Remote-Lab Emulation of Grid-Connected Photovoltaic Generation System Suported by Cloud and IoT Technology

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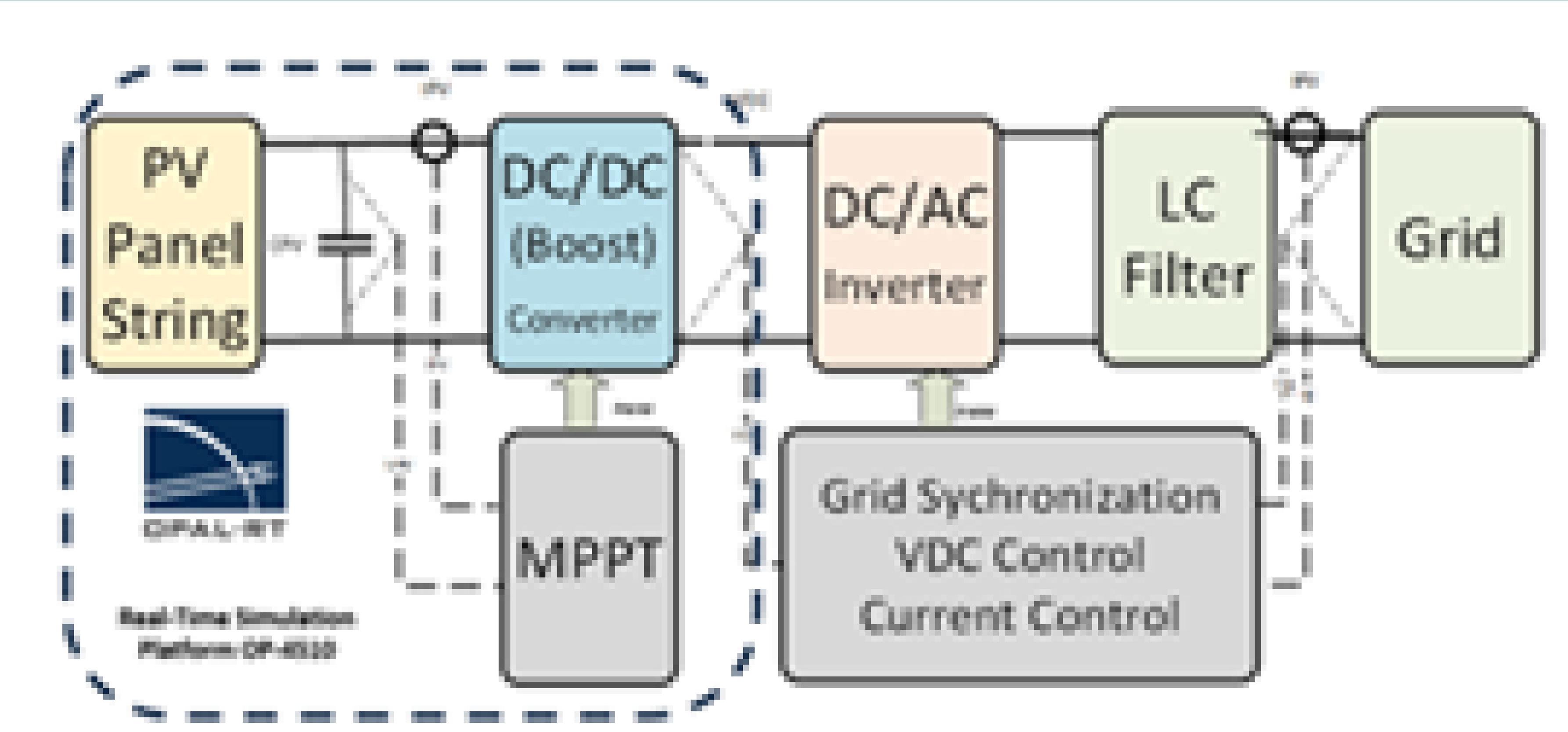
Abstract

This work presents the design and implementation of a real-time emulation system for grid-connected photovoltaic (PV) generation, supported by Internet of Things (IoT) and cloud technologies. The proposed platform integrates remote environmental data acquisition, cloud data processing, and a Power Hardware-in-the-Loop (PHIL) experimental setup to reproduce realistic PV generation scenarios and enable testing of control strategies and power converters under actual conditions.

