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A Retrofit Strategy for Real-Time Monitoring of Building Electrical Circuits Based on the SmartLVGrid Metamodel

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Abstract: The Internet of things (IoT) paradigm promotes the emergence of solutions to enable energy-management strategies. However, these solutions may favor the disposal or replacement of outdated but still necessary systems. Thus, a proposal that advocates the retrofit of pre-existing systems would be an alternative to implement energy monitoring. In this sense, this work presents a strategy for monitoring electrical parameters in real time by using IoT solutions, cloud-resident applications, and retrofitting of legacy building electrical systems. In this implementation, we adapted the SmartLVGrid metamodel to systematize the insertion of remote monitoring resources in low-voltage circuits. For this, we developed embedded platforms for monitoring the circuits of a building electrical panel and application for visualization and data storage in the cloud. With this, remote monitoring of the consumer unit was carried out in relation to energy demand, power factor, and events of variations of electrical parameters in the circuits of the legacy distribution board. We also carried out a case study with the proposed system, identifying events of excess demand in the consumer unit, mitigating the individual contribution of the installation circuits in this process. Therefore, our proposal presents an alternative to enable energy management and maximum use of existing resources.

Keywords: retrofit; SmartLVGrid; real-time systems; IoT; energy monitoring; energy efficiency

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1. Introduction

Society drives the development of new technologies for automation, processes, and systems in the most diverse sectors. Industries, cities, homes, and building installations are examples of environments with constant technological transformations. In this context, the digital paradigms of this millennium, such as Industry 4.0, Internet of things (IoT), smart grids, smart cities, and smart buildings, promote technological convergence processes by using digital integration solutions for monitoring and control of assets and inputs [1]. In addition, through digital paradigms it is possible to optimize the assets present in these environments, promoting flexibility, scalability, dynamism, and efficiency, in addition to other socioeconomic benefits [2].

The digital transition obtained from the implementation of these paradigms can occur abruptly or not [3]. The implementation time and the cost of digital solutions for this are preponderant factors, because short-term transformations may require larger investments. Usually, these types of solutions promote the disposal or replacement of resources that could still be useful or with acquisition costs not fully amortized [4]. In such cases, it is

necessary to employ processes that steer the technological transition gradually through strategies based on leveraging legacy resources; otherwise, these processes would only be feasible for absolutely new solutions.

The electricity sector, indispensable for the realization of many social and economic practices, maintains much of its legacy structure from its conception [5]. This involves performing manual processes to carry out maintenance and management of the legacy electrical systems in operation [4]. Thus, specialized professionals are still needed in the field to perform these activities, which makes it difficult to record and access data in real time or which, occasionally, may lead to failures or field accidents. Thus, the implementation of digital paradigms provides the opportunity for the emergence of new techniques to automate electrical systems and enable energy management and efficiency. In this sense, IoT solutions can be employed in energy-efficiency strategies through the addition of real-time communication capabilities, distributed computing processing, and the control and sensing of objects through interconnection in data networks [6,7]. In smart grids and smart building models, in which the automation of electrical systems is widely applied, IoT solutions ensure safety, efficiency, and maximum system excellence in their operations [8–11]. However, despite the use of IoT in implementing new solutions for energy monitoring and control, there is a lack of strategies to integrate new solutions with legacy electrical systems.

The retrofit strategy, on the other hand, presents itself as a solution to this problem. Through retrofitting, it is possible to update and customize old or technologically outdated but still necessary systems, in order to preserve them and reduce costs in the addition of new functionalities in legacy systems [12]. In addition, this strategy enables a gradual rather than an abrupt technological transition in legacy electrical systems, making the maximum use of pre-existing resources. Still, in order for retrofit to be used systemically in the upgrade and integration of legacy electrical systems with IoT solutions, it is necessary to use a reference model based on architectural definitions endowed with standardized logic layers, protocols, and interaction interfaces applied to the specificities of this particular context. However, the literature presents few works that employ retrofit techniques from reference models to standardize their implementations, especially in the electrical sector.

At [5], the authors proposed a reference metamodel for smart grids, named SmartLV-Grid. It enables the transition from a legacy passive low-voltage power distribution plant to the smart grid paradigm by using the retrofit strategy in conjunction with systems engineering concepts. SmartLVGrid is composed of protocol stacks that enable the integration of legacy structures with compatible middleware (hardware and firmware). In addition, these protocols specify how to realize the logical link (interoperability) of the developed middlewares with a supervision and control center.

Interoperability, scalability, flexibility, and system efficiency are some of the essential aspects to make energy management in the electricity sector viable, developed, and mature [13]. However, the SmartLVGrid metamodel does not address methods or resources that advocate data analysis for real-time energy management, including virtualization and integration of legacy systems with IoT solutions and computational tools such as cloud computing, dashboards, and databases, for example. With data presented centrally in the cloud, it is possible to use virtual environments to manage energy consumption more effectively [14]. From this, we proposed a new method for managing low-voltage legacy circuits based on the adaptation of the SmartLVGrid metamodel and the use of the retrofit strategy. This way, we were able to make the most of pre-existing resources, in addition to providing technological means to analyze energy efficiency by monitoring electrical parameters with interactive dashboards in cloud software applications. In this context, no studies were found in the literature that carried out investigations or practical implementations of strategies, including a reference model and the use of retrofit, as the authors in [5] found, to perform energy management in the proposed way.

In this article, we present a strategy, which employs IoT solutions, retrofit of legacy electrical systems and cloud-resident applications, for real-time monitoring of legacy elec-

trical parameters and energy management. As a proof of concept, the proposed strategy was used to insert energy-monitoring resources in building circuits of a low-voltage power distribution board. To implement remote monitoring, we developed embedded hardware platforms and, respectively, their firmware, in order to implement the middleware and interoperability layers of our adaptation of the SmartLVGrid metamodel, but adapted to meet the circuits of the switchboard in use. Throughout this article, the details of the software applications and platforms developed are described, at the physical and architectural levels, with the necessary information to make it possible to use the same methodology in the implementation of new solutions and guarantee the insertion of new functionalities, preserving as much as possible the legacy infrastructures. In this sense, we raise the following contributions related to this work.

(1) We introduce energy monitoring through the adaptation of the SmartLVGrid metamodel, use of IoT solutions, and the use of the retrofit strategy in a systemic way, enabling energy management and maximum preservation of legacy electric circuits.
(2) We develop hardware devices and their respective firmware, enabling the retrofit of the circuits of a distribution board, based on the premises of the reference model.
(3) We develop a software application for circuit virtualization, with dashboards, database and cloud computing resources, systematically integrated with the implementation of the metamodel adapted in this work.
(4) We present the resources for monitoring the electrical quantities of each legacy circuit of a low voltage building switchboard.

To present the proposal of this article, we divided the sections as follows. In Section 2, we present a survey of the state of the art related to the theme. In Section 3, we present a survey of the theoretical framework for the implementation of our proposal. Section 4 presents our model proposal, based on the retrofit of legacy low-voltage circuits of a power distribution board. In Section 5, we present the materials and methods used, making them compatible with the architecture exposed in the previous section. In Section 6, we present the results obtained. In Section 7, we present the conclusions, along with proposals for future work.

2. Related Work

2.1. Energy Monitoring Solutions in the Context of the IoT Paradigm

Energy monitoring improves efficiency and management in the electricity sector, enabling analysis of the grid's electrical parameters, the demand consumed and the power quality, and providing managers with resources (e.g., computational and data) for decision making. In this context, IoT solutions contribute to provide remote and real-time monitoring and control in the residential, building, industrial and metropolitan sectors, interconnecting devices to the energy system and integrating these devices with computing systems, including cloud solutions [15,16].

Real-time applications enable monitoring in deterministic time, without conflicts and in a prioritized manner so that all events and tasks are executed as expected. The relevant literature presents work with real-time IoT solutions to implement energy-monitoring systems. At [17], real-time energy monitoring was implemented via interconnected hardware devices in a narrowband IoT (NB-IoT)-based mobile network for smart grid applications. Similarly, the authors of [18,19] have developed hardware devices to make energy-consumption data available in real time to users over a wireless data network. The authors of [20] used the Raspberry Pi 3 platform as an interface between an energy meter and a graphic application for displaying data obtained in real time. At [21], the authors exposed a study evaluating the performance of different real-time IoT solutions. On the other hand, the authors of [22] presented a decentralized solution for real-time energy monitoring from mobile devices.

In addition to real-time communication and monitoring, IoT solutions use computing resources for data storage, processing, and visualization to analyze and expose parameters for decision-making. From these, it is possible to elaborate databases to analyze and expose

the main parameters of value for decision making. In this sense, the literature presents works that use these resources in energy monitoring applications. In [23], the authors used structured query language (SQL) databases, along with the graphical interfaces of the developed application, to store and display the main electrical parameters and the consumed demand of a building circuit. The authors of [24] presented energy consumption and temperature measurements of a climate control system by using interactive dashboards. At [25], the authors discussed IoT solutions for energy monitoring, including cloud data storage and processing.

It is important to comment on the contributions of the literature in the IoT area for improving energy efficiency. In this area, proposals involve energy-demand management and power quality analysis of facilities. Energy-demand management uses monitored data to develop strategies and make decisions for reducing energy consumption. The authors of [26] presented a survey of the energy demand consumed by the School of Telecommunication Engineering of the Polytechnic University of Madrid over the course of one year. From the obtained data, the authors used a wireless network that employed market devices to control the energy demand in the school. On the other hand, the authors of [27] managed the energy demand of residences in a Simulink software model, considering the insertion of renewable sources and networked devices. In addition, the work [28] described an energy-management system that uses real-time IoT platforms in order to improve energy efficiency.

Proposals in the literature that use IoT for facility power quality analysis seek to improve power quality in metropolitan, industrial, building, or residential settings. In the works [29–32], for example, the authors have developed hardware devices to remotely monitor voltage sags, swells, and the electrical parameters of the circuits used. In [33], the authors proposed an algorithm for disturbance and event analysis in the context of power quality. For this, they employed real-time IoT devices in monitoring the parameters and stored the obtained data in the cloud for further use of the algorithm. In [34], the authors motivated the need to monitor electrical parameters to improve power supply reliability and power quality. In this same work, the authors also presented the development of a device capable of remotely monitoring the number and duration of power interruptions and voltage variations on both sides of circuit switching devices, with the possibility of local storage in case of failures of communication.

Tables 1–4 summarize the works associated with the context of this article and cited in the subsection. However, in our literature search, we did not find works that use retrofit strategies to take advantage of legacy systems based on IoT solutions and computational resources in order to offer resources to improve energy efficiency and power quality. Thus, the solutions exposed are focused on the particular context of their applications, which may make it infeasible to implement the proposed strategies in other cases. In addition, we did not find studies that propose metamodels capable of providing the insertion of automation, electronic control, distributed processing and communication resources in electrical systems from retrofit techniques for the same purpose of energy management.

Table 1. Works with emphasis on energy efficiency.

Work	Year	Application
[26]	2021	Demand control from WSN
[27]	2018	Demand Management with Renewable Sources
[28]	2019	Demand Management with IoT Solutions

Table 2. Works with emphasis on computational resources for energy management.

Work	Year	Application
[23]	2019	Use of databases and interfaces to display electrical parameters and the demand of a circuit
[24]	2018	Interactive dashboards for consumption display energetic
[25]	2021	Methods of viewing, storing and cloud energy data processing

Table 3. Work on real-time systems for energy monitoring.

Work	Year	Application
[17]	2020	Energy demand monitoring in a real-time NB-IoT network
[18–20]	2018, 2020 2020	Development of devices for real-time consumption monitoring
[21]	2020	Evaluation of real-time solutions for energy monitoring
[22]	2020	Decentralized monitoring solution energy in mobile devices

Table 4. Work with emphasis on power quality analysis.

Work	Year	Application
[29–32]	2019, 2018 2019, 2021	Devices for monitoring sags, swells and electrical parameters
[33]	2020	Algorithm for disturbance and event analysis of power quality with IoT devices
[34]	2020	Development of a device and an algorithm applied to the remote monitoring of power interruptionsand voltage variations in switching circuits

2.2. Retrofit

The retrofit strategy uses techniques to take advantage of old but still necessary systems, through the inclusion of new features [12]. However, the use of this strategy requires prior and specific knowledge of the pre-existing elements and infrastructures, in order to perform the proper interfaces for implementation of the desired functionalities without causing damage or accidents.

The integration of legacy systems with digital ecosystems by using retrofit and IoT techniques is a well-cited topic in the literature. In [35], the authors propose strategies for using retrofit to reduce energy consumption and improve the comfort of legacy building facilities. The authors of [36] implemented a wireless sensors network (WSN) for controlling and monitoring legacy air conditioners from retrofit devices. In [37], the author presented solutions for automation of legacy infrastructure using retrofit strategies. Also, the authors of [38] proposed a model based on the building energy management system (BEMS) method and the worldwide web consortium (W3C) specifications for monitoring and controlling energy consumption from a WSN, in the context of smart buildings, from a retrofit strategy.

Table 5 shows the retrofit works discussed above. These works presented satisfactory results regarding the technological upgrade of pre-existing systems using retrofit strategies. However, the proposed methods serve a pre-established number of cases and systems, making scalability, distributed processing, or even interoperability with other applications difficult. Furthermore, the authors did not employ generic architectural models to standardize the presented strategies in the use of larger numbers of devices, of the same nature or not. In contrast to the aforementioned works, the present work distinguishes itself by presenting retrofit techniques performed in a systemic way from a strategy and an architecture developed to promote energy management in legacy building circuits.

Table 5. Works with contributions from retrofit techniques.

Work	Year	Application
[35]	2015	Using retrofit to reduce energy consumption and improving the comfort of old buildings
[36]	2017	Using retrofit to enable control and air conditioner monitoring
[37]	2018	Retrofit Strategies for Automation legacy infrastructure
[38]	2021	Retrofit strategy for monitoring and control of energy consumption from a model based on the BEMS method and the W3C specifications

2.3. Middleware and Interoperability

Middlewares provide physical or logical interfaces between heterogeneous systems, and are challenges in terms of hardware and software development for IoT [39,40]. On the other hand, there are situations in which it is necessary to provide, in addition to physical or logical interfaces, interaction between different systems. In these cases, it is necessary to use methods that enable interoperability, especially in IoT applications that need to interact regardless of the communication protocol used [41,42]. Therefore, middleware and interoperability solutions are important allies in the integration of IoT solutions with legacy systems, reducing the complexity of integrating new technologies with existing resources and helping in the scalability of IoT applications.

