battery arbitrage under time-varying electricity prices and subsequently deployed on the proposed HiL system.



### Experiment setup for the studied DC microgrid:

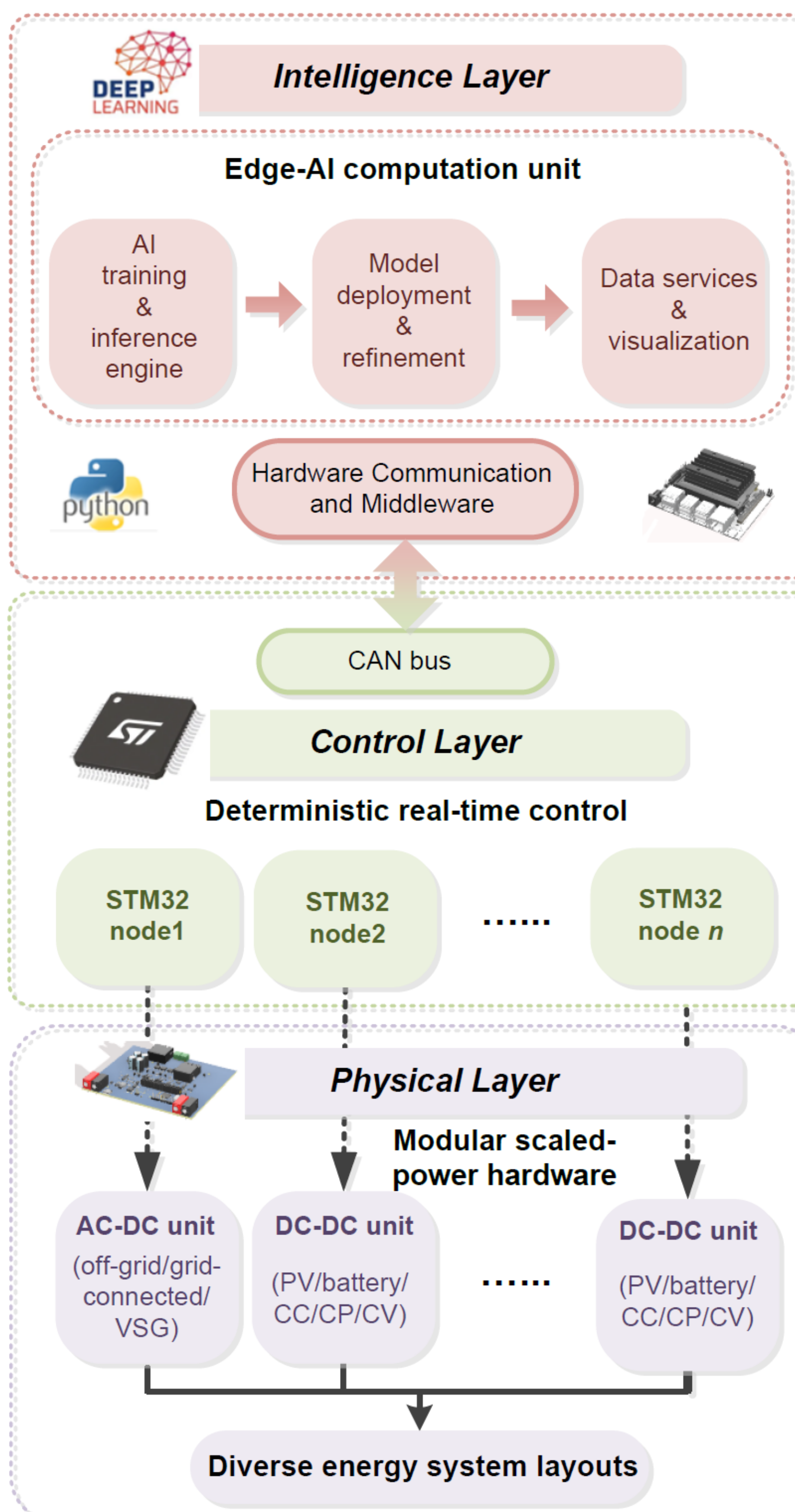


| AC-DC converter     |                           |
|---------------------|---------------------------|
| Control mode:       | DC voltage control (22 V) |
| Power rating        | 50 VA                     |
| Switching frequency | 50 kHz                    |
| AC bus voltage      | 12 V (RMS)                |

