Design and Validation of an IoT System for an Experimental Laboratory Microgrid

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***Abstract*—In the energy transition context, electrical microgrids facilitate the integration of renewable generation into the electrical grid, improving the electrical system's reliability and accelerating its decarbonization. However, to promote the technological advancement of these grids, it is necessary to develop tools to validate new technologies and solutions, such as using the Internet of Things (IoT) for their operation and control. This work presents the design, implementation, and validation of an IoT system for an experimental laboratory microgrid developed at Universidad Industrial de Santander. The main design phases of the IoT system are described, beginning with the definition of requirements and extending through the component selection. Validation tests are proposed to verify the functionalities of the IoT system. The results demonstrate that the IoT system successfully enables the transmission and reception of data from external users and servers. The reported experience and the proposed validation tests are relevant for researchers interested in implementing IoT-based stages in existing or future laboratory microgrids.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9281

***Index Terms*—Distributed Generation, Internet of Things, Laboratories, Microgrids, Test Systems.**

I. Introduction

THE energy transition that is developing worldwide focuses on replacing fossil fuels with renewable energy sources, seeking to reduce greenhouse gas emissions and, thus, slow down global warming [1]–[3]. Although this transition is ongoing in most countries, there are still multiple challenges to successfully incorporating distributed energy resources into the electrical grids [4]–[6]. In this context, electrical microgrids appear as critical elements since they enable the interconnection of users (loads) with distributed energy resources [7]–[10]. Although technologies and solutions for microgrids are developing rapidly, it is necessary to use validation platforms and laboratories to test operation scenarios as a prior step to their implementation in local electrical systems.

Given the few experiences in this regard in Colombia, an experimental microgrid is being developed at Universidad Industrial de Santander (UIS) in the Energy Integration Laboratory (EIL). This work presents the implementation process of an IoT-based monitoring and control stage for the experimental microgrid. As part of the design of the IoT system, the requirements are defined, and commercially available components are selected. Once the IoT system has been implemented, a series of tests are proposed to validate and verify its functionalities. These tests validate the capability of receiving and sending data from the local communications server, the interaction with local users, the system's flexibility, and the capability of publishing and subscribing of data from an MQTT server, among others. The results show that with the implementation of the IoT system, interaction with the microgrid is enhanced locally and remotely, facilitating its monitoring and control.

The rest of this paper is organized as follows: Sections II and III review general concepts on microgrids' laboratories and IoT systems. Section IV describes the system requirements, used as a starting point for the design stage. Section V details the selection of components based on commercial offer. Section VI describes in detail the proposed validation to verify the functionalities of the IoT system. Finally, in Section VII main conclusions are drawn.

II. Experiences on Microgrid Laboratories

In the energy transition context, microgrid laboratories are essential to promote the technological advancement of this type of systems [11], [12]. The development of microgrid laboratories is relevant for the following reasons:

- Microgrid laboratories are tools to validate control strategies, communications schemes, and demand response alternatives at different technology readiness level [13].
- In these laboratories is possible to emulate events such as electrical failures, electrical disturbances or outages in communications systems in a controlled manner, to evaluate the impact they may have on the power quality, resilience, flexibility, stability, and reliability of the electrical energy supply [14].
- Microgrid laboratories make it possible to certify if new solutions and devices meet the standards required by technical regulations before operate them into real environments.

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- Microgrid laboratories are ideal platforms for evaluating the operational implications of incentives, penalties, changes in the regulatory framework, and new energy market conditions.
- Microgrid laboratories can be used to support the training of specialized personnel through practical experiences that allow the development of technological competencies.

Considering the above, universities and research centers in different parts of the world have implemented infrastructure to investigate the operation, control, and monitoring of electrical microgrids [15], [16]. Among the most relevant microgrid laboratories, commonly used as reference cases for new designs and implementations, are those located at Aalborg University (Denmark) [17], Polytechnic University of Catalonia (Spain) [18], Florida International University (United States) [19], Tianjin University (China) [20], Korea Electrotechnology Research Institute (KERI) [21], University of Texas (United States) [22], RWTH Aachen University (Germany) [23] and the Canadian Renewable Energy Laboratory (Canada) [24], among others.

For its part, in Latin America some microgrid laboratories stand out, such as the one located at the Universidad Nacional de Rosario (Argentina) [25], the microgrid test of the Universidade Federal do Paraná (Brazil) [26], the laboratory microgrid at Universidad de Chile [27], the experimental nanogrid at Universidad del Valle (Colombia) [28], the HIL renewable energy laboratory at the Universidad Michoacana de San Nicolás de Hidalgo (Mexico) [29] and the electrical microgrid laboratory of Universidad de Cuenca (Ecuador) [30], among others. The main characteristics of these mentioned microgrid laboratories are presented in Table I.