The literature also presents work that enables technology convergence processes through interoperability middleware solutions. The authors of [43] proposed a method by which to realize interoperability of legacy industrial systems in the context of Industry 4.0 by employing minor changes to existing communication media. In [44], the authors proposed an architecture model to enable the interoperability and interconnection of devices located on the Malaga University campus, as a proof of concept for future applications of the model in smart city deployments. The work [45] presents a middleware solution that enables the interfacing of devices located in intelligent office environments. In [46], the authors deployed a smart grid model from a middleware architecture based on retrofitting legacy meters for monitoring electrical parameters in WSNs. The same authors, in [47], contributed a methodology to enable interoperability of legacy meters in smart grids from WSNs.

Table 6 presents the main characteristics of the above-mentioned works. These works contribute with solutions for standardization of technological convergence processes. However, they do not propose middleware solutions for energy management that make available physical and logical interfaces with legacy systems. Still, in the context of energy efficiency, the works do not present resources, which enables the communication interoperability of the proposed systems. Furthermore, the works in the literature did not conceive generic methodologies that could be applied to new systems and scenarios, beyond those exposed in the respective works. In this work, we proposed a generic architecture for retrofitting legacy building circuits, based on middleware and interoperability resources, which allows virtualization, communication and the insertion of IoT devices, enabling energy management from the monitoring of electrical parameters in real time.

Table 6. Work with emphasis on middleware and interoperability solutions.

Work	Year	Application
[43]	2017	Method for system interoperability legacy industrialists in the context of Industry 4.0
[44]	2019	Model for device interoperability in a university campus
[45]	2010	Middleware for device interface located intelligent office environments
[46]	2018	Model based on a middleware architecture for retrofitting legacy meters to WSNs
[47]	2018	Methodology for Enabling Interoperability of legacy meters from WSNs

2.4. Metamodels

Just as models are abstractions of some reality, metamodels are abstractions of models to design new modeling languages or extend existing modeling languages [48]. They are employed in the analysis, design, development, and integration of models for any system. This includes the integration of legacy systems with middleware and interoperability interfaces [1,49]. Therefore, metamodels enable the technological transition of pre-existing systems.

In this context, the literature exposes successful cases using the metamodel approach. In [50], the authors proposed an IoT metamodel to connect heterogeneous objects by using the premise of interoperability. The authors of [51] also implemented an IoT metamodel capable of transforming a software solution written in a specific modeling language for a Java application in order to standardize the development in a guided way. In [52], a metamodel was proposed for device interaction in intelligent environments from a modeling of relationships and attributes. In [4], the authors introduced a metasystem to enable the transition of legacy electric power distribution systems to the smart grids paradigm through the retrofit strategy. Table 7 presents the main characteristics of the aforementioned works.

Table 7. Papers with contributions based on metamodels.

Work	Year	Application
[50]	2018	Metamodel for device interoperability heterogeneous
[51]	2017	Metamodel for transforming solutions from software in a targeted manner
[52]	2016	Metamodel for device interaction in intelligent environments
[4]	2017	Retrofit-based meta-system for transition from legacy power distribution systems to the Smart Grid paradigm

Further on, the [4] metasystem evolved into the SmartLVGrid metamodel, which presents itself with primitives and protocols for using middleware solutions and interoperability resources through the retrofit of legacy low-voltage electrical systems [5]. Because this metamodel describes generic interfaces to be used for upgrading pre-existing systems, it is possible to extend the applications and resources made available by it to any technological niche, including in the electric sector itself. We found no other similar approaches in the literature to enable energy management in building environments from the individual monitoring of each circuit in the installation. Therefore, the SmartLVGrid metamodel is used as a basis to perform retrofits of electrical circuits enabling the remote monitoring of electrical parameters.

3. SmartLVGrid

Smart low-voltage grids (SmartLVGrid) is a metamodel for modeling legacy low-voltage circuits in power distribution systems based on the smart grid paradigm. It consists of a protocol stack and uses a retrofit strategy to add control, monitoring, and communication capabilities to pre-existing systems. This model is structured both at the local level, close to the final consumer, and at the central level, in the supervisory centers of the energy utilities. The geographical separation of these levels requires the use of local area network interfaces (LANs) or metropolitan area network interfaces (MANs) to establish logical links between the legacy systems and the operation and command centers. Figure 1 illustrates the protocol stack established in the SmartLVGrid model.

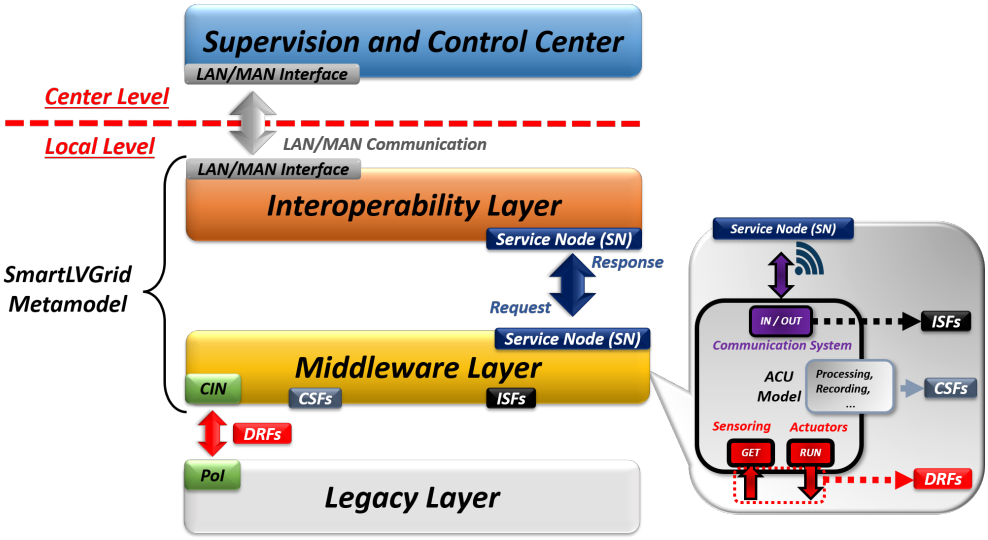


Figure 1. The protocol stack of the SmartLVGrid metamodel. The protocol stack of the SmartLVGrid metamodel [1].

As per Figure 1, the SmartLVGrid metamodel is composed of the interoperability and middleware layers. According to the metamodel, the retrofit is performed under the legacy structure at interface points called points of interface (PoI). The middleware layer interfaces with the legacy layer through the coupling and interaction node (CIN), allowing the execution of microprocesses called domain retrofitting functions (DRFs), one of the classes of operational primitives (OPs) of the metamodel.

The OPs are processes previously performed by field operators in the legacy electrical system that are now executed through service nodes (SNs) and CIN nodes, logical units responsible for the interfaces between the interoperability/middleware and middleware/legacy layers, respectively. The computational support functions (CSFs) implement processing and storage services in the middleware layer, and the interdomain support functions (ISFs) perform the communication processes in the same layer.

3.1. A Middleware Layer

The middleware layer is at the lowest level of the stack of the metamodel. Physically, this layer is implemented by means of retrofit devices, composed of embedded hardware, sensors, and actuators compatible with the DRFs to be executed. This layer is also called automation and communication unit (ACU), and its representation is illustrated in Figure 1. The representative model of the ACU consists of three ports: In/Out, Get, and Run. The communication processes and services of the ISFs are executed through the In/Out port. The Get port implements data collection by means of measurement and sensing DRFs. Finally, the Run port acts with control DRFs over the legacy layer. It should be noted that the ACU's processing and data storage routines are implemented through CSFs, as well as other computational support functions.

3.2. The Interoperability Layer

The interoperability layer is responsible for guaranteeing a set of rules and hierarchies and represents the infrastructure to implement network communication with the ACUs, aiming to interact remotely with these devices and use their functionalities. This layer classifies each ACU according to its position in the SmartLVGrid metamodel hierarchy. ACUs that supervise and monitor other ACUs and optionally run DRFs are called coordinators. ACUs that run DRFs on top of the legacy layer and are supervised by coordinators are called operators. In cases of expansion of the operating power system, which implies more computational capacity for the coordinator ACU, the metamodel provides subcoordinators for each cluster of operator ACUs. In this way, the subcoordinators will be associated with

a single ACU coordinator that will communicate with the supervision and control center to pass on information about the system. It is important to note that each ACU has its own processing unit, enabling the distributed processing of the system from the retrofit of each legacy asset.

The supervision and control center retains all control and monitoring of the system from the communication with all coordinators present in the power grid. Other functions are the administration of the consumer units, distribution busbars and transformer stations. It is up to the technical–administrative staff of the supervision center to delimit the DRFs and autonomous decision-making to be performed by the retrofit devices.

4. Methodology for Implementing the Proposed System

SmartLVGrid was initially designed to be used in conjunction with low-voltage consumer units and their interfaces with the legacy electrical system [5]. However, in [1], the authors presented a model based on the retrofit of a legacy building lighting circuit, showing the feasibility of adapting SmartLVGrid for smart buildings. In this sense, the present work contributes by extending the SmartLVGrid model and using the retrofit method for a new load profile: the legacy electrical circuits of a power distribution board. The term legacy, in this case, refers to the fact that, previously, the circuits did not have any element that provided the execution of interoperability, control, or remote monitoring functionalities. Figure 2 illustrates the retrofit strategy developed.

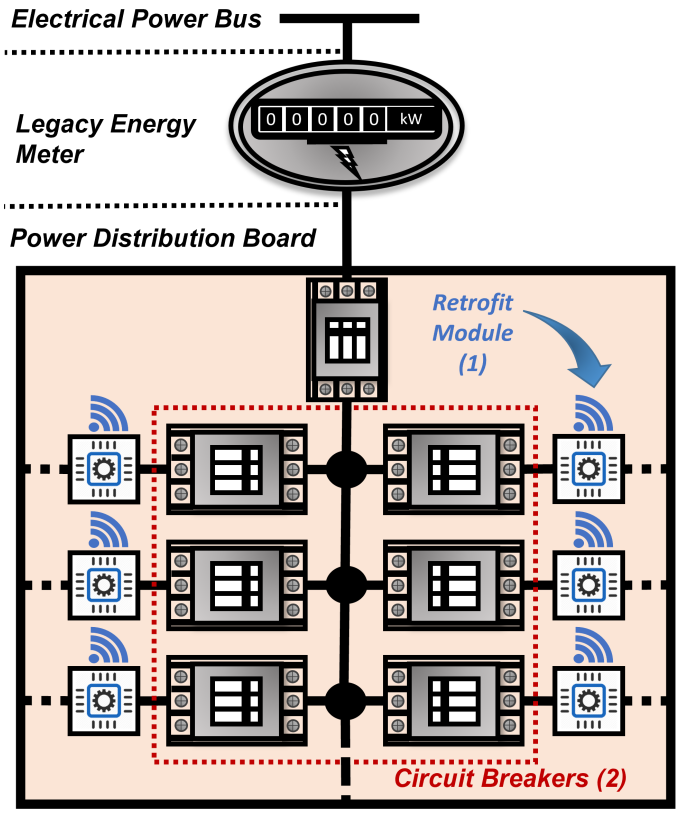


Figure 2. Proposed retrofit strategy for energy monitoring.

As illustrated, the strategy proposed in this work promotes the insertion of retrofit modules (1) consisting of specific hardware and firmware for network communication, processing, data storage, and for the acquisition of the electrical parameters of each circuit of the switchboard. It should be noted that the retrofit modules (1) are calibrated with a precision current and voltage source before being installed in the circuits. These modules (1) have been inserted next to the circuit breakers (2) of the power distribution board in order to

- standardize the development and installation of retrofit modules;
- reduce visual impacts by confining the solution within the switch cabinet;
- standardize the development and installation of retrofit modules; and
- preserve as much as possible the existing electrical installation

In this way, the disposal or removal of any element present in the circuit (cables, walls, socket points, circuit breakers, among others) was avoided. After retrofitting the circuits of the switchboard, it was possible to supervise them from a supervision and control center. In this work, the supervisory center is located in a cloud for accessing the monitored parameters from anywhere. In addition, the supervisory center was designed to provide energy management resources in real time, enabling the analysis of active demand consumed and other electrical quantities, such as voltages, currents, and power factor. It is noteworthy that the literature has not presented works with this approach, involving the extension and use of metamodels and retrofit techniques for this purpose. The tests of the proposal and the validation of the results were obtained from the integration of the retrofit modules with the supervisory center, through which it was possible to monitor, individually, each circuit and its respective electrical parameters and events.

The following section presents the modeling performed to extend the SmartLVGrid model and the conception of our proposal. Based on this modeling, it is possible to understand in more detail the hardware and software elements conceived for the development of our proposal and the adaptations made to the SmartLVGrid metamodel for the insertion of monitoring resources in the legacy building circuits of a distribution board.

4.1. SmartLVGrid Metamodel Adapted to the Proposed System

To insert a new load profile into the context of the SmartLVGrid metamodel, we extended the middleware and interoperability layers of this metamodel, creating the necessary interfaces to the switchboard circuits. These adaptations were made starting with the specifications of the operational primitives and the composition of the ACUs to be used. This also involves the methods for integrating the physical interfaces of the ACUs with the legacy switchboard circuits, detailed in the next section. In addition, the supervisory and control center was implemented by using cloud services with dashboards and databases, premises not explored by the original metamodel. Figure 3 illustrates the interfaces adapted from the SmartLVGrid metamodel for the proposal of this paper, along with the integration with the supervision and control center (SCC).