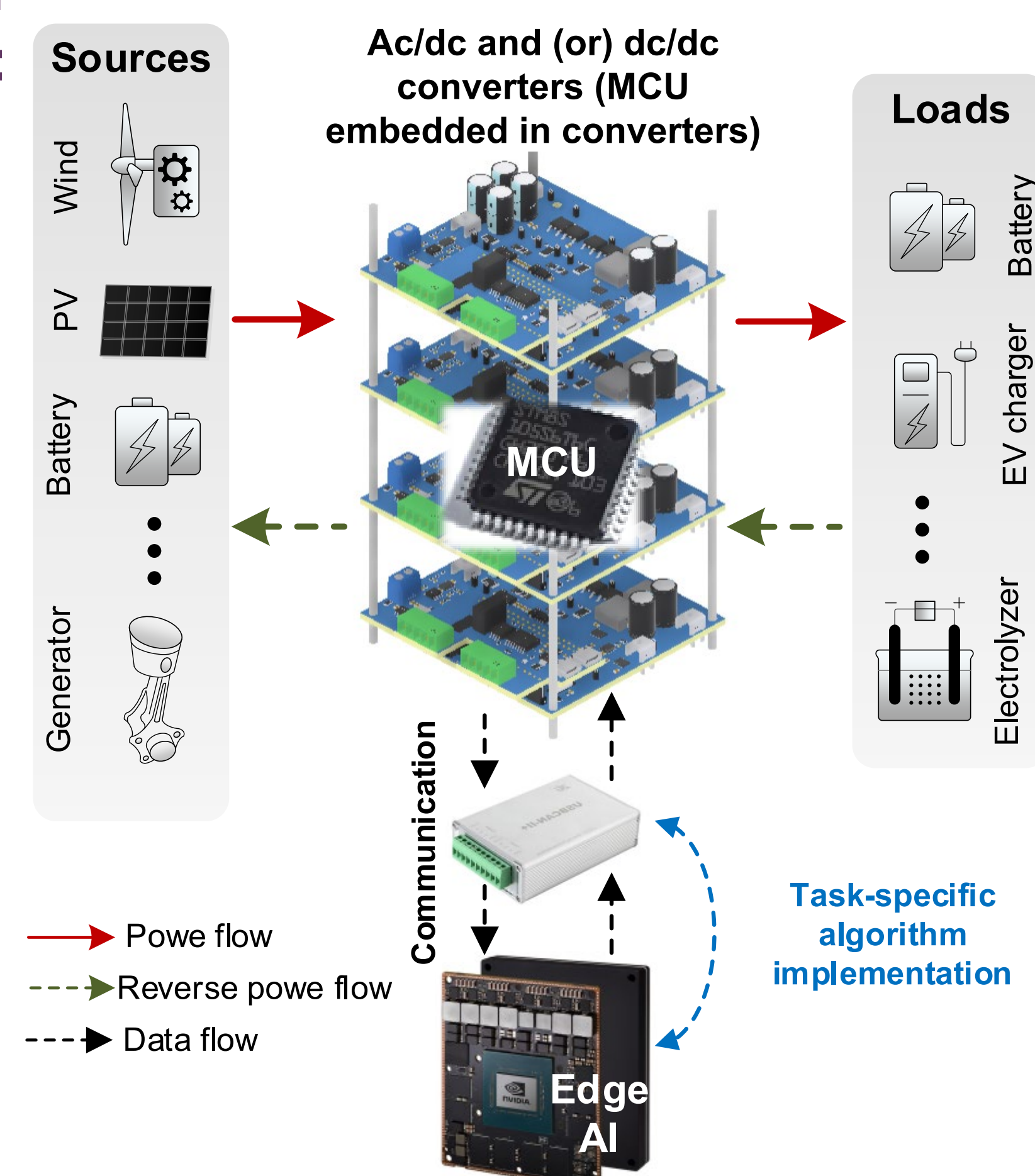
| DC-DC converter                        |                       |
|----------------------------------------|-----------------------|
| Control mode:                          | HV side power control |
| Power rating                           | 50 W                  |
| Switching frequency                    | 70 kHz                |
| DC bus voltage (PV and battery sides)  | 15 V                  |
| Resistor bank (battery and load sides) | 8 Ω                   |