TABLE I
MAIN CHARACTERISTICS OF THE MICROGRID LABORATORIES REVIEWED AS CASE STUDIES

Ref.	Location	MG Type	Generation	Storage	Comm.
[17]	Denmark	Hybrid	PV+WT	BT	Ethernet
[18]	Spain	AC	EMU	EMU	Ethernet
[19]	USA	Hybrid	PV	BT	Ethernet
[20]	China	Hybrid	PV+WT+FC	BT+UC+FW	Ethernet
[21]	Korea	AC	PV+WT+DI	BT	Modbus
[22]	USA	AC	PV+WT+DI+FC	BT	-
[23]	Germany	AC	PV+WT+DI	BT	Ethernet
[24]	Canada	AC	PV+WT+Diesel	BT	-
[25]	Argentina	Hybrid	PV+WT	BT+FW	CAN
[26]	Brazil	Hybrid	PV	Batt.	Ethernet
[27]	Chile	Hybrid	EMU	-	-
[28]	Colombia	AC	PV	BT.	Modbus
[29]	Mexico	Hybrid	PV+WT	Batt.	Serial
[30]	Ecuador	Hybrid	PV+WT+DI	BT+UC	Ethernet

PV: Photovoltaic; WT: Wind Turbines; EMU: Emulated; FC: Fuel Cell; DI: Diesel generator; BT: Batteries; UC: Ultracapacitors; FW: Flywheel.

As can be seen, each laboratory has a particular composition of microgrid type, generation sources, storage systems, and communications systems, among other features. These particularities usually respond to the needs of each laboratory according to its geographic location or the interests of its users, mainly related to the type of tests, validations, and events that want to be simulated. Although the laboratories presented above serve as reference cases, the design of the experimental microgrid of the EIL must comply with the specific requirements of the Colombian context of the Universidad Industrial de Santander (UIS). To contextualize the design of the IoT-based monitoring and control stage design for the experimental microgrid, Section IV will describe the particular requirements sought in the IoT system design.

III. IoT FOR ELECTRICAL MICROGRIDS

The IEEE defines the IoT as *a network of items —each embedded with sensors— which are connected to the Internet* [31]. In a more detailed way, the IoT can also be understood as a *dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols, where physical and virtual 'things' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network* [32]–[34]. Certainly, there is no single definition for IoT, as the concept is continually reviewed and complemented according to the appearance of new technological elements [35]; however, in [36] a methodological review of more than 100 definitions of IoT is presented, to propose a basic conceptual framework.

Recently, the IoT has evolved to provide specific solutions to particular applications, such as the Industrial Internet of Things (IIoT) [37]. This new concept implies greater solidity and security architectures to improve productivity, integrate processes, provide better services, and reduce costs in industrial sectors [38]. The importance of the IIoT is such that it is considered, together with industrial automation and cyber-physical systems, as one of the pillars of the so-called industry 4.0 [39].

Commonly, IoT architectures can be described in 3 layers: *The perception or sensing layer*, composed of devices that collect information from the environment or interact with it. *The network layer*, made up of communication protocols that allow connectivity between the different resources of the IoT system, as well as data processing. Finally, the *application layer*, in charge of interaction with the end-user and visualization of data [40].

As mentioned in the previous sections, microgrid laboratories are ideal tools to validate the operational performance of new technologies through emulation of multiple scenarios. An example of this is the use of the IoT for the energy industry, which is recently being investigated for functions such as the operation of energy management systems, the control of distributed devices, and the prediction and monitoring of load supply [41]–[43].

In this sense, some microgrid laboratories have incorporated IoT functionalities. For example, in the Combined Smart Energy Systems (CoSES) laboratory at the Technical University of Munich (Germany), the information of some IoT sensors is stored in InfluxDB databases and connected to a cloud database (Prometheus) using the Grafana Cloud tool [44]. In [45], the implementation of an IoT monitoring system of a microgrid is described at the University of Paderborn (Germany). This system aims to measure voltages, frequency, and harmonic distortions in the grid using ADE7912 modules, ATSAMD51 microcontrollers, and SIM7070G data transmission modules that generate load profiles in real-time. Once the data is obtained, it is sent to a server to be stored in a Redis database. Finally, the data is subscribed using the MQTT protocol and visualized in Thingsboard. In [46] is presented a campus microgrid implemented on the University of Coimbra (Portugal). This grid is used to perform tests, including the integration of a smart thermostat that uses an IoT system to link decentralized local HVAC microcontrollers with the microgrid to improve its flexibility [47], [48]. Other similar developments can be found in [49], [50] and [51], where experiences of using IoT for the monitoring and control of electrical microgrids are presented.