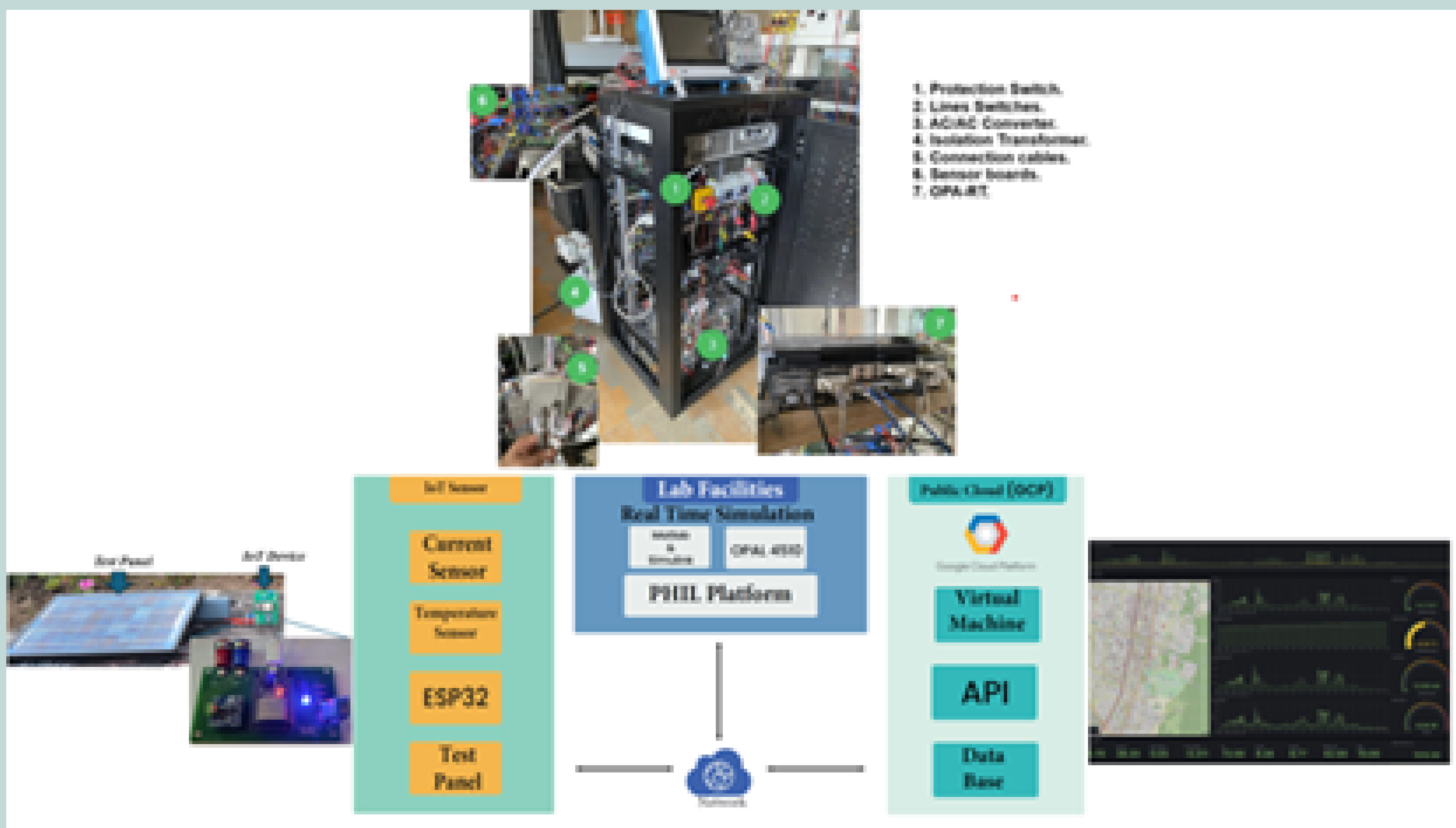
Power Hardware in the Loop Platform (PHIL)



Architecture

- IoT Sensor Node: A portable device equipped with a test PV panel and sensors for irradiance and temperature, interfaced through an ESP32 microcontroller. Real-time data are transmitted via Wi-Fi to the cloud platform.
- Cloud Platform: Implemented on Google Cloud Platform (GCP) using virtual machines, databases, and APIs for data storage, monitoring, and visualization. Grafana dashboards provide real-time tracking of irradiance and temperature, as well as sensor geolocation.
- PHIL Experimental Platform: Based on OPAL-RT real-time simulation, it includes reconfigurable PV array and DC–DC converter models, supplying a physical Semikron inverter connected to the grid. The inverter can operate in single- or three-phase configurations up to 10 kW.