## 2 Edge AI-Based Hardware and Software Co-Integration

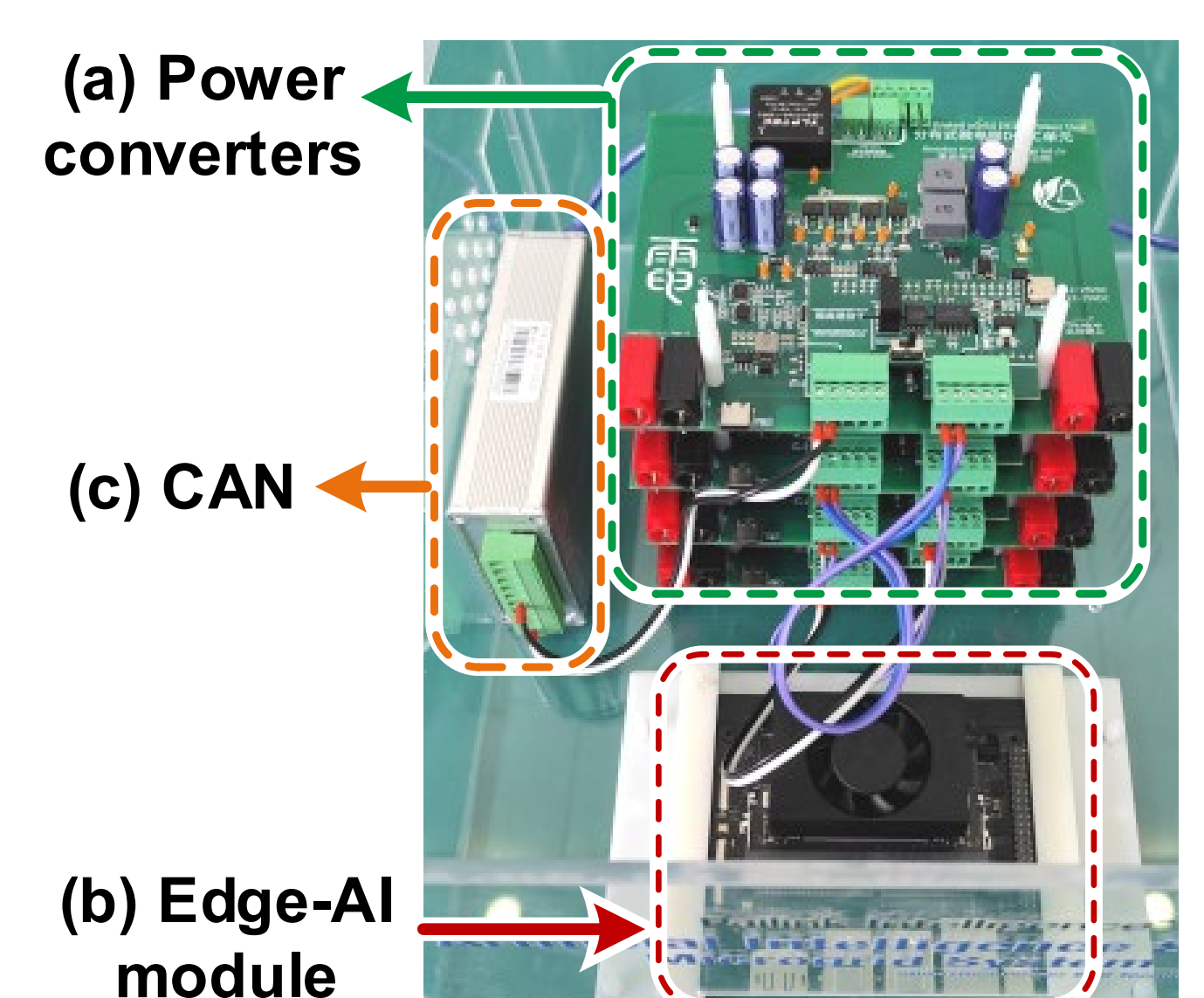
### Structures of the novel power converter HiL system for energy-domain AI study:



### Overall architecture:



### Hardware layout of power converter HiL system:



## 3 Scaling Principle

Dynamic equivalence (guaranteeing invariance of per-unit representations):