Compared with other methods for monitoring and controlling microgrids, IoT-based solutions offer remarkable advantages, such as:

- Interoperability: IoT devices are designed to support various communication protocols, enabling seamless integration with a wide range of technologies and devices without requiring specialized hardware interfaces.
- Scalable architecture: Microgrids are composed of multiple decentralized energy resources. Similarly, IoT is designed for distributed environments, allowing new devices and systems to be easily integrated. This scalability ensures that the microgrid can expand without major overhauls to the existing control infrastructure.
- Cost reduction: IoT sensors and communication devices are relatively inexpensive, and the system does not require extensive hardware installation. This can result in the reduction of costs and long-term operational expenses.
- Remote access and cloud integration: Unlike traditional monitoring methods, which often require on-site presence or have limited remote capabilities, IoT solutions can be easily integrated with cloud platforms. This enables remote access and control from any location, allowing for quicker response times, reducing the need for physical interventions, and improving the resilience of the microgrid.
- Enhanced demand response and energy management: IoT improves demand response and energy management by enabling communication with smart devices and loads to reduce energy consumption during peak times. Additionally, IoT sensors can monitor weather conditions to predict renewable energy generation (e.g., solar or wind) and adjust energy flows accordingly.

The above confirms that the advantages offered by IoT have great potential to be applied in electrical microgrids, so it is key that laboratories equip themselves with this type of technology.

IV. Description of the Microgrid and System Specifications

The starting point for designing a microgrid IoT system is establishing the technical requirements. For this, the constructive and operational specifications of the microgrid in its power and control stages must be considered, as well as the needs expressed by the main users of the laboratory. This section presents the main requirements of the IoT system of the Energy Integration Laboratory (EIL).

A. Microgrid Description

Fig. 1 presents a single-line diagram of the EIL three-phase microgrid. The system is composed of a grid emulator based on a Chroma 61511 programmable AC source. This equipment provides programmable output voltage and frequency settings, making it ideal for evaluating and testing the operation of the microgrid under various power grid conditions. The distribution lines are emulated using three-phase impedances and isolating transformers. The microgrid includes two types of loads: three local loads and one global load. All loads are resistive, and their configuration is adaptable through a module that allows modifying the resistance per phase and performing balanced and unbalanced configurations. The microgrid comprises three distributed generators (*DG*). Fig. 2 and Fig. 3 presents in detail the scheme and a photo of each distributed generator (*DG*). A programmable DC Source ITECH IT6012C-500-80 is connected to the DC bus of the power inverter. The key functionalities of this source include constant voltage, constant current, and constant power modes, enabling various testing configurations. In addition, this source can emulate the operation of photovoltaic generators, batteries, and fuel cells. For the full-bridge three-phase inverter is employed the Semiteach IGBT module stack from Semikron. This module is composed of a three-phase rectifier SKD 51/14, IGBT modules SKM 50 GB 123 D, and drivers, among other elements. Additionally, an LCL filter is used for connecting the inverter to the microgrid. This filter allows the mitigation of high-frequency harmonics due to the inverter commutation. The sensing stage was developed using LA 25-NP current sensors, LV-25 voltage sensors, and other elements to adapt the sensed signals to be acquired through a controller board. Table II summarizes the main components of the microgrid.

The design of the power stage of the microgrid laboratory is motivated by the main research lines that will be addressed. In particular, it is interesting to study the performance of new control strategies. For this reason, emulated power generation is prioritized to enable consistent and repeatable experiments, ensuring that generation conditions remain constant regardless of the availability of specific energy resources at the EIL location. Furthermore, "open-box" inverters have been implemented, allowing direct control over operational parameters, unlike "closed-box" commercial inverters, in which it is not possible to modify operation parameters. Line impedances are used to emulate distribution lines for practicality, safety, and space limitations. At the same time, the main electrical grid is replicated through a controllable source, thereby preventing any impact on the local electrical network.

B. IoT System Requirements

The main requirements of the EIL microgrid IoT system are presented below. These requirements were collaboratively defined by the primary users and administrators of the EIL laboratory, taking into account the power and control features discussed in the previous subsection. The motivation behind

TABLE II
MAIN COMPONENTS OF THE MICROGRID

Feature	Description
Nominal Capacity	12 kVA
Grid Emulator	Chroma 61511 programmable AC source
Loads	Resistive
Power emulation	DC Source ITECH IT6012C-500-80
Inverters	Semikron Semiteach IGBT

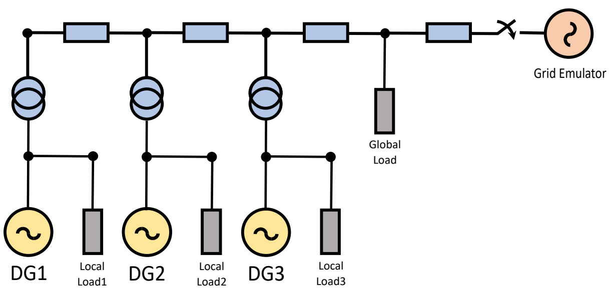

Fig. 1. Single-line scheme of the EIL microgrid.