In this paper, retrofit modules for measuring electrical parameters act as ACU operators in the system. They were called ACU-BREAKERs, because they are located next to the circuit breakers of the legacy circuits. In addition, the proposed implementation relies on a router to communicate and interface with the cloud services responsible for housing the dashboard and database. Therefore, in the proposed architecture, this device has been classified as an ACU coordinator, and is referred to as ACU-ROUTER.

Figure 3 illustrates the interoperability between the ACUs over the local area network (LAN) interface. The ACU-ROUTER, in the role of coordinator, communicates with the supervisory and control center (SCC), which, in this paper, is located in the cloud next to the other computational services for visualizations and data processing in the context of energy efficiency and power quality. With the ACUs interconnected, each circuit can be virtualized by the SCC in order to individually organize the parameters obtained by each circuit. It should be noted that the interface point is located between the circuit breaker and the electrical circuit, from where the Get port extracts the measurement data up to the CIN. In this case, the service nodes act as the interface of the available communication media with the LAN network, providing the data and access paths for this (TCP ports, IP addresses, SSID, among others). The following subsection presents a brief description of the architecture of each ACU developed in our proposal.

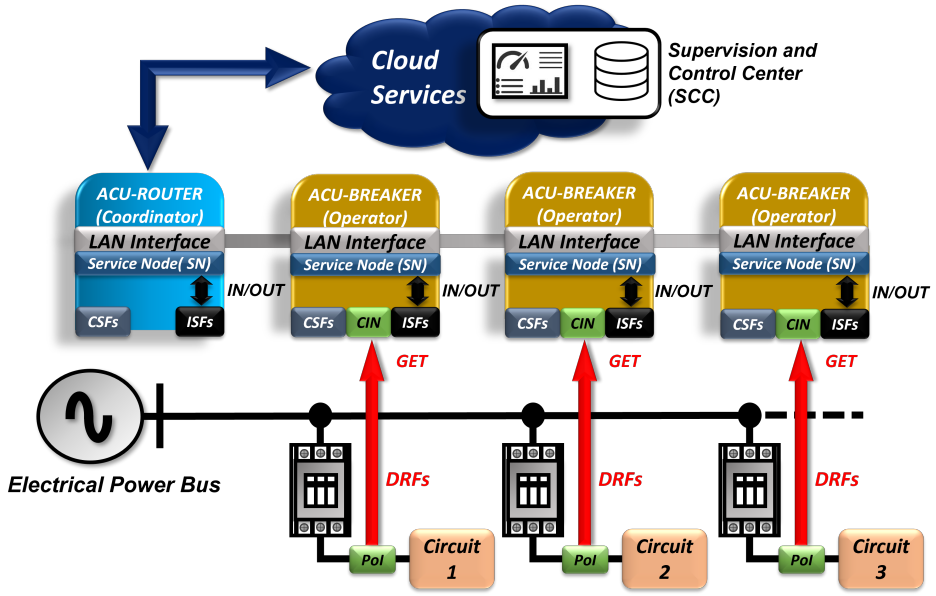


Figure 3. SmartLVGrid architecture adapted to the proposed model.

4.1.1. ACU-BREAKER Modeling

Figure 4 exposes the architecture diagram of the ACU-BREAKER and its interfaces. As mentioned, this ACU is responsible for collecting the electrical parameters of the legacy circuit associated with its respective breaker. The measurement of the electrical parameters, according to the SmartLVGrid metamodel, is characterized as a DRF executed by the Get port of this ACU. Similarly, the communication of this ACU is done through the In/Out port, responsible for executing the ISFs of requests and responses to the ACU coordinator (ACU-ROUTER). Moreover, the ACU-BREAKER has CSFs associated with data storage, device configuration, and network connection management. To perform the abovementioned operational primitives, it should be noted that this ACU has digital processing resources for acquisition and adjustments of the measured electrical parameters, communication, transduction, and conditioning of electrical signals, and also protection against possible overcurrent and overvoltage surges.

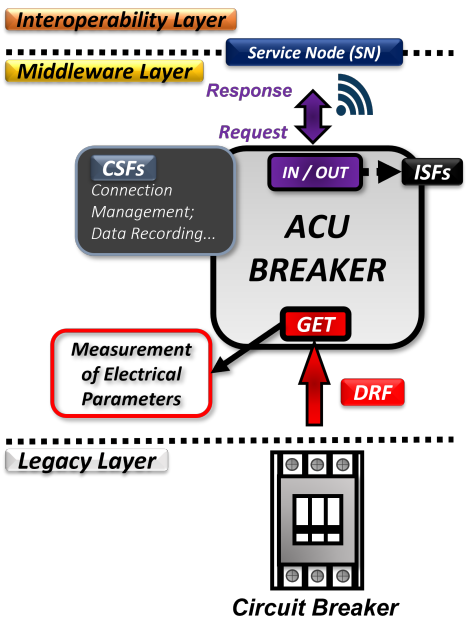


Figure 4. ACU-BREAKER architecture diagram.

4.1.2. ACU-ROUTER Modeling

Similarly, Figure 5 illustrates the ACU-ROUTER architecture diagram and its respective interfaces. Although this ACU does not have interfaces with the legacy layer and does not have Get and Run ports for DRF execution, it plays an important role in the proposed system. Through it, it is possible to interface the ACU operators, responsible for measuring the electrical parameters, with the supervisory control center (SCC), which is located in the cloud. The ACU-ROUTER/SCC interface is also performed through In/Out ports, by means of ISFs associated with request and response messages. Regarding CSF, the ACU-ROUTER performs the connection management of the ACU operators on the data network used.

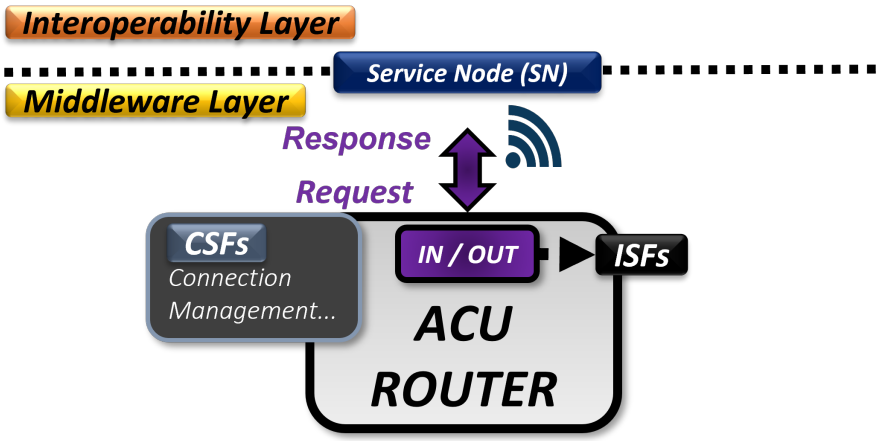


Figure 5. ACU-ROUTER architecture diagram.

5. Materials and Specifications for System Implementation

This section presents the strategies used to develop the middleware and interoperability layers and the supervision and control center (SCC) of the monitoring system in this paper. To this end, the software features, message exchange patterns, and hardware and firmware specifications of the retrofit modules will be defined, according to the specifications of our proposal.

5.1. Definition of the System Interoperability Layer

Because our proposal is based on retrofit, we reused existing network and infrastructure resources in the scenario used for the case study. In this sense, to provide network interconnection for the ACUs, we reused the wi-fi network infrastructure available in the vicinity of the power distribution board and jointly employed the MQTT communication protocol. From this, we established the premises to enable interoperability with the ACU devices in our proposal.

We used the Mosquitto MQTT broker running on a cloud-resident virtual machine (DigitalOcean Droplet), along with the applications and software services of the SCC. The packets were transmitted in the system with QoS 0, to reduce the latency of the data exchange between the ACUs and the broker [53,54]. The virtual machine's IP address and TCP port 1883 were used to provide access to the MQTT broker. This address and port was passed to the firmware for networking the ACUs via messages presented later in the paper. Thus, the service nodes (SNs) recommended in the metamodel were implemented with the establishment of the network connection of the ACUs to the MQTT broker. It is important to mention that in order to have interoperability between the ACU-ROUTER and ACU-BREAKER middleware, the In/Out ports and the SNs must use the same standard and communication network.

To enable interoperability between ACUs via Wi-Fi LAN and the MQTT protocol, we used request and response messages in JSON format, implemented via the cJSON

library [55]. Because the SCC is hosted in the cloud, its connection to the ACU-ROUTER takes place via the Internet. The MQTT messages were transmitted in the SCC/ACUs direction and the responses transmitted in the opposite direction. In this context, messages were used for electrical parameter requests, updating device network registration, and updating device calibration parameters. Figure 6 illustrates the process adopted to enable the communication of the ACUs with the cloud-hosted SCC, according to the proposed architecture, for a request to send electrical parameters as follows:

- The SCC, via the Internet, establishes communication with the Wi-Fi LAN interface of the ACU-ROUTER and ACU-BREAKER (1);
- The configuration of the service nodes (SNs) of the ACU-ROUTER and ACU-BREAKER is performed (2);
- The request message (3) is transmitted;
- By means of MQTT messages, the ISFs for synchronizing communication and sending data from the ACUs (4) are executed.

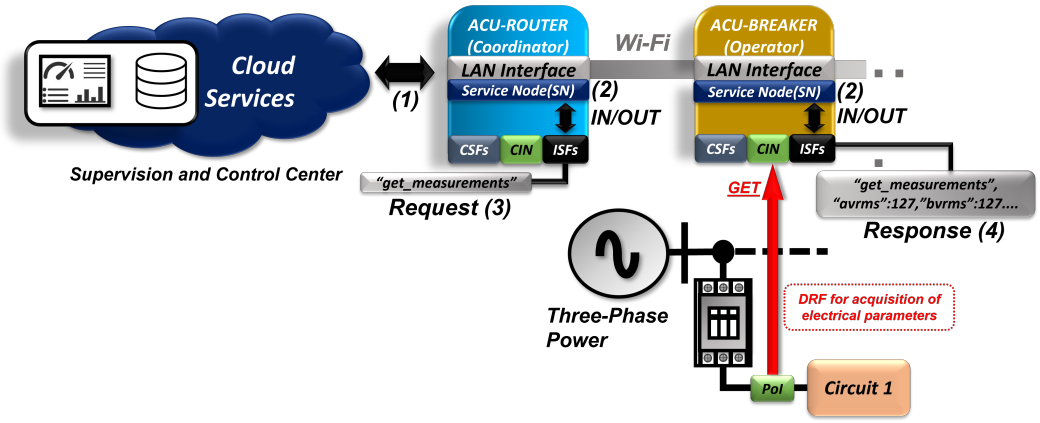


Figure 6. Communication process of the proposed system.

5.2. Implementation of ACU-BREAKER Middleware

The conception of the ACU-BREAKER was based on the development of a hardware device, and respective firmware, to monitor the electrical parameters in real time of a three-phase circuit located in a power distribution board, being possible to use it to monitor two-phase or single-phase circuits. To monitor the switchboard circuits through the retrofit strategy recommended in the proposed system architecture, we designed a panel containing six ACUs-BREAKER, power supplies, and battery backup for continuous operation in cases of power interruption. In this way, it is possible to detect power interruption or voltage and current variation events in cases of re-energization of the monitored circuits.

Each ACU panel was installed next to six circuit breakers in the switchboard. Thus, for 48 circuits present in the electrical panel, eight panels containing six ACUs each were developed. The ACU-BREAKER was designed with reduced dimensions in order to facilitate its installation. Figure 7 illustrates the strategy described above for installing the ACU-BREAKER and the hardware features present in its design. On the other hand, the main hardware components of the ACU-BREAKER are detailed in Figure 8, including the connections to the support board that distributes the power supplies and battery backup to each ACU.

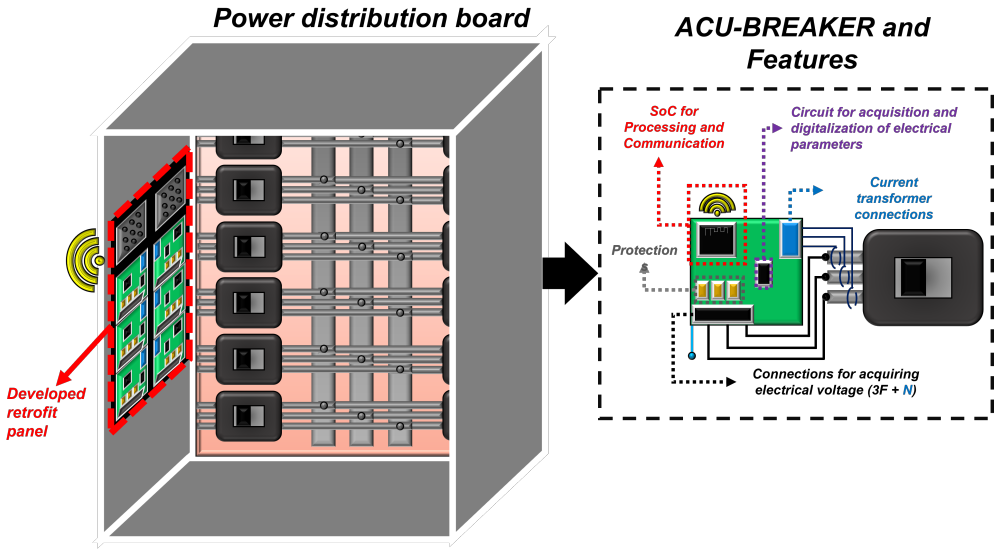


Figure 7. Strategy for using ACU-BREAKER.