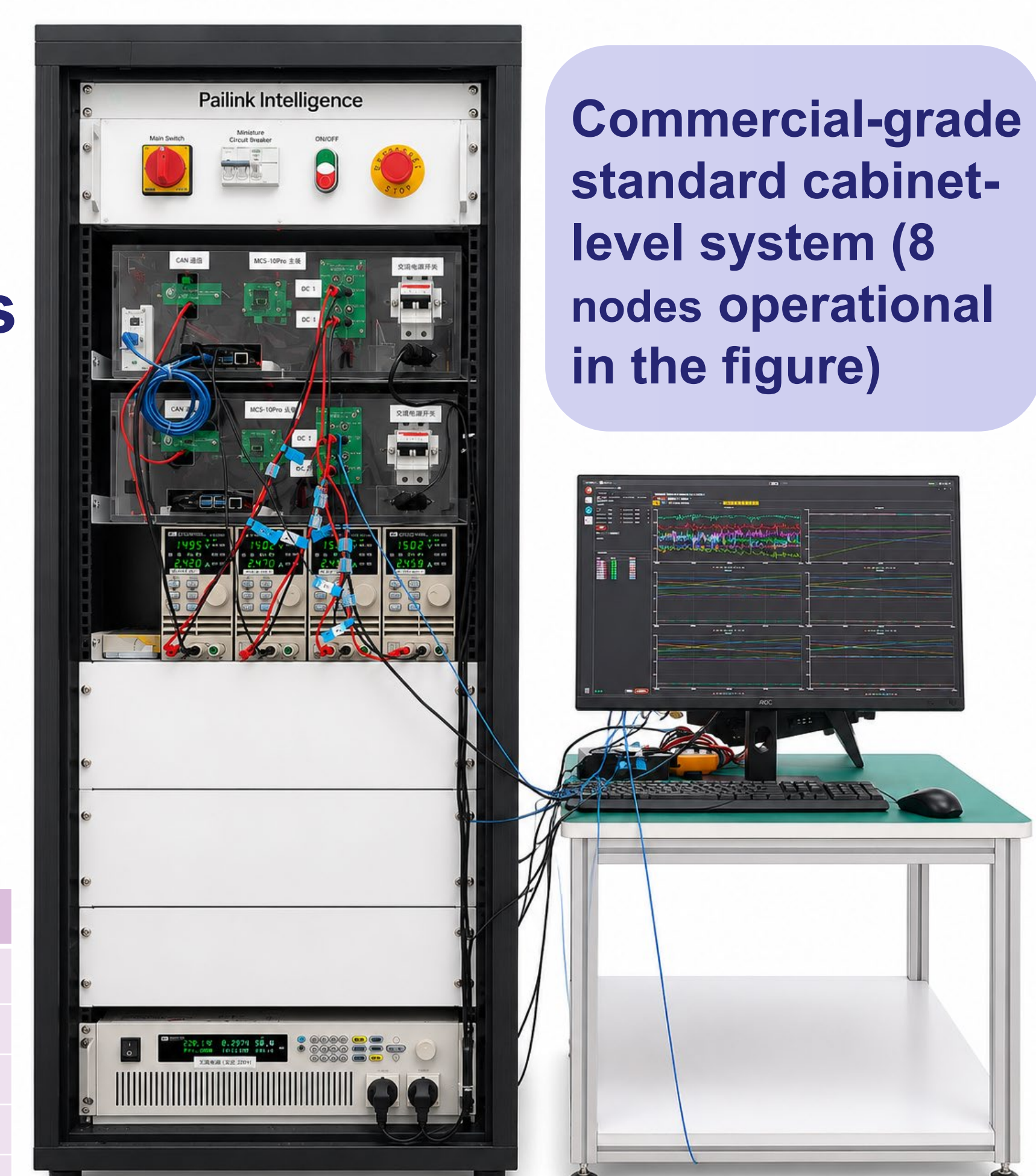
$$V' = k_v \cdot V, \quad I' = k_i \cdot I, \quad \text{and} \quad (1) \quad P' = k_v \cdot k_i \cdot P, \quad Z' = \frac{k_v}{k_i} \cdot Z, \quad (2)$$

$$R' = \frac{k_v}{k_i} \cdot R, \quad L' = \frac{k_v}{k_i} \cdot L, \quad C' = \frac{k_i}{k_v} \cdot C \quad (3)$$

Small signal plant dynamics remain structurally unchanged:

$$G'(s) = \frac{k_v}{k_i} \cdot G(sT_s), \quad \text{and} \quad (4) \quad \mathcal{G}'(s') = \mathcal{G}'(sT_s) = G(s'/T_s) = \frac{k_v}{k_i} \cdot G(s'), \quad (5)$$

Scalability to 8+ nodes



Commercial-grade standard cabinet-level system (8 nodes operational in the figure)