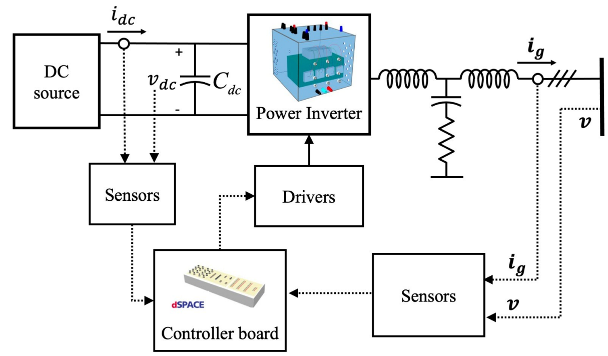

Fig. 2. Scheme for the emulation of distributed generators.

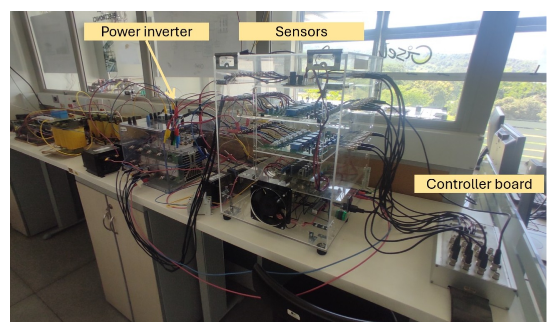

Fig. 3. Photo of an emulated distributed generator in the EIL microgrid.

each requirement and the desired functionality of the IoT system will be detailed.

- **Global load monitoring:** The global load is the main load of the microgrid. This was designed to be adaptable, allowing changes in the resistors connected in each phase to emulate different variable or unbalanced loads. To support this flexibility, the system requires a monitoring solution capable of sensing and remotely storing electrical variables during different experimental scenarios.
  Motivation: The need to store historical data of changes in the electrical variables of the global load during experimental scenarios, in order to design and evaluate control strategies.
  Desired Functionality: The IoT system should provide real-time current and voltage sensing and remote data storage capabilities to facilitate efficient monitoring and analysis during experimental tests.
- **Control flexibility:** Given the experimental nature of the microgrid, users must be able to test the impact of various control actions. Therefore, the control boards should enable users to adjust key operating parameters while having communication ports to interact with the IoT monitoring system.
  Motivation: The experimental setup requires flexibility for users to explore different control strategies. These strategies could use as input electrical variables measured by different IoT devices of the microgrid.
  Desired Functionality: The control boards should allow users to manipulate critical operating parameters and integrate and exchange in real-time variables sensed by other IoT devices.
- **Remote visualization:** The EIL is located in a campus building outside the city, so it is convenient to have a platform that allows remote viewing of data obtained in experiments. The platform can be expanded in the future to integrate more devices and be adapted to control variables to launch partially or totally remote experiments.
  Motivation: Ensuring that users can remotely access the system with an easy-to-use interface will enable access to more users, increasing laboratory utilization.
  Desired Functionality: The IoT system should provide a remote-access interface with equipment configured using intuitive and user-friendly software.
- **Industrial technologies:** Given that microgrid users will primarily be students and researchers, the design should prioritize the use of commercial devices commonly employed in industrial applications.
  Motivation: Using industrial devices enables students and researchers to gain hands-on experience with real-world technologies, enhancing their practical skills.
  Desired Functionality: The design must incorporate commercial IoT devices with features suitable for industrial environments.

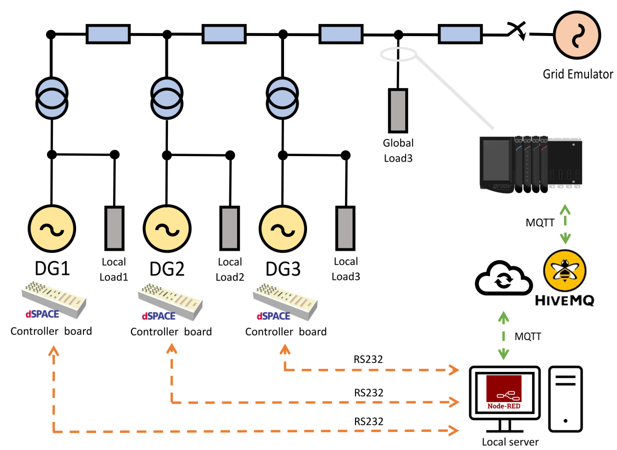

Fig. 4. Single-line scheme of the laboratory microgrid including the elements of the IoT system.

TABLE III
MODULES CONNECTED TO THE GRV-EPIC-PR2

Module	Description
Module 1	GRV-CSERI-4: 4 serial commu. channels (RS232 and RS485)
Module 2	GRV-ODCI-12: DC outputs (5 to 60 VDC)
Module 3	GRV-OACI-12: AC outputs (12 to 250 VAC)
Module 4	GRV-IVAPM-3: Monitors power quality in three-phase systems

V. SELECTION OF COMPONENTS AND PROTOCOLS

Based on the requirements described in the previous section, the elements of the IoT system were selected. These are presented in Fig. 4 and described in the following subsections.