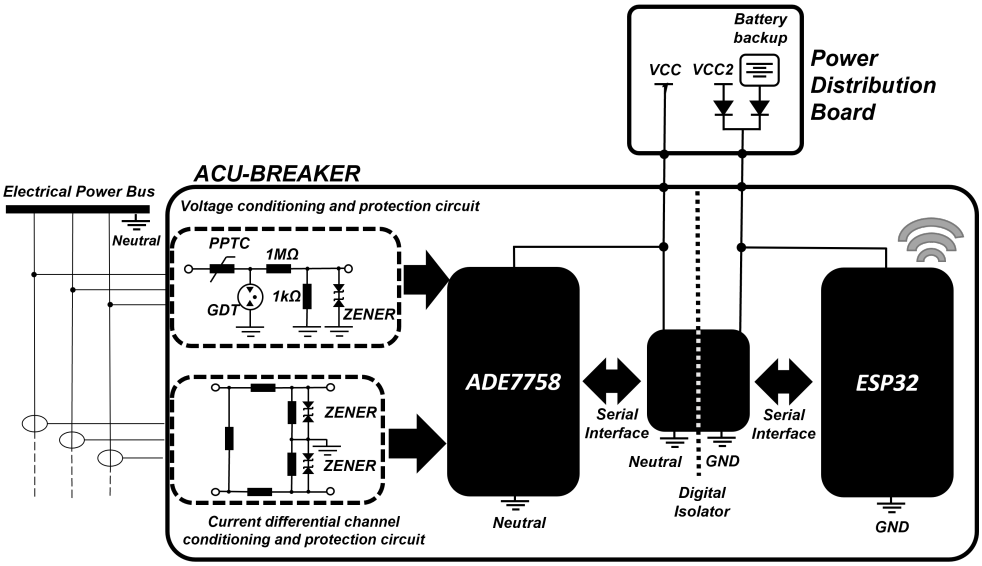


Figure 8. Main hardware components of the ACU-BREAKER.

5.2.1. SoC for Processing and Communication

As mentioned, the ACU-BREAKER has a system-on-a-chip (SoC), with processing and communication capabilities, through which we develop the DRFs, CSFs, and ISFs of the ACU. To do this, we used the ESP32-D0WD-V3 SoC present in the ESP32-WROOM-32E module from the manufacturer Espressif [56,57]. Through the ESP32 module, it was possible to take advantage of wi-fi communication resources and the MQTT protocol to implement the ISFs through request and response messages, and network connection management (one of the CSFs). In addition, the ESP32 module has serial communication peripherals used to debug the developed firmware and to communicate with the electrical signal acquisition circuitry. The ESP32-WROOM-32E module has a 4 MB flash memory, which was used to implement the CSF for storing the calibration settings parameters and for storing the communication network configuration parameters.

5.2.2. Circuit for Acquisition and Digitalization of Electrical Parameters

To ensure the reliability of the obtained electrical parameters, even in nonsinusoidal conditions, we chose to use an integrated circuit dedicated to the acquisition and digiti-

zation of the electrical parameters by means of the mean value technique. To do this, we employed the ADE7758 integrated circuit and the discrete components associated with it. This integrated circuit communicates with the processing unit by means of a serial interface and its function is to receive the electrical parameters of voltage and current previously conditioned, and then to digitize and process these parameters. The use of this integrated circuit in the ACU-BREAKER is detailed in Figure 8. Through this process, we obtained the parameters of effective voltage and current, network frequency and active, reactive and apparent power. The active, reactive and apparent power and power factor parameters were computed by the ESP32 module by using the active, reactive, and apparent power parameters obtained. All the technical aspects, equations, and diagrams used to support the use of the ADE7758 as commented above are detailed in its datasheet [58].

Through the integrated circuit ADE7758, we performed a procedure for calibration of the parameters obtained through gain and offset adjustments as described in its datasheet, ensuring the accuracy of the acquired values. To perform the calibration, we used a precision source, PPS400.3 from the manufacturer MTE [59], to provide known parameters of voltage and current. In this way, it was possible to adjust the gain and offset parameters based on the values provided by the precision source and the measurement performed by the ADE7758. We developed a routine in the firmware of the ACU-BREAKER to receive, adjust, and update the parameters in the internal registers of the ADE7758, as specified in its datasheet. It is important to note that each ACU-BREAKER was calibrated individually, as each was affected differently by the tolerance or precision of the components used for signal conditioning or transduction. In the tests performed, it was possible to obtain a measurement with about 1% error through the calibration adjustments. Figure 9 illustrates the ACU-BREAKER on a bench to be calibrated by using the precision source used.

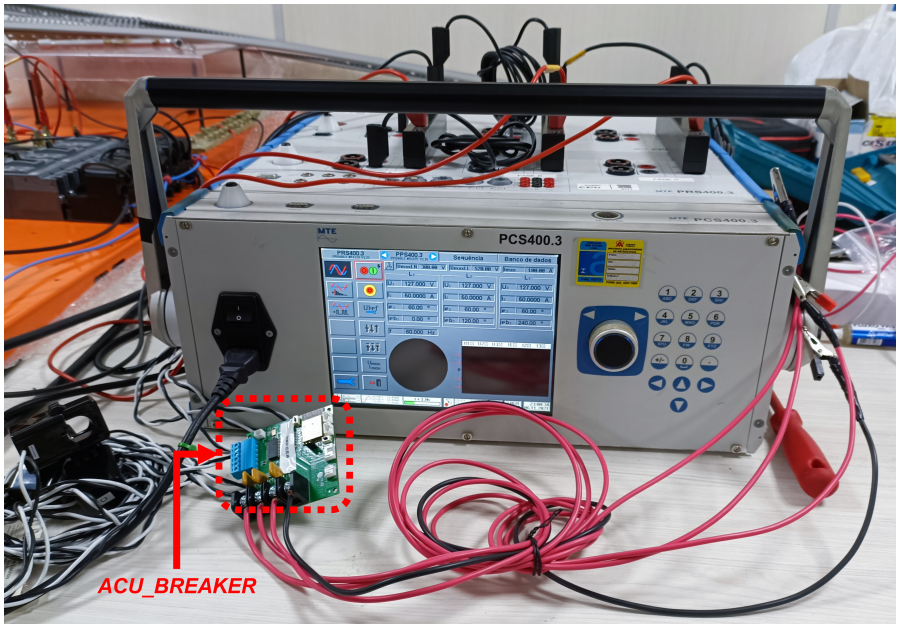


Figure 9. Benchtop ACU-BREAKER for calibration with precision source.

5.2.3. Protections and Connections for Measuring Voltage and Current

As illustrated in Figures 7 and 8, the ACU-BREAKER has discrete components responsible for the protection and conditioning of the electrical signals to be introduced in the integrated circuit ADE7758 and, which were previously obtained through the connections of acquisition of the electrical voltages and the connections with the current transformers with the differential channels of the mentioned circuit. It is important to note that these connections physically implement the Get port of this ACU.

The internal ADCs of the ADE7758 rely on pre-conditioned voltage and current signals with low values, being 500 mV the maximum peak value of the signals inserted into the

three voltage and current channels [58]. Consequently, in order to be able to perform maximum 500 V peak readings from the mains, we set up the voltage transduction circuit by using a resistive divider to create the 500 mV/500 V ratio on the voltage channels. Considering the neutral as the reference, we use a resistive divider of 1 (MΩ) and 1 (kΩ) after the voltage connector. In this way we establish the conditioning of the voltage channels. It is important to note that the resistors used are accurate to 1%, to maximize the effectiveness of the system, and operate with powers of up to 250 mW, avoiding overheating due to the high electrical potentials to which they can be subjected.

The current transformers were sized to meet the circuit breaker currents. To meet this demand, we chose to use the noninvasive current transformers of the AcuCT mV series, produced by the manufacturer Accuenergy [60]. Regardless of the nominal current of these transformers, their full-scale outputs are 333 mV. However, to use them with the differential current channels of the ADE7758, it was necessary to make adjustments to the signals obtained from these transducers. The maximum full scale of the current channels is 500 mV peak, but it can be adjusted to 250 mV or 125 mV peak. In this sense, we used a resistive divider to adjust the current transformer output to 250 mV peak in each circuit and set the current channel full scale to the same value, changing the internal gain registers of the ADE7758.

Because the electrical voltage transduction is performed in a non-isolated manner, to ensure protection against surges, overcurrents and overvoltages, the input protections of the ACU-BREAKER voltage channels are composed of gas discharge tubes (GDTs), polymeric positive temperature coefficient (PPTC) resettable fuses and Zener-type diodes. To ensure the protection of the ESP-WROOM-32E module in serial communication with the ADE7758, we used a digital isolator to separate the main's neutral from the module's digital reference. Thus, it was necessary to use two power supplies in the panel of the designed ACUs, one for power supply to the ADE7758 and one for power supply to the ESP-WROOM-32E and its peripherals. On the other hand, the current channels rely on galvanic isolation and the noninvasive measurement of current transformers. Therefore, only Zener-type diodes have been used to prevent overdrafts from damaging the ACU-BREAKER current channels.

5.2.4. Electrical Schematic and Layout

The electrical schematic and layout of the ACU-BREAKER were developed in Altium 21 software. Figure 10 illustrates a three-dimensional (3D) perspective of the layout designed for the ACU-BREAKER.

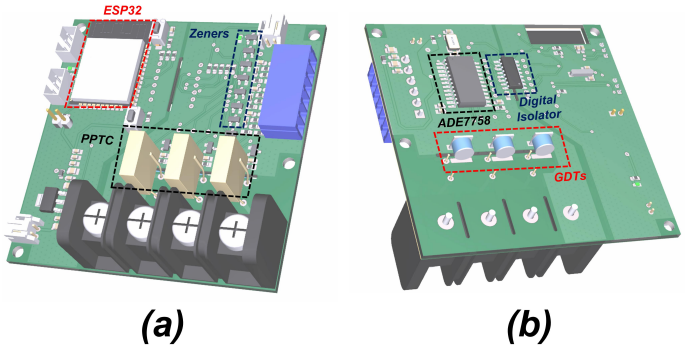


Figure 10. Perspective of the ACU-BREAKER from above (**a**) and below (**b**) in 3D.

5.2.5. ACUs Panel

As mentioned earlier, a panel containing six ACU-BREAKERs, two 5 V power supplies, one for the ESP32-WROOM-32E module's digital circuit and one for the ADE7758's acquisition circuit, and a battery backup were designed. Additionally, a power distribution board was designed and positioned on the panel to share power from the power supplies with the ACUs via connectors. The board was designed to be positioned internally to the

distribution board and installed on six of the circuits present. For a total of 48 circuits, eight panels were developed. Figure 11 illustrates the ACU panel previously developed in Inventor software.

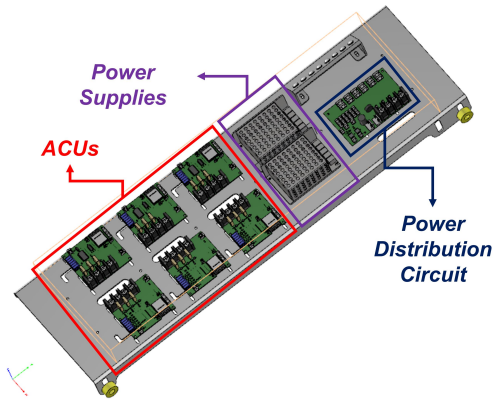


Figure 11. Perspective of the elaborate ACU panel.

5.3. The ACU-ROUTER Middleware

An ACU does not necessarily have to be a hardware device to be developed based on the premises of the SmartLVGrid metamodel. Because it is based on a retrofit strategy, the technological adaptation process can occur through existing devices with the necessary interfaces to enable interoperability with other system applications. In this sense, to interface with the other ACU operators (e.g., ACU-BREAKER) and enable system communication, the ACU-ROUTER (coordinator) was selected to be a wi-fi router in the vicinity of the electrical panel used to implement the proof of concept of this article. The router used was the AP 310 model from Intelbras manufacturer [61].

The wi-fi router does not implement control or monitoring functionality on the electrical circuits or any host system. Therefore, as an ACU, it does not perform DRFs on the host system. However, through it, you can perform message exchanges and communication synchronization with other ACU operators. Thus, through its In/Out port, implemented through its wireless communication transceivers, it was possible to perform ISFs in the system. In addition, this device counts on computational resources for connection management and network configuration, which characterizes its CSFs. For future implementations based on the SmartLVGrid metamodel, it is important to emphasize that the desired operational primitives (DRFs, CSFs and ISFs) depend on the application of ACUs in future systems. Thus, if a market device allows for a non-abrupt technological transition and meets the needs for interfaces to existing/developed systems, it can be used as an ACU. However, for customized solutions, like the ACU-BREAKER, it is necessary to develop the hardware resources and the respective firmware to enable the interaction with other ACUs and the legacy layer, preserving it as much as possible.

5.4. Implementation of the Supervision and Control Center

The supervision and control center was implemented by means of software services and applications, including databases and dashboards, located in a virtual cloud machine on the DigitalOcean [62] provider. Through the SCC, it was possible to view the update of monitored electrical parameters in real time and to register ACUs in order to virtualize the energy monitoring of each circuit in the switchboard.

To develop the screens and dashboards we used the Angular framework in version 10, an open source platform for Web application development [63]. On the other hand, Python language version 3.9 was used to develop software services to transport data to the developed Web application and support the management of other services, such as data storage and device registration. The websocket protocol was used to enable real-time communication between the MQTT broker and the Web application, because through it, it

is possible to send requests and receive event-driven responses without the need to consult a server to update the interface [64].

In order to enable the storage of the monitored data in real time, we used the MongoDB database. On the other hand, the event history and device registration were stored in the PostgreSQL database for organization according to data type. Figure 12 illustrates the architecture of the SCC described in this section and its integration with the devices in our proposal.

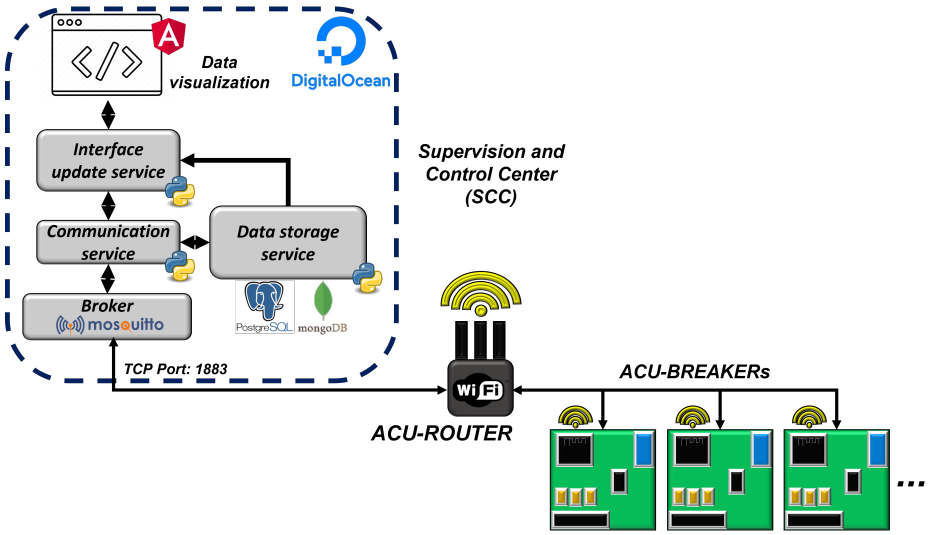


Figure 12. Structure of the supervision and control center.