Structure of the Proposed Platform

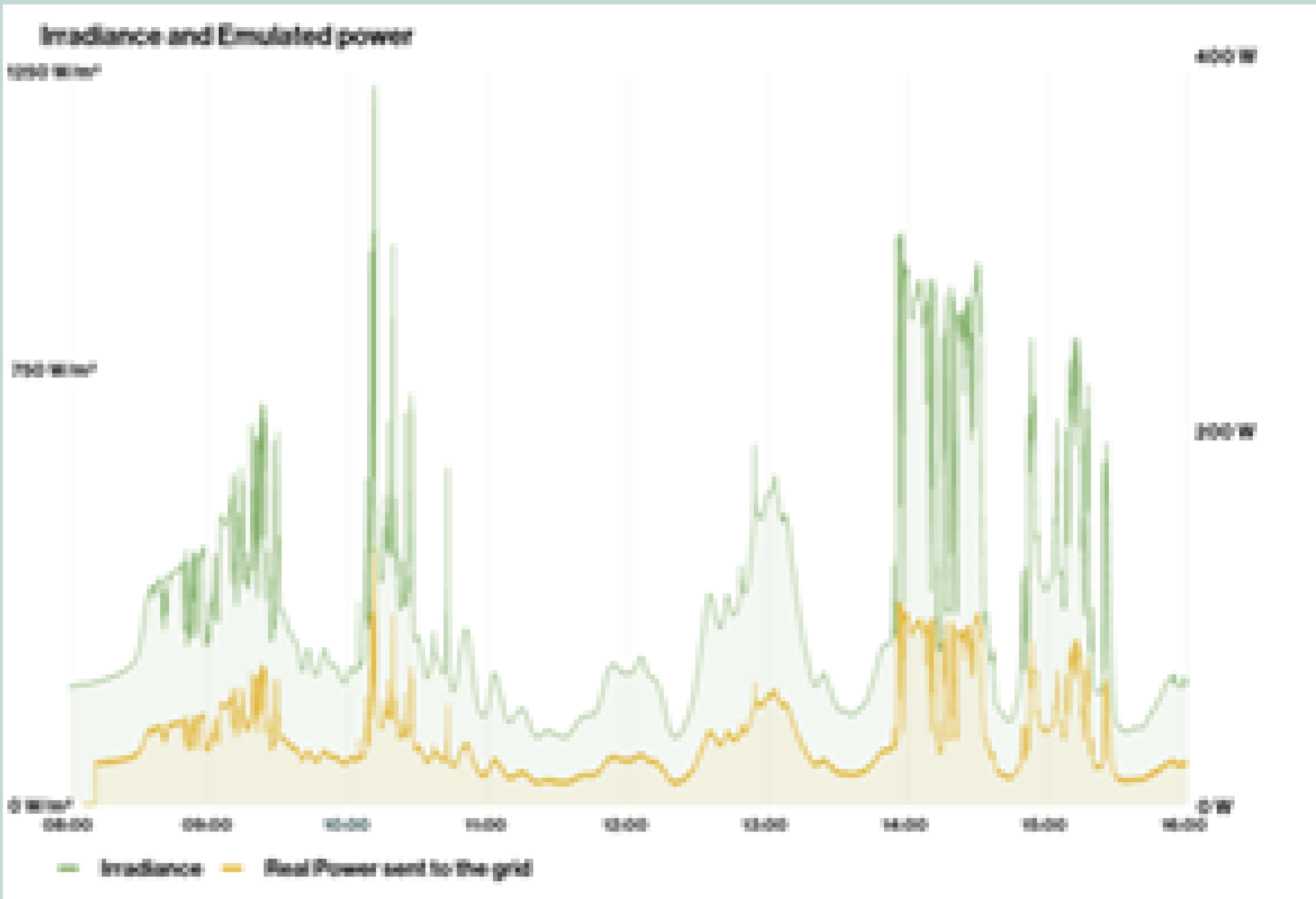


Geographical location of the IoT sensor and the experimental Platform.

These two locations are in different cities within Cundinamarca, Colombia, with a distance of approximately 28 km between them.

Measured Irradiance and Power generated in real time

A PV generator with a capacity of 355 W under STC (Standard Test Conditions) was tested for the real time experiment. Figure shows the measured irradiance at the IoT sensor's location, and the power delivered to the grid by the PHIL system.



Conclusions

The integration of IoT measurement, cloud computing, and PHIL experimentation enables a scalable and flexible environment for testing PV systems, inverters, and energy management algorithms under realistic, and reproducible conditions. The architecture provides a cost-effective alternative for research, teaching, and pre-deployment analysis of distributed PV systems. Future work will focus on incorporating edge computing and AI-based prediction models to enhance system autonomy and data-driven control optimization.

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