A. Monitoring Unit of the Global Load

For the global load monitoring stage, the Groov EPIC GRV-EPIC-PR2 from Opto22 was selected. This is a programmable controller, widely used in the industry, designed for edge computing, automation, and IIoT applications. It integrates real-time control, data processing, and cloud connectivity into a single platform characterized by its modularity, allowing the addition of modules based on specific application needs. For this case, four modules were added, which are described in Table III. Thanks to the Module 4 (GRV-IVAPM-3) variables such a I_{rms}, V_{rms}, the currents and voltages in RMS, respectively, the active power P, the frequency f, and the power factor, among others, are measured and monitored in a three-phase node.

The Groov EPIC GRV-EPIC-PR2 supports different communication protocols, including Ethernet/IP, Modbus, and MQTT, making it highly compatible with different industrial systems and IIoT applications. Additionally, Groov EPIC supports multiple programming environments, including IEC 61131-3 languages, flowchart-based programming, Python, and Node-RED for IoT and event-driven programming. One of the key features of Groov EPIC is its ability to handle edge computing directly on the device, enabling it to process data locally. This offers a significant advantage over other PLCs that rely heavily on cloud computing, enhancing response time and reducing latency.

TABLE IV
MAIN TECHNICAL FEATURES OF THE DSPACE DS1104 CONTROL BOARD

Feature	Description
PC Interface	PCI or PCIe
Processor	MPC8240
Memory	32 MB SDRAM
Timer resolution	80-ns
ADC resolution	12-bit
DAC Converter DAC	16-bit
Serial Communication Ports	RS232/RS422/RS485 compatibility

The selection of this IoT system component meets the **Global load monitoring** and **Industrial technologies** requirements, as it guarantees real-time sensing of the main electrical variables of the microgrid's global load, using a controller from a long-established company in the automation industry. This last aspect provides an excellent learning opportunity for students and researchers to gain hands-on experience with industrial controllers while benefiting from a strong user community and extensive resources.

B. Control Boards

For the inverter control stage, dSPACE DS1104 control boards were selected. This type of control board is connected to a PC through a PCI or PCIe port. Additionally, through an I/O module analog–digital and digital–analog converters are accessible, together with PWM control outputs and serial communication ports (RS232/RS422/ RS485). The main technical features of this board are presented in Table IV.

While there are lower-cost alternatives for controlling inverter operations, the selected control cards stand out for their real-time performance with high-resolution capabilities. They offer practical and intuitive data visualization through the user-friendly ControlDesk software interface. One of the key advantages of the dSPACE DS1104 control boards is their seamless integration with Matlab/Simulink, simplifying the design and implementation of control algorithms. As these cards are widely used in academia and research, it is possible to access extensive documentation and technical support. The selection of this IoT system component meets the **flexibility** requirement, as it allows users to easily adjust control parameters and routines while integrating external inputs into the control strategies.

C. User Interaction

To meet the **Remote visualization** requirement, Ignition 8.1 IIoT platform from Inductive Automation was selected. Ignition features web-based deployment, enabling users to configure, monitor, and control systems remotely through any web browser without additional software installations. This platform is widely adopted in industrial automation, control, and monitoring due to its ability to create unlimited clients, screens, functionalities, and manage variables. It also supports popular languages like SQL and Python.

While Ignition is known for its robust security features, including SSL encryption, user authentication, and role-based access control, it also provides a user-friendly, drag-and-drop interface that simplifies project development and configuration, making setup and deployment quicker and easier than more rigid platforms. Additionally, extensive educational resources, such as *Inductive University*, offer comprehensive training modules that facilitate understanding of Ignition's components and capabilities.

D. Communications Protocols and Cloud Server

The selection of the communications protocols must ensure interoperability between the elements of the IoT system, including data exchange between control boards and external servers. With this in mind, Modbus was chosen as the protocol for the dSPACE DS1104 control boards, a widely used industrial protocol based on a master/slave architecture. Modbus is known for its simplicity and ease of implementation, making it a popular choice for industrial communication. In this case, Modbus was implemented over RS232 serial communication, enabling efficient information exchange between the PC and the control boards using pre-defined functions.

On the other hand, the MQTT protocol was selected to publish data from the control cards and the Groov EPIC controller. As the leading protocol in IIoT, MQTT is favored for its efficiency, scalability, and low resource consumption. It utilizes a *publish/subscribe* communication model, where devices publish data to and subscribe to *topics*, enabling real-time and asynchronous communication. In this system, the Sparkplug B specification was implemented to standardize the syntax of the communication.

A HiveMQ server was deployed in the cloud to handle MQTT communication. HiveMQ offers low latency and broad compatibility with a wide range of MQTT clients. Its extensibility allows users to customize functionality through plugins without compromising performance, making it an ideal solution for tailored, scalable IIoT applications.

The selected communication protocols and cloud server solution meet the requirements of the **Remote visualization** and **Industrial technologies**, ensuring reliable, real-time data monitoring and control. The communications protocols ensure interoperability by combining MQTT's efficiency with Modbus's widely adopted standard for industrial device communication.