5.5. Proposal Evaluation Scenario

Our retrofit proposal for monitoring electrical circuits in smart buildings was evaluated in the dental polyclinic of the State University of Amazonas, located in the Cachoeirinha neighborhood, in Manaus. The demands contracted by the distributor are 115 kW during peak hours, from 08:00 pm to 10:59 pm, and 160 kW during off peak hours during the rest of the day. The peak and off-peak tariff schedules for each energy distributor in Brazil can be consulted on the website of the National Agency for Electrical Energy, ANEEL, under "Tariffs and Economic-Financial Information" [65]. Currently, in the case of the polyclinic in question, the electric power distributor is Amazonas Energia.

The polyclinic has an electrical power distribution board, a switchboard, that operates with a nominal voltage of phase-neutral 127 V_{rms}, voltage to which the ACU-BREAKERs were calibrated on the bench. The board in question has 48 circuits and all were monitored by each ACU individually. Each ACU-BREAKER was identified according to the circuit enumeration of the board. The Wi-Fi network configuration parameters, containing the IP address of the virtual machine and the TCP port for MQTT communication, along with the identification of the ACUs, were passed on and stored in the ACUs after the bench calibration procedure. After this, it was possible to assemble the panels with the ACU-BREAKERs, power supplies, batteries, backing plates, and the necessary cabling for installation.

Each ACU-BREAKER was connected to its respective circuit via voltage connectors and current transformers. The panel, in turn, was positioned on the inside of the switchboard. Figure 13 illustrates the ACU panel installed in that scenario. Then, illustrating the retrofit of the switchboard circuits, Figure 14 exposes the ACU-BREAKER connections that interface with the legacy layer of the system. Once powered up, the ACUs, preconfigured with network parameters, began communicating with the MQTT broker running on the virtual machine hosting the SCC applications in the cloud.

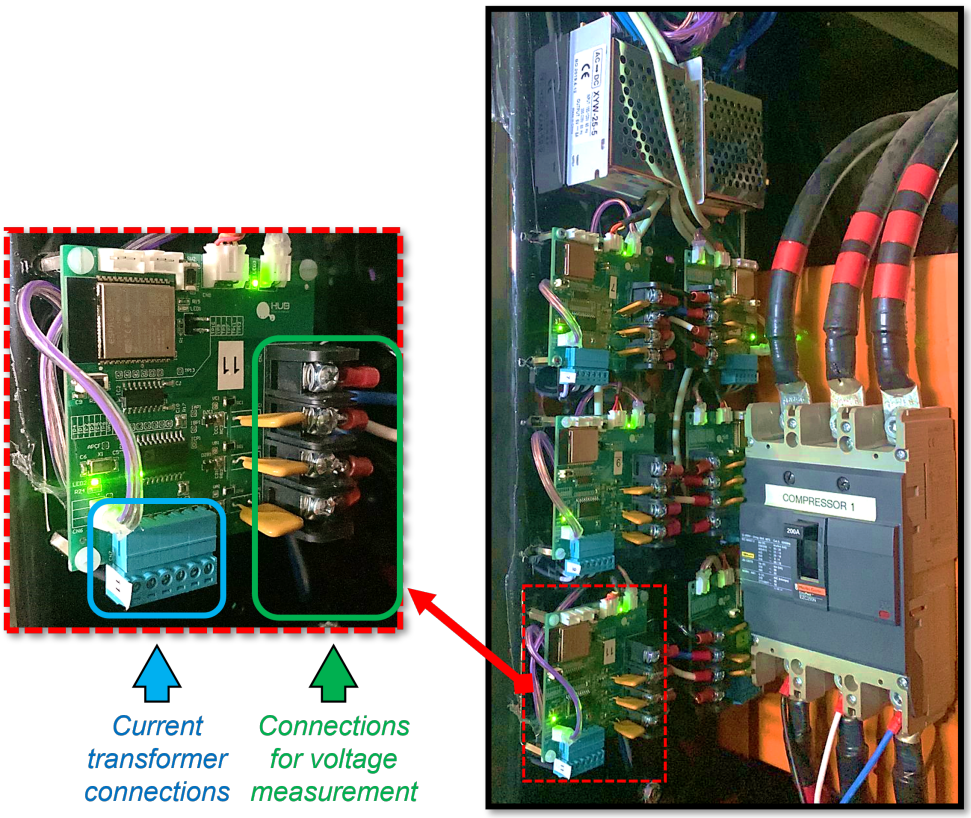


Figure 13. Panel with ACUs installed in the switchboard.

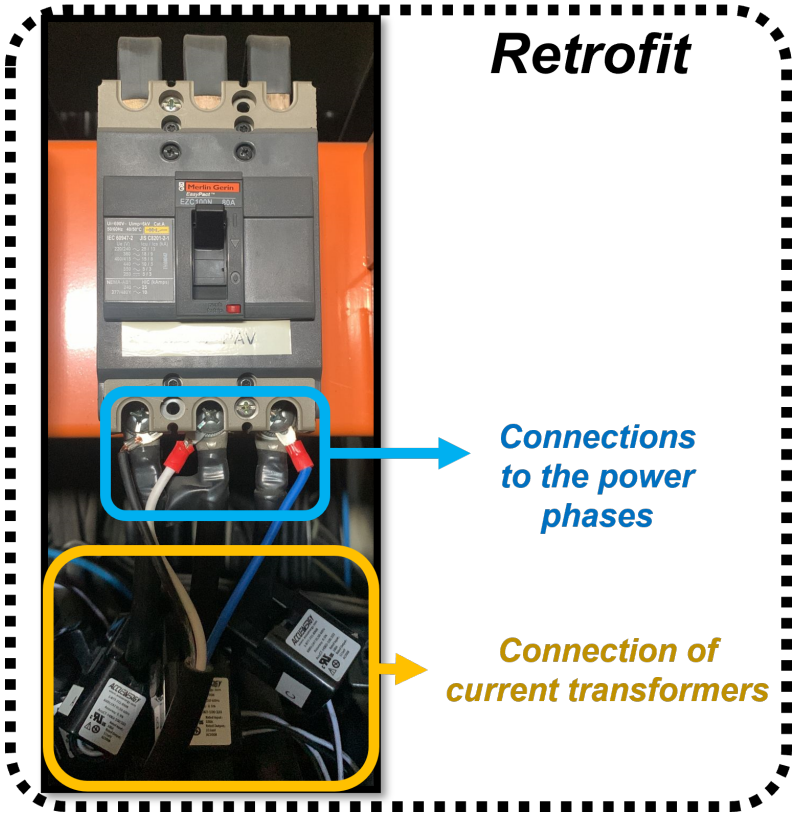


Figure 14. Retrofitting the electrical circuit with ACU-BREAKER connections.

6. Results

In this section, the results obtained from the implementation and performance evaluation of our monitoring proposal for the legacy electric power distribution board will be presented. Initially, the service nodes (SNs) were established by connecting the ACUs to the supervision and control center (SCC) through pre-registered network data. From this, it was possible to evaluate the execution of the operational primitives (DRFs, ISFs, and CSFs) established for the ACU-BREAKER and the ACU-ROUTER, which validates the adaptation of the SmartLVGrid metamodel and the retrofit strategy used. To present the energy management capabilities made available by the proposal, we developed software interfaces that record and expose events and electrical parameters obtained in real time.

6.1. Validation of CSFs

CSFs have been implemented to manage network services and store network configuration data. To illustrate the execution of this operational primitive, Figure 15 exposes some of the logs from the CSF routines implemented in the ACU-BREAKER, obtained by debugging through the universal asynchronous receiver/transmitter (UART) serial interface. In a dual form, these logs also represent the establishment of the network connection made through the LAN interface to the ACU-ROUTER, which in turn establishes communication with the MQTT broker through the Internet.

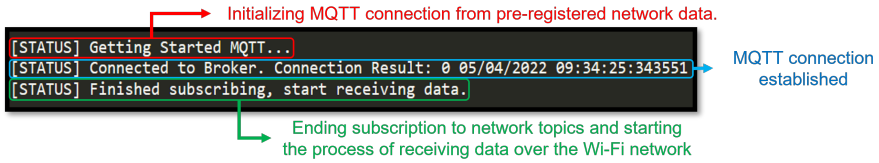


Figure 15. Logs regarding the CSFs implemented in ACU-BREAKER.

6.2. Validation of ISFs and DRF Monitoring of Electrical Parameters

The message exchange process established through the ISFs made it possible to send requests and receive responses between the ACU-BREAKER and the supervision and control center (SCC). This was accomplished via encapsulated packets in JSON format, transmitted via the MQTT protocol with QoS 0. To validate this operational primitive, we captured the sending and receiving data logs from the communication service implemented in Python language in the SCC. From this, it was possible to configure the ACUs, calibrate them, and request the measured electrical parameters of each circuit, characterizing the DRF performed by the ACU-BREAKER. Figure 16 illustrates the logs of the responses of the electrical parameter requests made to the ACU-BREAKER connected to the different circuits of the legacy power distribution board.



Figure 16. Logs of receiving parameters from the switchboard circuits.

It can be seen in the "datetime" field that the electrical parameters were collected at practically the same timestamp, which characterizes the synchronism of the proposed real-time system. In circuit 35, the measured voltages are far below the nominal voltage (127 V_{rms}), indicating an undervoltage event. Note that the voltages of phases A and B of the other circuits are below the nominal voltages, but within the 5% of variation allowed according to the resolution of quality of electric power supply established by ANEEL [66].

6.3. SCC Interfaces

The proposed SCC has the premise of enabling real-time energy management with resources for analysis of power quality and energy efficiency, which is one of the contributions of this work. Its access was accomplished by accrediting users through a login and security key after accessing the address and TCP port of the cloud virtual machine where the application was installed. With the software services in operation, it was necessary to develop interfaces that indicated changes in the power factor, energy demand, monitored electrical quantities and quality of service parameters such as overvoltage and overcurrent [67]. The electrical parameters provide subsidies for the analysis of energy quality, which ensure the reliability of the electrical energy supply service also in low-voltage consumer units [68]. Thus, the importance of this monitoring is justified.

Figure 17 illustrates the interface developed to identify the ACUs in operation associated with each circuit in the frame, including a dashboard to view the instantaneous electrical quantities per phase, the power factor and demand factor, the installed power of the circuit, energy consumption and events related to power quality and energy efficiency. In the "Device Information" field, the unique identification of the ACU in the network (ID) is noted. The consumer unit is also informed, along with the circuit ID (Circuit 32), the installed power and the firmware version of the ACU. There is an indicator as to whether the ACU is connected or not. The field that exposes the occurred events presents the time (timestamp) of occurrence and which event occurred, the value and the percentage of variation of the parameter in relation to the nominal conditions. In Figure 17, the ACU of this circuit has identified consecutive overcurrent events.

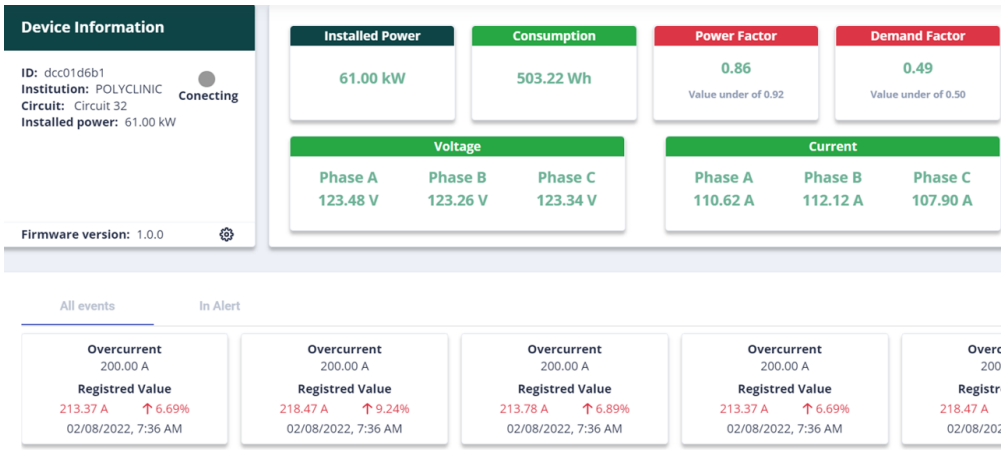


Figure 17. Operational interface for monitoring the circuits via ACUs.

In the dashboard, the cards signal in red the nonconformities with the observed parameters. The demand factor, for example, which represents the ratio of active power measured by the installed power, is below 50%. This value was the threshold set for this metric for analyzing the usage of each circuit in the facility. We established with the building's engineering team that below 50%, the circuit would be underutilized; hence, the definition of this threshold, for this case.

Similarly, Figure 18 exposes the information resulting from the consumer unit, based on the parameters monitored by the ACUs. In the "Consumer Unit Information" field, one can see the consumer unit identification (1780), the consumer unit, and the values of the

demands contracted by the utility at peak (115 kW) and off-peak (160 kW) hours. In the dashboard on the side it is possible to view the last registered values of the power factor, active, apparent and reactive power, and energy consumption. According to module 8 of the Brazilian normative resolution ANEEL nº 956/2021, a power factor of the installation below 0.92 results in fines in the energy bill, and this is the threshold for this ratio [66]. In Figures 17 and 18, respectively, it is possible to observe the power factor card of circuit 32 and the installation in red, as they are below the previously defined threshold. In addition, Figure 18 exposes alerts that identify events of exceeding the demand contracted by the utility in off-peak hours, thus events signaling the reduction of the facility's power factor below 0.92.

