

Supplementary Document

P-HIL Laboratory description and equipment

A P-HIL setup involves the actual power hardware connected to the simulated network in a closed loop. The P-HIL test facility has been installed at IEC, located at the University of Delaware, Newark, DE, USA. The facility consists of a grid emulator, two programmable PV simulators and two residential grid-tied smart PV inverters from different manufacturers. Table S1 shows the components and manufacturers of the setup. All the equipment is the actual hardware supplied by 480 V from the real grid in the IEC building. The inverter brands are labeled as Inverter-A and Inverter-B to avoid sensitive cyberattack information disclosure. They represent well-established legacy brands that are commercially available in the U.S. The inverter manufacturers have announced compliance of their inverters with UL 1741 and California Rule 21, as well as being certified for IEEE 1547-2018 standards. Additionally, these inverters must be able to operate without module-level power electronics (MLPE) since there is no physical PV array involved. Inverter-A is part of an AC-coupled PV system with battery backup where a regular PV grid-tied inverter and a battery-based inverter are required. The Automatic Backup Unit (ABU) switches Inverter A subsystem operation between grid-tied and backup mode depending on the grid condition.

Table S1. Description of P-HIL equipment

Equipment Model Number	Capacity	Manufacturer	Description
61830	30 kVA	Chroma	3-phase grid emulator
62050H	5 kW	Chroma	Programmable PV power supply (2 units)
66204	-	Chroma	4-channel power meter
Inverter A	3.8 kW	A	Grid-tied PV inverter
Inverter B	3.8 kW	B	Grid-tied PV inverter
SBS-ABU-200-US-10	-	A	Automatic Backup Unit

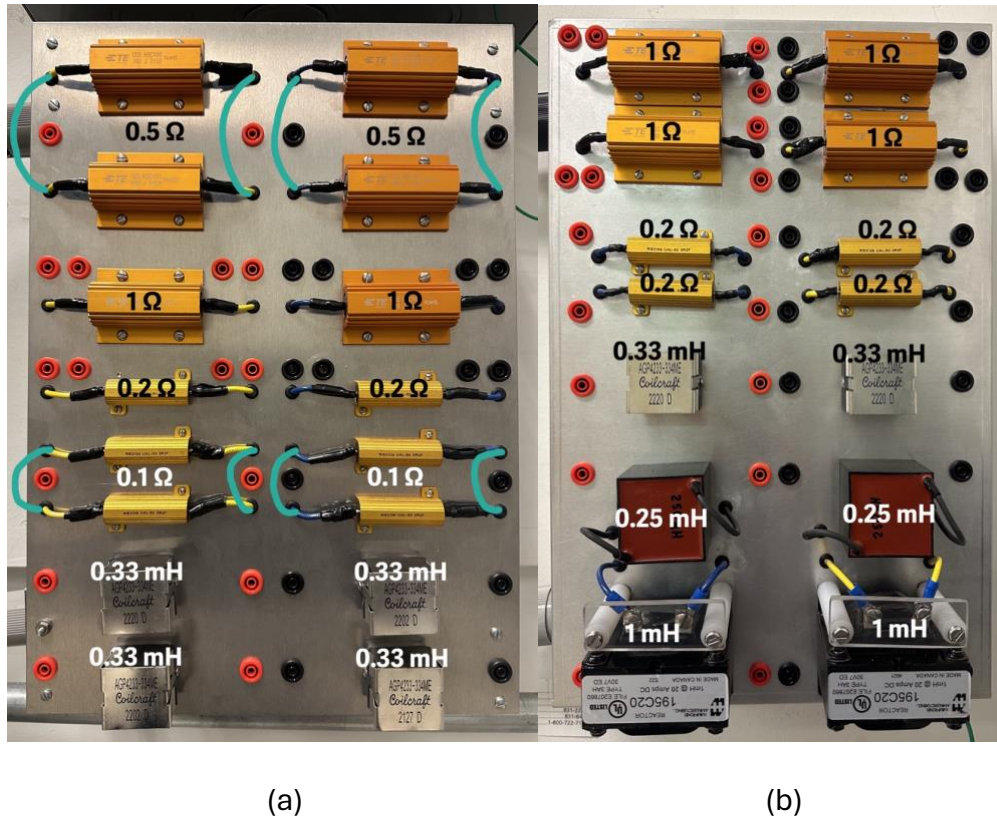


Figure S1. Actual photos of the two impedance circuits installed (a) at the grid emulator and (b) at Inverter-A. The green lines represent the resistors soldered together inside the circuit box to have fixed parallel connections.

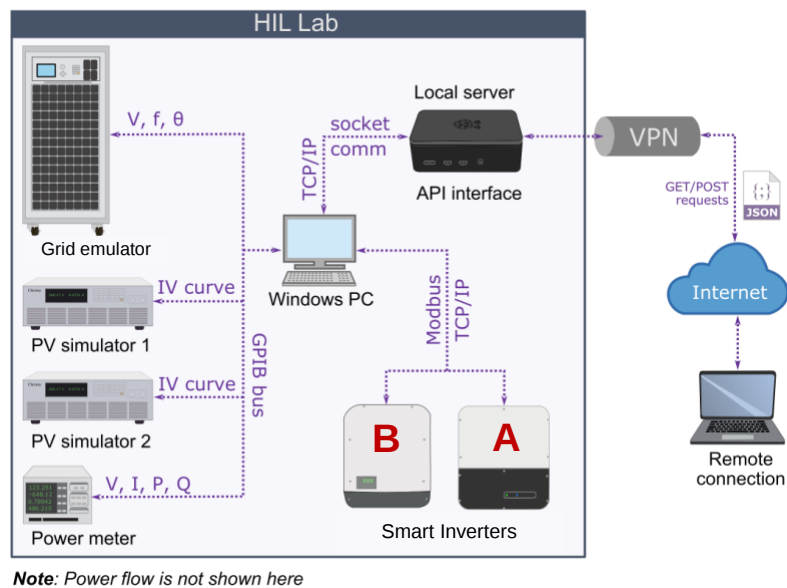


Figure S2. Communication diagram of the P-HIL laboratory. Modbus port ID is 502.