Table V provides an overview of the devices, protocols, and solutions selected to meet the IoT system design requirements described in Section IV. This IoT system differs in terms of device composition, communication protocols, and cloud server solution compared to the existing solutions presented in Section III. As can be seen, the elements of the IoT system allow compliance with the defined requirements, being a suitable proposal for the LIE. Now, to verify the IoT system's functionalities, a series of validation tests are proposed.

TABLE V
MEETING OF THE DESIGN REQUIREMENTS FOR THE IOT SYSTEM

Requirement	IoT system element
Global load monitoring ✓	Groov EPIC GRV-EPIC-PR2
Control flexibility ✓	dSPACE DS1104
Remote visualization ✓	Ignition 8.1 + GRV-EPIC-PR2 + MQTT + HiveMQ
Industrial technologies ✓	Ignition 8.1 + GRV-EPIC-PR2 + HiveMQ

VI. VALIDATION TESTS

After selecting the elements that will be part of the IoT monitoring and control system, its operation must be validated. The process was carried out progressively using easy-to-implement experimental circuits. Initially, the local communications system responsible for collecting and sending data was validated. Subsequently, validations related to the data transmission from an external server were carried out. Finally, the system's ability to interact with users from any location was tested. The validation tests were classified into two groups and 8 types, explained in detail below and presented in Fig. 5.

A. Validation of the Local Sever

This set of tests aims to validate the correct integration of the local communications system, which has a local server responsible for collecting and sending information to and from the control boards. For the particular case of the EIL, the central server was implemented first in the Groov EPIC and then in a dedicated PC. Therefore, this group of tests will validate the correct sending of information to and from the DS1104 control cards. This validation is closely related to the **Control flexibility** requirement, since the possibility of exchanging information between the control cards through the local server allows integrating real-time variables measured by different IoT devices of the microgrid.

1) Test 1: Receiving and sending data from the local communications server.: The first test starts by validating the server's communication capacity with other devices. The central server was implemented in the Groov EPIC, this device received information from the DS1104 control cards using Modbus. The circuit designed for this test, as depicted in Fig. 6, incorporates a resistive divider implemented with a monitored potentiometer. The information is then collected from the communications server and sent to another controller board, which activates an LED based on a preset threshold.

2) Test 2: Bidirectional communication validation.: The next test consists of validating the bidirectional exchange of information between the local server and the controller boards. For this, voltage value data is sent from the server to each DS1104 controller board, which set this voltage in a DAC outputs. This output is connected to an ADC input of the same controller board, and the data is sent back to the local server. Then, the data is displayed in an interface developed in Ignition 8.1. In this test, it is possible to obtain metrics such as latency and evaluate the synchronization delay between control cards. The test scheme is presented in Fig. 7.

3) Test 3: Testing the interaction with the local user.: The following test seeks to validate the implementation of dynamic control actions by a local user through an interface in Ignition 8.1. For this, the user can establish voltage values for each DS1104 control card, each of which will have a pin of an RGB LED connected to one of its DAC outputs. Each color is associated with DS1104 board: the first controls the color red, the second controls the color green, and the third controls

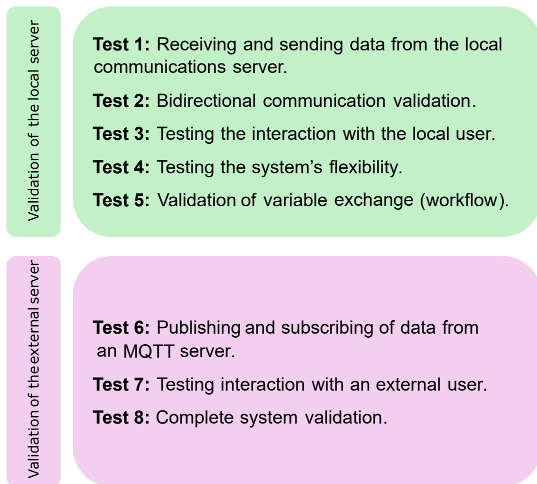

Fig. 5. Tests proposed to validate IoT system functionalities.

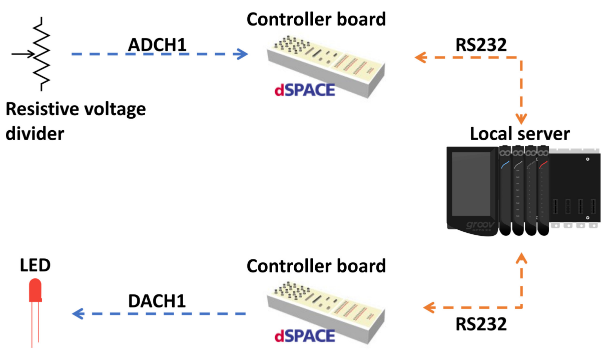

Fig. 6. Scheme for Test 1: Receiving and sending data from the local communications server.

the color blue. Once the user changes the voltage signals associated with each card and, therefore, each color, it is possible to observe the operation of the local communications system visually. The test scheme is presented in Fig. 8.