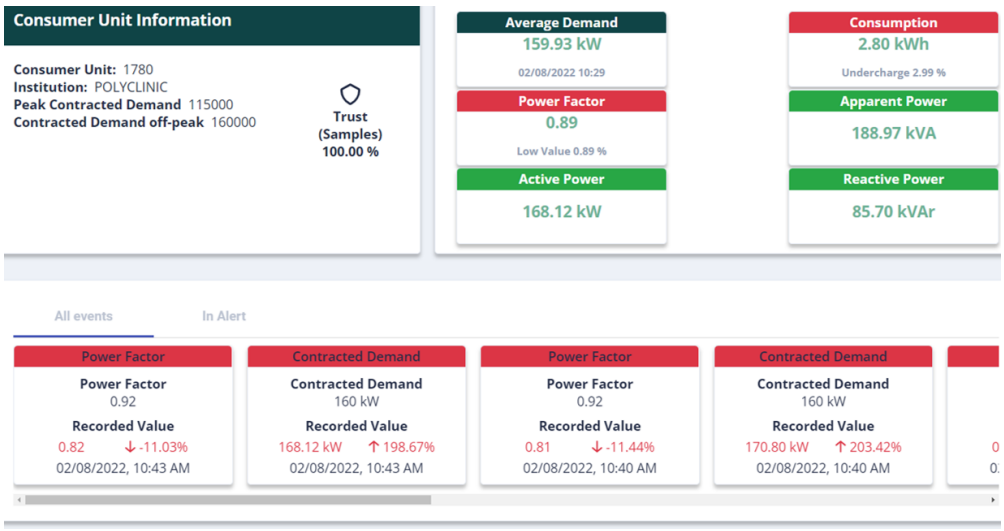


Figure 18. Operational interface for consumer unit analysis.

By using the SCC, it is also possible to observe the time series collected from the ACUs. Figures 19 and 20 expose the active power (a) and the power factor (b) of circuit 47 of the facility and the consumer unit, respectively. Circuit 47 supplies a refrigeration compressor in the installation. In these figures, phases A, B, and C are represented by the curves in blue, red, and green, respectively. The time graphics display up to two monitored electrical quantities per phase or the graphics of the three phases of a single parameter. It should be noted that the viewing history can be selected through the time gap icon and that below the graph the instantaneous values of the quantities are displayed as the cursor is positioned on the screen. In Figures 19 and 20, the visualization period is from 1–2 August 2022.

To visualize the demand and the power factor of the consumer unit with respect to the contract previously established with the utility from the monitored board, we developed differentiated interfaces for analyzing the demand and the power factor. During the same period from 1–2 August 2022, Figures 21 and 22 illustrate the three-phase energy demand and power factor of the installation, respectively. In Figure 21, the three-phase power resulting from the active power of each phase of the consumer unit is observed. As established in the Brazilian normative resolution ANEEL no. 1000/2021, the measured demand must be computed from the average of the three-phase active power every 15 min [69]. Thus, we show in Figure 21 a bar graph to illustrate the demand measured every 15 min of monitoring. We insert the dotted orange curve to represent the demand contracted by the utility at peak and off-peak times. At times when the bar graphs are red, it shows the excess of contracted demand. Otherwise, the graph remains blue. Below the graph, as we position the cursor on the screen, the instantaneous parameters of the graph are shown. On the other hand, Figure 22 shows the installation's power factor, including the limit line that establishes the minimum power factor (0.92).



Figure 19. Active power (**a**) and power factor (**b**) in each phase (A, B, and C) of circuit 47.

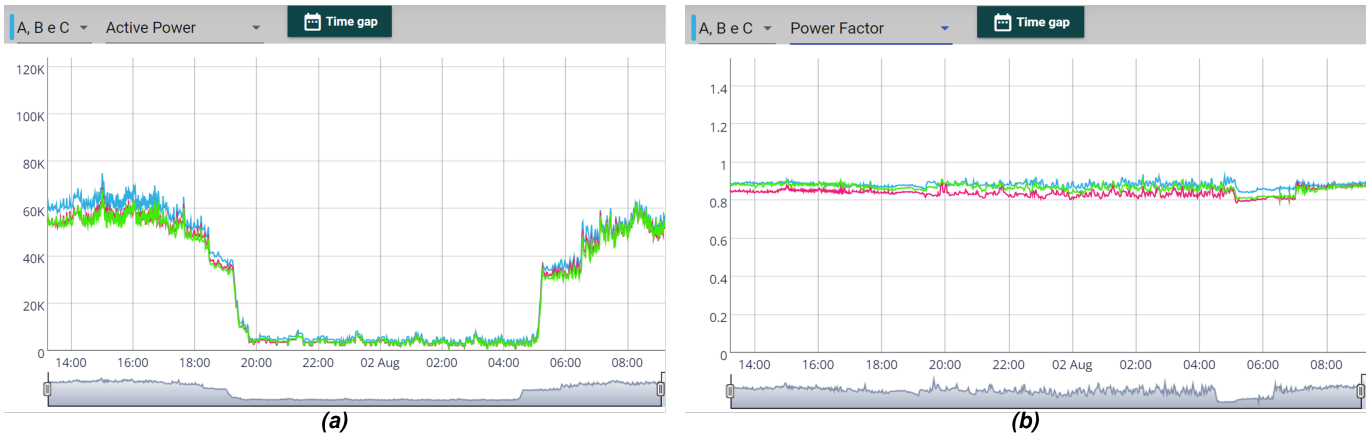


Figure 20. Active power (**a**) and power factor (**b**) in each phase (A, B, and C) of the consumer unit.

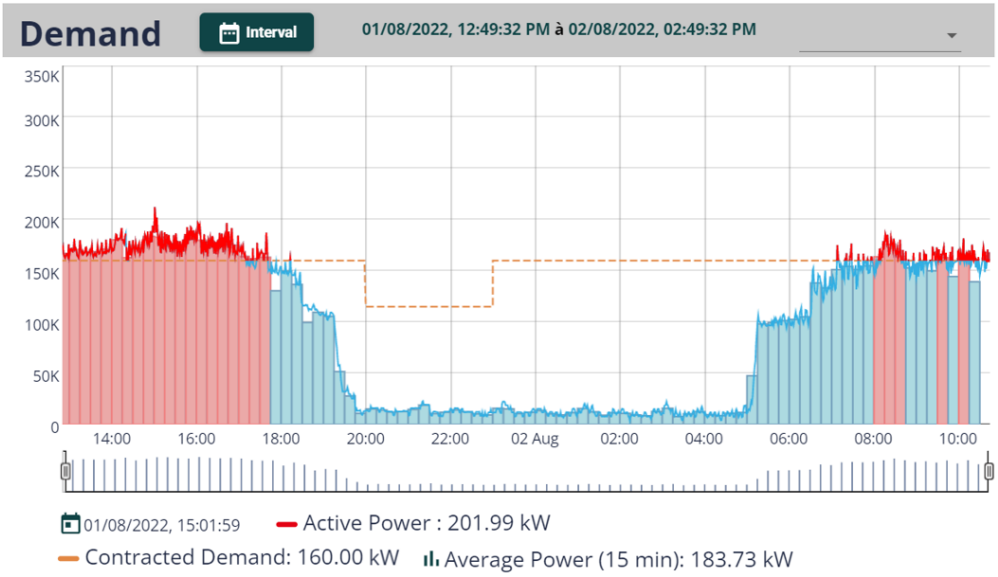


Figure 21. Graph for analyzing the demand of the consumer unit.

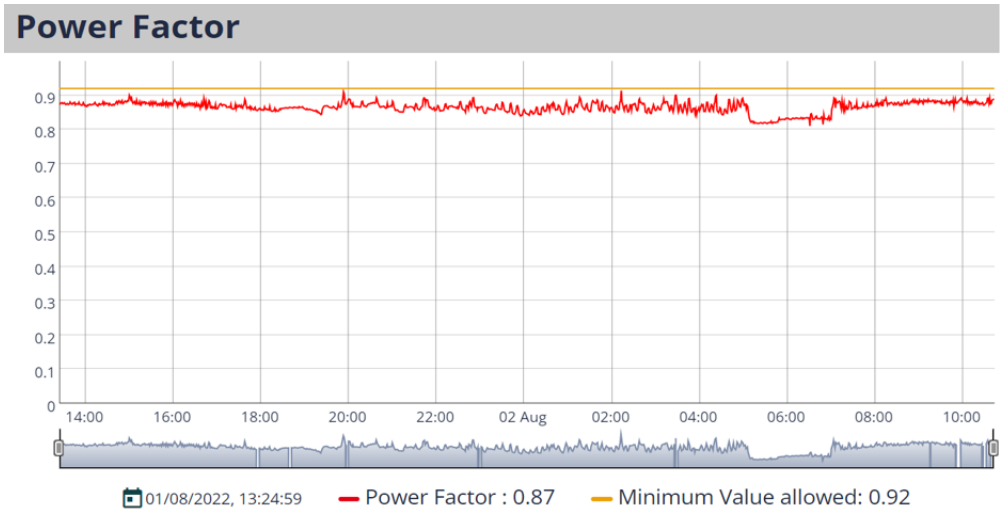


Figure 22. Graph for analyzing the power factor of the consumer unit.

6.4. Case Study with Proposed System

In Brazil, the consumer units can be classified according to the tariff group, according to the contracting options defined by the National Agency of Electric Energy in the Brazilian normative resolution ANEEL nº 1000/2021 [69]. Consumer units of group A are usually medium and high-voltage consumers (industrial, shopping malls, buildings), while consumer units of group B are low-voltage consumers (houses, apartments) [70,71]. Although group B consumer units are charged only for energy consumption, group A consumer units are said to be binomial, and can be charged both for energy consumption and for an energy demand previously contracted with the energy provider [72]. In addition, if the average demand of the 15 min is higher than the contracted demand, the consumer unit will pay a fine for exceeding the demand.

The dental polyclinic of the State University of Amazonas fits in group A and has a contracted off peak demand of 160 kW and peak demand of 115 kW since its inauguration. Currently, the university usually receives monthly increases in its energy bill as a result of excessive energy consumption and excess demand. Subsequently, we identified that since the inauguration, some equipment has been installed in the polyclinic, which has led to increased energy demand. An example of this is circuit 32, which represents the circuit of a compressed air compressor that serves all floors of the facility. Through the ACU-BREAKER responsible for monitoring this circuit, we identified that it is responsible for raising the demand by about 42 kW, approximately 14 kW per phase, as illustrated in Figure 23. In this figure, phases A, B, and C are represented, respectively, by the curves in blue, red, and green.

From our proposal, we identify between May and June 2022 contracted demand exceedances, as shown in Figure 24. It can be observed that at times when the active power is reduced in Figure 23, the demand of the installation is reduced in Figure 24. This way, it can be inferred that circuit 32 is one of the circuits responsible for exceeding the contracted demand in the dental polyclinic facility. Because this circuit supplies an essential load for the activities in the facility, regarding the clinical care of patients, the demand control or equipment replacement are infeasible alternatives at the present moment. In this case, it will be necessary to renegotiate the contracted energy demand, because the initial contracted demand is still being exceeded due to the growth of the polyclinic over the years and the use of energy-intensive equipment. In this way, it is expected that, even with the increase in the contracted demand from the energy concessionaire, the excess fines for exceeding the contracted demand will be reduced, and, with this, the monthly bill. In other words, with the measurements taken from the retrofit strategy implemented in our proposal, it is possible to monitor the energy demand and define actions for the rational use of electricity.

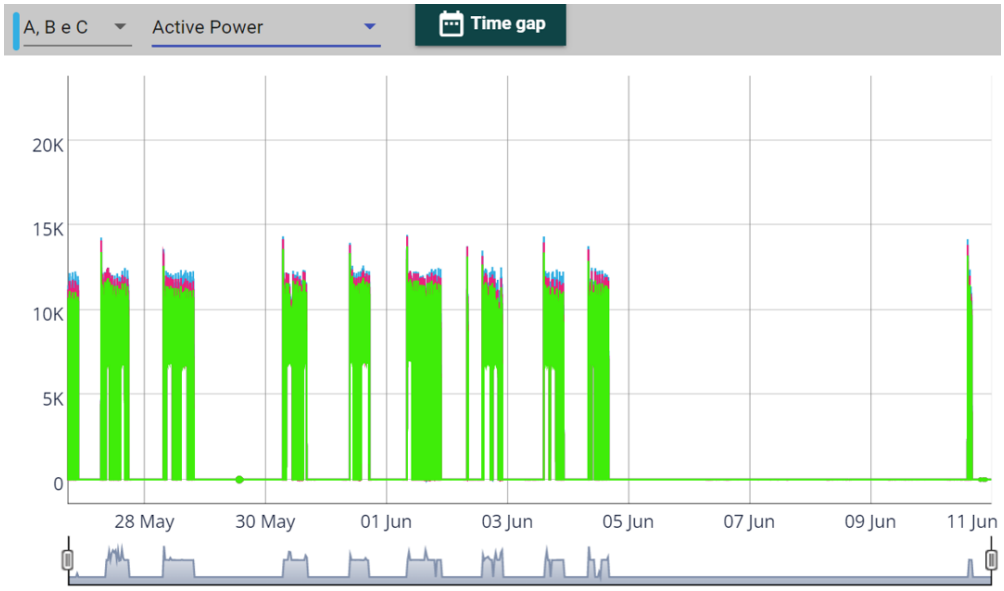


Figure 23. Curve of active powers per phase in circuit 32 of the installation.

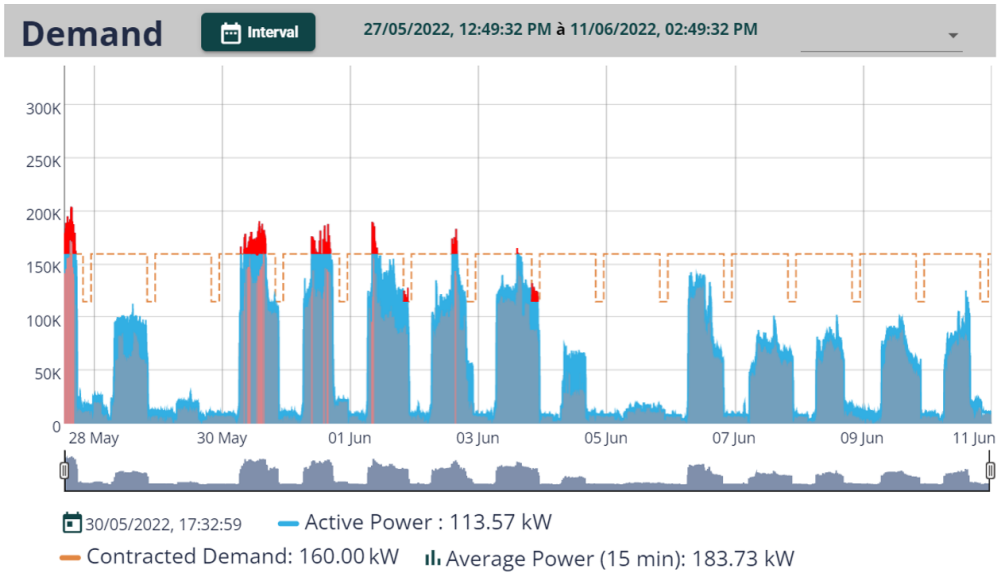


Figure 24. Demand curve for the installation between May and June 2022.

6.5. Discussion

Based on the tests and analysis to validate the retrofit functions and operational primitives of the measurement modules, the conformity of the results with respect to the proposed architecture was noted. Thus, it can be inferred that there was success in adapting the SmartLVGrid metamodel to enable the monitoring interfaces of the electrical circuits of a legacy building installation. It is noteworthy that both ACUs enabled the insertion of remote monitoring resources in a network of devices from the retrofit performed, especially the ACU-BREAKER, which in its operation domain enabled the obtainment of the electrical parameters of each circuit in the grid. Another important validation was the exchange of messages between the supervisory center (SCC) and each ACU-BREAKER, as established in the premises of the interoperability layer.

The parameters monitored by our proposal are of utmost importance for power quality and energy-efficiency studies, because they enable the implementation of energy audit processes to optimize the use of electric energy and reduce costs to the final consumer. In this context, the final consumer can audit and mitigate energy consumption and power

quality in a sectored way, analyzing the contribution of each circuit to the increase in energy demand or change in energy quality parameters. With this, the consumer can study the feasibility of contractual changes in energy demand, make changes to the facilities or reduce the use of installed equipment, if possible. Thus, the use of stationary measurement of circuits as proposed in this work is justified. Examples of this were presented in the verification of excess demand and the low power factor of the installation's circuits, as well as of the consumer unit itself. According to the case study shown, the demand of the installation is higher than the contracted demand, suggesting the readjustment of the demand contracted with the concessionaire. It is important to mention that our proposal can be applied to mitigate similar problems in electrical circuits present in large industries and other building facilities, helping managers of these sectors in decision making that lead to significant reductions in energy demand and adequacy of energy quality parameters.

The retrofit strategy used made it possible to take advantage of the entire legacy infrastructure, from the available data network to the electrical materials present in the facility. Despite being a gradual and not-abrupt technological process, the proposed strategy added new resources for building energy management. Considering the deployment of clusters from the proposed architecture, our strategy enables the scalability of the monitoring system as well as the distributed processing of electrical parameters.

The cost of the retrofit carried out in relation to the costs of existing solutions on the market for monitoring building electrical circuits was also analyzed. Initially, before the proposal presented in this work, the maintenance team of the dental polyclinic carried out initial quotations to evaluate the possibility of acquiring devices for monitoring electrical parameters. This survey was conducted through regional and national distributors. At the best quote obtained, each monitoring device was budgeted at about $213.41. In addition, most solutions on the market would not be customized to the needs of the building maintenance team or would take advantage of part of the pre-existing infrastructure in the installation, requiring more resources to operate in the desired way. However, each ACU-BREAKER has a unit production cost of $41.79, not counting the solution development cost (hardware and firmware) and SCC costs. It is known that for large quantities, the cost of the ACU-BREAKER tends to be reduced. Even so, our solution, adapted to the customer's needs, exceeded almost 80% of the cost of the market solution quoted in the region and in Brazil by the maintenance team itself.

The studies found in the literature do not address the use of metamodels based on the retrofit strategy to enable energy management. In addition, most of these studies present specific solutions for pre-established cases, without the use of architectural models that enable the use of legacy infrastructure, in a scalable manner, in order to perform energy monitoring. Furthermore, many of them do not address the reuse of legacy resources. However, the system proposed in this paper distinguishes itself by presenting a method, based on the SmartLVGrid metamodel, dedicated to energy management from the retrofit of legacy low-voltage electrical circuits of a distribution board. More than that, the proposal presents a cloud-based supervisory center, ensuring security and access to data regardless of location, with dashboard capabilities for viewing the history of electrical parameters and events associated with power quality and energy efficiency. Thus, this approach fills a gap observed in the state of the art and technique for energy monitoring, in a systemic and hierarchically well-defined way.

7. Conclusions

In this work, the SmartLVGrid metamodel was used to enable energy management through the monitoring of electrical parameters in real time from the retrofit of the circuits of a legacy switchboard. To do this, an architecture based on the adaptation of the physical and logical interfaces of the original metamodel was proposed so that this new load profile, the circuits of a building installation, could receive new technological functionalities making the most of the pre-existing elements. To validate the strategy presented, it was necessary to develop the hardware and respective firmware of a retrofit module for monitoring electrical

quantities, called ACU-BREAKER. This device was assigned operational primitives (DRFs, CSFs, and ISFs), based on the SmartLVGrid metamodel, to execute its functionalities. In order to enable the interconnection of each ACU-BREAKER in a wireless data network, a wi-fi router was used as the system hub, called ACU-ROUTER in the proposed architecture. The ACU-BREAKER and the ACU-ROUTER implement, respectively, the role of operator and coordinator of the proposal. In addition, a cloud-based supervisory system (SCC) was developed to store the monitored parameters and make them available in interactive dashboards for quality and energy efficiency analysis. The monitored parameters were the reactive, active and apparent powers, the power factor, the current and the effective voltage in the three phases of each circuit of the board. Based on the results obtained, it was verified that the proposal enables energy management through a transparent process of technological transition, allowing the maximum use of the available infrastructure of the pre-existing legacy circuits. The proposed architecture is customizable to the installation's needs, because the retrofit can be applied according to the physical and logical interfaces available. In addition, the system's middleware and interoperability layers allow for systemic development and enable distributed processing and scalability for cases of energy monitoring expansion. It is emphasized that, through the results presented, it is possible to mitigate possible excess demand, the reduction of the power factor, and the conformity of the electrical parameters of the installation from the individual analysis of each circuit. In this way, a first step is taken to implement an energy audit process. For future work, we suggest the integration of the proposal of this work with monitoring systems in smart grids and the implementation of clusters based on the proposed architecture, including the analysis of the harmonics present in the system and the evaluation of the performance of the SCC hosted in the cloud with the increase of monitored data. We also suggest the integration and evaluation of our proposal with new dynamic energy markets, involving the apportionment of energy through other alternative energy sources. In addition, with the data collected, it is suggested to label and treat them to predict the demand for energy and other electrical quantities to control the demand of the installation by using electrical drive devices for this purpose. It is also suggested that an economic analysis of the consumer unit through the proposed system be performed.

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Abbreviations

The following abbreviations are used in this manuscript:

ACU	Automation and communication unit
ANEEL	Agência Nacional de Energia Elétrica
BEMS	Building energy management system
CIN	Coupling and interaction nodes
CSFs	Computational support functions
DRFs	Domain retrofitting functions
GDT	Gas discharge tubes
GPIO	General-purpose input–output
IoT	Internet of Things
ISFs	Interdomain support functions
JSON	JavaScript object notation
LAN	Local area network
MAN	Metropolitan area network
MQTT	Message queue telemetry transport
NB-IoT	Narrowband IoT
OPs	Operational primitives
PoI	Points of interface
PTC	Positive temperature coefficient
QoS	Quality of service
rms	Root mean square
SmartLVGrid	Smart Low Voltage Grids
SN	Service node
SoC	System-on-a-chip
SQL	Structured query language
TCP	Transmission control protocol
W	Watts
W3C	World Wide Web Consortium
WSN	Wireless sensor network

References

1. Fernandes, R.A.; Gomes, R.C.S.; Dias, O.; Carvalho, C. A Novel Strategy for Smart Building Convergence Based on the SmartLVGrid Metamodel. *Energies* **2022**, *15*, 1016. [CrossRef]
2. Dileep, G. A survey on smart grid technologies and applications. *Renew. Energy* **2020**, *146*, 2589–2625. [CrossRef]
3. Miceli, R.; Favuzza, S.; Genduso, F. A perspective on the future of distribution: Smart grids, state of the art, benefits and research plans. *Energy Power Eng.* **2013**, *5*, 36–42. [CrossRef]
4. Gomes, R.C.S.; da Costa, C.T.; Silva, J.R.; da Silva, P.R.N. Automation meta-system applied to smart grid convergence of low voltage distribution legacy grids. In Proceedings of the 2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 14–17 August 2017; pp. 400–413.
5. Gomes, R.C.S.; Costa, C.; Silva, J.; Sicchar, J. SmartLVGrid Platform—Convergence of Legacy Low-Voltage Circuits toward the Smart Grid Paradigm. *Energies* **2019**, *12*, 2590. [CrossRef]
6. Routray, S.K.; Sharmila, K.P.; Javali, A.; Ghosh, A.D.; Sarangi, S. An Outlook of Narrowband IoT for Industry 4.0. In Proceedings of the 2020 Second International Conference on Inventive Research in Computing Applications (ICIRCA), Coimbatore, India, 15–17 July 2020; pp. 923–926. [CrossRef]
7. Metallidou, C.K.; Psannis, K.E.; Egyptiadou, E.A. Energy Efficiency in Smart Buildings: IoT Approaches. *IEEE Access* **2020**, *8*, 63679–63699. [CrossRef]
8. Höglund, J.; Ilic, D.; Karnouskos, S.; Sauter, R.; Goncalves da Silva, P. Using a 6LoWPAN smart meter mesh network for event-driven monitoring of power quality. In Proceedings of the 2012 IEEE Third International Conference on Smart Grid Communications (SmartGridComm), Tainan, Taiwan, 5–8 November 2012; pp. 448–453. [CrossRef]
9. Hoy, M.B. Smart buildings: An introduction to the library of the future. *Med. Ref. Serv. Q.* **2016**, *35*, 326–331. [CrossRef] [PubMed]
10. Karimi, R.; Farahzadi, L.; Sepasgozar, S.M.; Sargolzaei, S.; Sepasgozar, S.M.E.; Zareian, M.; Nasrolahi, A. Smart Built Environment Including Smart Home, Smart Building and Smart City: Definitions and Applied Technologies. In *Advances and Technologies in Building Construction and Structural Analysis*; IntechOpen: London, UK, 2021; pp. 1–36.
11. Campagna, N.; Caruso, M.; Castiglia, V.; Miceli, R.; Viola, F. Energy Management Concepts for the Evolution of Smart Grids. In Proceedings of the 2020 8th International Conference on Smart Grid (icSmartGrid), Paris, France, 17–19 June 2020; pp. 208–213.