4) Test 4: Testing the system's flexibility.: One of the key characteristics of an IoT communications system is its flexibility. In tests 1, 2, and 3, data was sent unidirectionally and bidirectionally without performing processing or operations beyond comparison with a predefined threshold. For this reason, test 4 consists of receiving data from two control cards, performing a mathematical operation with them and, based on the result, performing a control action on a third controller board.

For the particular case, the diagram in Fig. 9 presents two DS1104s that collect voltage data from a DC source. These values are sent to the Groov EPIC. In this case, data processing can be done in two ways: directly on the communications server or in a visualization interface, as is the case with Ignition 8.1. For the first alternative, it was observed that, even with simple mathematical operations, the Groov EPIC operated close to its total processing capacity. For this reason, the second alternative was chosen, processing the data in Ignition. Finally, the result of the operation is compared with a predefined or dynamic threshold, and according to what is

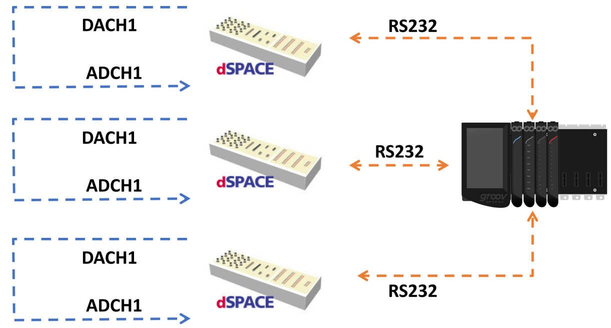

Fig. 7. Scheme for Test 2: Bidirectional communication validation.

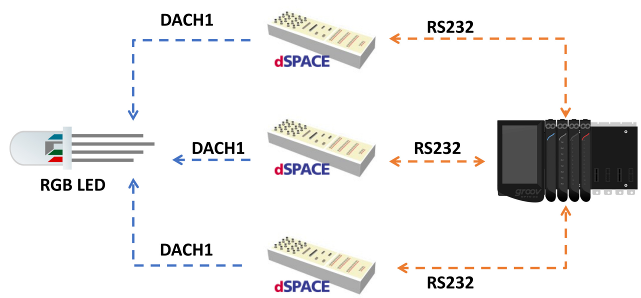

Fig. 8. Scheme for Test 3: Testing the interaction with the local user.

obtained, an LED connected to a third control card is turned on.

5) Test 5: Validation of variable exchange (workflow).: In the following test, data is sent and received from the devices simultaneously to recreate a real workflow situation. For this, input data from each control card will be collected while its available outputs are activated. For this and the next tests, the PC was used as the local communications server, preventing the Groov EPIC from being used at its maximum capacity. This enables the implementation of more complex configurations, key for the scale-up of the electrical microgrid.

The diagram in Fig. 10 describes the data acquisition from resistive dividers connected to each DS1104. The value of this data is compared to a threshold and used to activate an LED on the other control board. In this way and through this visual aid, it is proposed to validate the exchange of variables simultaneously with bidirectional communications.

B. Validation of the External Server

The execution of the previous tests has successfully validated the functionality of the local communications. For this reason, this set of tests aims to validate the data publishing to an external server. This will enable the integration across multiple locations via an MQTT server. This validation is closely related to the **Remote visualization** requirement, as publishing real-time data to an external server establishes a reliable foundation for a remote-access interface.

1) Test 6: Publishing and subscribing data from an MQTT server.: For the particular case of the EIL, the MQTT protocol was selected to publish data to a HiveMQ MQTT server. Additionally, the Sparkplug B standard was selected to define the topics. The diagram in Fig. 11 presents the implemented

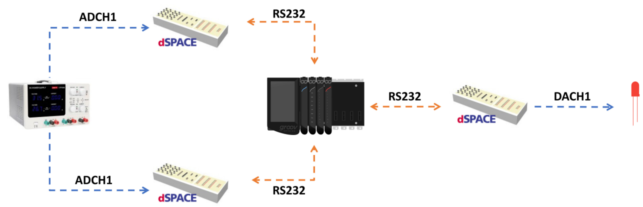

Fig. 9. Scheme for Test 4: Testing the system's flexibility.

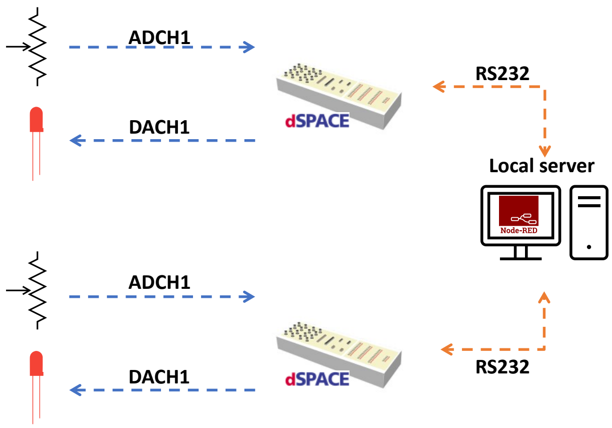

Fig. 10. Scheme for Test 5: Validation of variable exchange (workflow).