12. Seri, F.; Arnesano, M.; Keane, M.M.; Revel, G.M. Temperature Sensing Optimization for Home Thermostat Retrofit. *Sensors* **2021**, *21*, 3685. [CrossRef]
13. Schaefer, J.L.; Siluk, J.C.M.; de Carvalho, P.S. An MCDM-based approach to evaluate the performance objectives for strategic management and development of Energy Cloud. *J. Clean. Prod.* **2021**, *320*, 128853. [CrossRef]
14. Schaefer, J.L.; Siluk, J.C.M.; de Carvalho, P.S. Critical success factors for the implementation and management of energy cloud environments. *Int. J. Energy Res.* **2022**, *46*, 13752–13768. Available online: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.8094 (accessed on 2 November 2022). [CrossRef]
15. Al-Turjman, F.; Altrjman, C.; Din, S.; Paul, A. Energy monitoring in IoT-based ad hoc networks: An overview. *Comput. Electr. Eng.* **2019**, *76*, 133–142. [CrossRef]
16. Hossein Motlagh, N.; Mohammadrezaei, M.; Hunt, J.; Zakeri, B. Internet of Things (IoT) and the Energy Sector. *Energies* **2020**, *13*, 494. [CrossRef]
17. Sultania, A.K.; Mahfoudhi, F.; Famaey, J. Real-Time Demand Response Using NB-IoT. *IEEE Internet Things J.* **2020**, *7*, 11863–11872. [CrossRef]
18. Alaudin, A.H.b.; Zan, M.M.M.; Mahmud, A.R.; Yahaya, C.K.H.C.K.; Yusof, M.I.; Yussoff, Y.M. Real-Time Residential Energy Monitoring Device using Internet of Things. In Proceedings of the 2018 IEEE 8th International Conference on System Engineering and Technology (ICSET), Bandung, Indonesia, 15–16 October 2018; pp. 97–101. [CrossRef]
19. Muralidhara, S.; Hegde, N.; Rekha, P.M. An internet of things-based smart energy meter for monitoring device-level consumption of energy. *Comput. Electr. Eng.* **2020**, *87*, 106772. [CrossRef]
20. Mudaliar, M.D.; Sivakumar, N. IoT based real time energy monitoring system using Raspberry Pi. *Internet Things* **2020**, *12*, 100292. [CrossRef]
21. Govindarajan, R.; Meikandasivam, S.; Vijayakumar, D. Performance Analysis of Smart Energy Monitoring Systems in Real-time. *Eng. Technol. Appl. Sci. Res.* **2020**, *10*, 5808–5813. [CrossRef]
22. Shivaraman, N.; Saki, S.; Liu, Z.; Ramanathan, S.; Easwaran, A.; Steinhorst, S. Real-Time Energy Monitoring in IoT-enabled Mobile Devices. In Proceedings of the 2020 Design, Automation Test in Europe Conference Exhibition (DATE), Grenoble, France, 9–13 March 2020; pp. 991–994. [CrossRef]
23. Agyeman, M.O.; Al-Waisi, Z.; Hoxha, I. Design and Implementation of an IoT-Based Energy Monitoring System for Managing Smart Homes. In Proceedings of the 2019 Fourth International Conference on Fog and Mobile Edge Computing (FMEC), Rome, Italy, 10–13 June 2019; pp. 253–258. [CrossRef]
24. Prouzeau, A.; Dharshini, M.B.; Balasubramaniam, M.; Henry, J.; Hoang, N.; Dwyer, T. Visual Analytics for Energy Monitoring in the Context of Building Management. In Proceedings of the 2018 International Symposium on Big Data Visual and Immersive Analytics (BDVA), Konstanz, Germany, 17–19 October 2018; pp. 1–9. [CrossRef]
25. Ahmad, T.; Zhang, D. Using the internet of things in smart energy systems and networks. *Sustain. Cities Soc.* **2021**, *68*, 102783. [CrossRef]
26. Moura, P.; Moreno, J.I.; López López, G.; Alvarez-Campana, M. IoT Platform for Energy Sustainability in University Campuses. *Sensors* **2021**, *21*, 357. [CrossRef] [PubMed]
27. Zunnurain, I.; Maruf, M.N.I.; Rahman, M.M.; Shafiullah, G. Implementation of Advanced Demand Side Management for Microgrid Incorporating Demand Response and Home Energy Management System. *Infrastructures* **2018**, *3*, 50. [CrossRef]
28. Reddy, V.; Rabbani, M.; Arif, M.T.; Oo, A.M. IoT for Energy Efficiency and Demand Management. In Proceedings of the 2019 29th Australasian Universities Power Engineering Conference (AUPEC), Nadi, Fiji, 26–29 November 2019; pp. 1–6. [CrossRef]
29. Madhu, G.M.; Vyjayanthi, C.; Modi, C.N. Design and Development of a Novel IoT based Smart Meter for Power Quality Monitoring in Smart Grid Infrastructure. In Proceedings of the TENCON 2019—2019 IEEE Region 10 Conference (TENCON), Kochi, India, 17–20 October 2019; pp. 2204–2209. [CrossRef]
30. Alonso-Rosa, M.; Gil-de Castro, A.; Medina-Gracia, R.; Moreno-Munoz, A.; Cañete-Carmona, E. Novel Internet of Things Platform for In-Building Power Quality Submetering. *Appl. Sci.* **2018**, *8*, 1320. [CrossRef]
31. Viciana, E.; Alcayde, A.; Montoya, F.G.; Baños, R.; Arrabal-Campos, F.M.; Manzano-Agugliaro, F. An Open Hardware Design for Internet of Things Power Quality and Energy Saving Solutions. *Sensors* **2019**, *19*, 627. [CrossRef]
32. Kumar, L.A.; Indragandhi, V.; Selvamathi, R.; Vijayakumar, V.; Ravi, L.; Subramaniyaswamy, V. Design, power quality analysis, and implementation of smart energy meter using internet of things. *Comput. Electr. Eng.* **2021**, *93*, 107203. [CrossRef]
33. Singh, R.S.; Mudhliar, Y.; Chavan, S.; Indragandhi, V.; Varadarajan, V.; Palani, S.; Subramaniyaswamy, V. IoT embedded cloud-based intelligent power quality monitoring system for industrial drive application. *Future Gener. Comput. Syst.* **2020**, *112*, 884–898. [CrossRef]
34. Bolshev, V.; Vinogradov, A.; Jasiński, M.; Sikorski, T.; Leonowicz, Z.; Gono, R. Monitoring the Number and Duration of Power Outages and Voltage Deviations at Both Sides of Switching Devices. *IEEE Access* **2020**, *8*, 137174–137184. [CrossRef]
35. Anand, A.; Vasudevan, R.; Bhattacharya, S.; Arun, R.; Sivanantham, A. Retrofit control solutions for old buildings using WSN. In Proceedings of the 2015 International Conference on Computer, Communications, and Control Technology (I4CT), Kuching, Sarawak, 21–23 April 2015; pp. 59–63.
36. Medina, B.E.; Manera, L.T. Retrofit of air conditioning systems through an Wireless Sensor and Actuator Network: An IoT-based application for smart buildings. In Proceedings of the 2017 IEEE 14th International Conference on Networking, Sensing and Control (ICNSC), Calabria, Italy, 16–18 May 2017; pp. 49–53. [CrossRef]

37. Martín-Garín, A.; Millán-García, J.; Baïri, A.; Millán-Medel, J.; Sala-Lizarraga, J. Environmental monitoring system based on an Open Source Platform and the Internet of Things for a building energy retrofit. *Autom. Constr.* **2018**, *87*, 201–214. [CrossRef]
38. Ibaseta, D.; García, A.; Álvarez, M.; Garzón, B.; Díez, F.; Coca, P.; Del Pero, C.; Molleda, J. Monitoring and control of energy consumption in buildings using WoT: A novel approach for smart retrofit. *Sustain. Cities Soc.* **2021**, *65*, 102637. [CrossRef]
39. Zhang, J.; Ma, M.; Wang, P.; Sun, X.d. Middleware for the Internet of Things: A survey on requirements, enabling technologies, and solutions. *J. Syst. Archit.* **2021**, *117*, 102098. [CrossRef]
40. Mishra, L.; Varma, S.; Vikash. Middleware technologies for smart wireless sensor networks towards internet of things: A comparative review. *Wirel. Pers. Commun.* **2021**, *116*, 1539–1574.
41. Lee, E.; Seo, Y.D.; Oh, S.R.; Kim, Y.G. A Survey on Standards for Interoperability and Security in the Internet of Things. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1020–1047. [CrossRef]
42. Rahman, H.; Hussain, M.I. A comprehensive survey on semantic interoperability for Internet of Things: State-of-the-art and research challenges. *Trans. Emerg. Telecommun. Technol.* **2020**, *31*, e3902. [CrossRef]
43. Givehchi, O.; Landsdorf, K.; Simoens, P.; Colombo, A.W. Interoperability for industrial cyber-physical systems: An approach for legacy systems. *IEEE Trans. Ind. Inform.* **2017**, *13*, 3370–3378. [CrossRef]
44. Fortes, S.; Santoyo-Ramón, J.A.; Palacios, D.; Baena, E.; Mora-García, R.; Medina, M.; Mora, P.; Barco, R. The Campus as a Smart City: University of Málaga Environmental, Learning, and Research Approaches. *Sensors* **2019**, *19*, 1349. [CrossRef] [PubMed]
45. Roalter, L.; Kranz, M.; Möller, A. A middleware for intelligent environments and the internet of things. In Proceedings of the International Conference on Ubiquitous Intelligence and Computing, Xi'an, China, 26–29 October 2010; pp. 267–281.
46. Araújo, P.R.C.; Filho, R.H.; Rodrigues, J.J.; Oliveira, J.P.; Braga, S.A. Middleware for integration of legacy electrical equipment into smart grid infrastructure using wireless sensor networks. *Int. J. Commun. Syst.* **2018**, *31*, e3380. [CrossRef]
47. De Araújo, P.R.C.; Filho, R.H.; Rodrigues, J.J.; Oliveira, J.P.; Braga, S.A. Infrastructure for integration of legacy electrical equipment into a smart-grid using wireless sensor networks. *Sensors* **2018**, *18*, 1312. [CrossRef] [PubMed]
48. Jeusfeld, M.A. *Metamodel*; Springer US: Boston, MA, USA, 2009; pp. 1727–1730. [CrossRef]
49. Mohanty, S.P. *Nanoelectronic Mixed-Signal System Design*; McGraw-Hill Education: New York, NY, USA, 2015.
50. Abdelouahid, R.A.; Marzak, A.; Sae, N. Towards to a New Meta-model of IoTs Interoperability. In Proceedings of the 2018 IEEE 5th International Congress on Information Science and Technology (CiSt), Marrakech, Morocco, 21–27 October 2018; pp. 54–63. [CrossRef]
51. Hassine, T.B.; Khayati, O.; Ghezala, H.B. An IoT domain meta-model and an approach to software development of IoT solutions. In Proceedings of the 2017 International Conference on Internet of Things, Embedded Systems and Communications (IINTEC), Gafsa, Tunisia, 20–22 October 2017; pp. 32–37.
52. Cicirelli, F.; Fortino, G.; Guerrieri, A.; Spezzano, G.; Vinci, A. A meta-model framework for the design and analysis of smart cyber-physical environments. In Proceedings of the 2016 IEEE 20th International Conference on Computer Supported Cooperative Work in Design (CSCWD), Nanchang, China, 4–6 May 2016; pp. 687–692.
53. Toldinas, J.; Lozinskis, B.; Baranauskas, E.; Dobrovolskis, A. MQTT Quality of Service versus Energy Consumption. In Proceedings of the 2019 23rd International Conference Electronics, Palanga, Lithuania, 17–19 June 2019; pp. 1–4. [CrossRef]
54. Mukherjee, A.; Dey, N.; De, D. EdgeDrone: QoS aware MQTT middleware for mobile edge computing in opportunistic Internet of Drone Things. *Comput. Commun.* **2020**, *152*, 93–108. [CrossRef]
55. Huang, S.; Li, W. A method of cross-platform network data exchange. In Proceedings of the 2016 International Conference On Communication Problem-Solving (ICCP), Taipei, Taiwan, 7–9 September 2016; pp. 1–2. [CrossRef]
56. Espressif. ESP32 Series Datasheet. 2022. Available online: https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf (accessed on 21 May 2022).
57. Espressif. ESP32-WROOM-32E and ESP32-WROOM-32UE Datasheet. 2022. Available online: https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32e_esp32-wroom-32ue_datasheet_en.pdf (accessed on 21 May 2022).
58. DEVICES, A. Datasheet ADE7758-Poly Phase Multifunction Energy Metering IC with Per Phase Information. 2011. Available online: https://www.analog.com/media/en/technical-documentation/data-sheets/ade7758.pdf (accessed on 27 May 2022).
59. Equipment, M.M.T. PPS 400.3: Three-Phase Portable Power Source (12 A or 120 A/300 V). 2004. Available online: https://www.mte.ch/data/files/PPS%20400.3%20English_R04%20(09.2004).pdf (accessed on 21 May 2022).
60. Accuenergy. AcuCT Hinged Series Datasheet. 2021. Available online: https://www.accuenergy.com/wp-content/uploads/acuct-hinged-series-compact-split-core-current-transformer-datasheet.pdf (accessed on 13 June 2022).
61. Intelbras. Ficha Técnica: AP 310. 2021. Available online: https://backend.intelbras.com/sites/default/files/2020-01/Datasheet_AP_310_02-19.pdf (accessed on 27 July 2022).
62. Alankar, B.; Sharma, G.; Kaur, H.; Valverde, R.; Chang, V. Experimental Setup for Investigating the Efficient Load Balancing Algorithms on Virtual Cloud. *Sensors* **2020**, *20*, 7342. [CrossRef]
63. Tripon, T.D.; Adela Gabor, G.; Valentina Moisi, E. Angular and Svelte Frameworks: A Comparative Analysis. In Proceedings of the 2021 16th International Conference on Engineering of Modern Electric Systems (EMES), Oradea, Romania, 10–11 June 2021; pp. 1–4. [CrossRef]
64. Pimentel, V.; Nickerson, B.G. Communicating and displaying real-time data with websocket. *IEEE Internet Comput.* **2012**, *16*, 45–53. [CrossRef]

65. National Agency of Electric Energy (ANEEL)—Rates and Economic-Financial Information. Available online: https://www.gov.br/aneel/pt-br/centrais-de-conteudos/relatorios-e-indicadores/tarifas-e-informacoes-economico-financeiras (accessed on 29 September 2022).
66. National Agency of Electric Energy (ANEEL)—Normative Resolution No. 956/2021. Available online: https://www2.aneel.gov.br/cedoc/ren2021956.html (accessed on 29 September 2022).
67. Alvarez de Sotomayor, A.; Della Giustina, D.; Massa, G.; Dedè, A.; Ramos, F.; Barbato, A. IEC 61850-based adaptive protection system for the MV distribution smart grid. *Sustain. Energy Grids Netw.* **2018**, *15*, 26–33. [CrossRef]
68. Yuan, M.; Liu, Y.; Liu, R.; Niu, X. Monitoring and Analysis of Power Supply Reliability of Low Voltage Consumers. In Proceedings of the 2006 International Conference on Power System Technology, Chongqing, China, 22–26 October 2006; pp. 1–4. [CrossRef]
69. National Agency of Electric Energy (ANEEL)—Normative Resolution No. 1000/2021. Available online: https://www2.aneel.gov.br/cedoc/ren20211000.pdf (accessed on 29 September 2022).
70. Guerhardt, F.; Silva, T.A.F.; Gamarra, F.M.C.; Ribeiro Júnior, S.E.R.; Llanos, S.A.V.; Quispe, A.P.B.; Vieira Junior, M.; Tambourgi, E.B.; Santana, J.C.C.; Maria Vanalle, R. A Smart Grid System for Reducing Energy Consumption and Energy Cost in Buildings in São Paulo, Brazil. *Energies* **2020**, *13*, 3874. [CrossRef]
71. Martins, V.A.; Branco, D.A.C.; Hallack, M.C.M. Economic Effects of Micro- and Mini-Distributed Photovoltaic Generation for the Brazilian Distribution System. *Energies* **2022**, *15*, 737. [CrossRef]
72. Rodrigues, V.; Moraes, R.; Berejuck, M. A Brazilian Legal and Technical Evaluation about Energy Binomial Tariff. In Proceedings of the 2021 IST-Africa Conference (IST-Africa), Online, 10–14 May 2021; pp. 1–8.