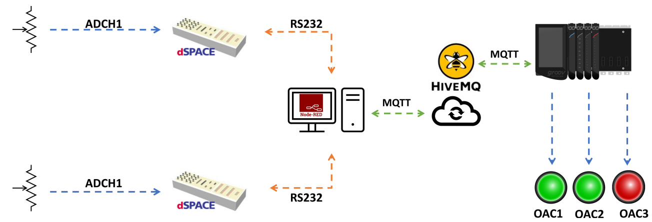

Fig. 11. Scheme for Test 6: Publishing and subscribing data from an MQTT server.

test. It can be observed that the controller boards are used to collect data from resistive dividers, which is published to HiveMQ. Subscribing to this information from the MQTT server, activates some of its front LEDs (located in the hardware) associated with each DS1104, and a third LED associated with the sum of the voltages with respect to a preset threshold.

2) Test 7: Testing interaction with an external user.: Once the operation of the MQTT server has been confirmed, a complete validation of the IoT system is proposed. For this, a remote user is enabled to visualize the collected data and perform actions on the devices defined for this purpose. At this point, a comprehensive validation will be carried out, simultaneously testing the local communications system, the MQTT server, and the interface designed for interacting with the user.

The diagram for this validation consists of two stages, as shown in Fig. 12. The first is similar to test 3, with an RGB LED connected through its pins to the three DAC ports of the three DS1104 boards. These boards will receive the action signals from the MQTT server to be applied to the DAC outputs controlling each color. On the other hand, from the same interface, the user can turn on or turn off the front LEDs of the Groov EPIC, simulating the activation of peripherals connected to the microgrid.

The implemented system enables real-time monitoring of electrical variables. However, it is essential to consider the IoT data transmission rate limitation, which is approximately 1 second. Therefore, it is recommended to focus monitoring on RMS values or changes in power exchange. In addition, if these values are used as inputs for control strategies, they should be applied in the secondary or tertiary control layers to align with their operational dynamics.

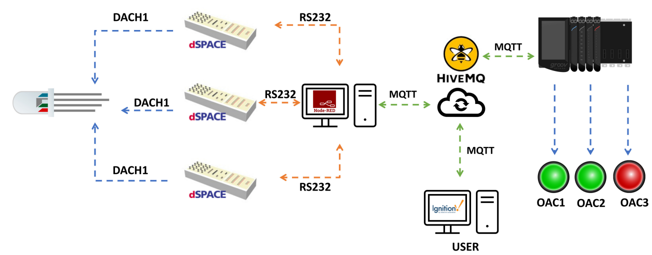

Fig. 12. Scheme for Test 7: Testing interaction with an external user.

3) Test 8: Validation on the complete system.: Finally, once the operation of all the elements of the IoT system has been verified, a test using the power stage of the experimental laboratory microgrid is proposed. In this case, the test is focused on one of the distributed generators of the microgrid (DG1 in Fig. 4).

This setup can be seen in Fig. 13. A controller board is used to control a power inverter and its data is published by the local server to HiveMQ, from where the interface developed for data visualization is linked. In this test, the inverter is connected to a filter and a load, and the voltage on the DC bus of the source, the line currents and the load voltages are sensed. In the developed interface, the user also has the possibility of turning the inverter on and off, verifying the capacity of the IoT system to interact with the power components of the experimental electrical microgrid.

VII. Conclusions

This work presented the design and validation of an IoT system for an experimental laboratory microgrid. For this, requirements were established, considering the microgrid's constructive and operational specifications in its power and control stages and the needs expressed by the laboratory's main users. With this input, the elements that compose the IoT system were selected.

A set of tests were proposed to validate the system's operation using easy-to-implement experimental setups. These tests allowed us to validate the local communications system, including the publishing and subscribing of data from an MQTT server. Finally, the system's ability to interact with users from any location was verified.

This work constitutes a relevant contribution for researchers interested in implementing future laboratory microgrids or incorporating IoT-based stages into existing microgrids. In future works, more details of the implementation of the EIL

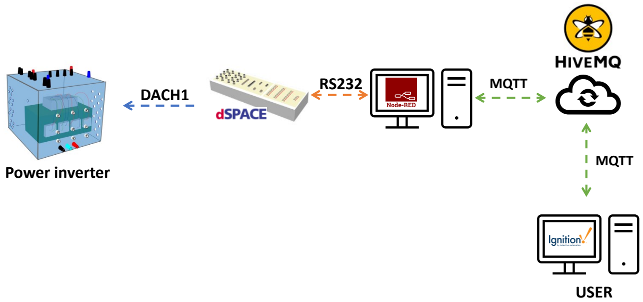

Fig. 13. Scheme for Test 8: Validation on the complete system.

will be presented, describing the characteristics of its different power, control, and monitoring stages, with the aim of sharing this experience with interested readers.

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