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Original Article

An IoT System for Real-Time Energy Supervision of Public Lighting Circuits in Electrical Distribution Networks

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Abstract *- Public lighting circuits require continuous supervision to relate their electrical consumption to the operating status of the luminaires and to detect deviations before a field inspection. An Internet of Things system is developed for real-time electrical supervision using a PZEM-004T v3.0, an ESP32, cellular communication through A9G, and a web-based supervisory platform. The node acquires voltage, current, active power, accumulated energy, frequency, and power factor; active power is used together with a configurable average power to estimate the number of luminaires in operation. Under a representative condition, 218.5 V, 5.844 A, 892.3 W, and 82658 Wh were recorded, with 13 estimated luminaires. In an alert test, a configuration of 14 luminaires produced an estimate of 11.9 units and activated the load-reduction record. The system also recorded a shutdown event with 12103.0 Wh and a deviation of -0.1 %. Historical profiles distinguish operation with relatively stable power from another with repetitive variations during the service period. The architecture converts aggregated electrical measurements into operational indicators for remote supervision and inspection prioritization. The evaluation corresponds to functional validation; metrological accuracy requires subsequent comparison with certified instrumentation.*

Keywords *- Electrical distribution networks, Energy supervision, IoT, Power profile monitoring, Public lighting.*

1. Introduction

Due to the spatial distribution, timing, and quantity of Public Lighting (PL), it imposes a distributed load on urban electrical networks. For supervision, it is not sufficient to know a circuit's on-or-off status; its electrical behavior during the service period must also be monitored. Voltage, current, Active Power (AP), Accumulated Energy, Frequency, and Power Factor (PF) may be used to describe the behavior of lighting circuits and to indicate any deviations from usual behavior. It is difficult to identify changes in load consumption, interruptions, or variations in the number of connected lighting fixtures due to the absence of continuous records. In the absence of continuous records, supervision of conventional PL often requires field inspections, user reports, and periodic checks by the staff. There is a lag between an irregularity in the service and the time that the staff becomes aware of it. This scheme also does not allow the actual on-off schedule to be reconstructed accurately, or the energy consumed to be related to the effective operating time. Growth in electrical demand and the need for more observable distribution networks have increased interest in systems capable of acquiring, storing, and remotely transmitting operational information [1]. Internet of Things (IoT)-based architectures integrate sensors, embedded devices, communication networks, and digital platforms to link physical infrastructure with remote supervision systems [2]. In PL, this line of development has concentrated much of the work on luminaire control, lighting level regulation, energy efficiency, and automation. LoRa-based systems have been proposed for remote supervision and control [3], as well as neural-network-based strategies to reduce energy consumption in residential areas [4]. Recent reviews of smart PL show a dominant presence of sensing techniques, wireless communication, dimming control, and integration with smart-city platforms [5, 6].

Aggregated electrical supervision of the circuit addresses a different function. Instead of acting on each luminaire, it uses the variables measured at the supply point to describe the overall behavior of the connected load. IoT systems applied to substations and smart grids have used electrical variables for load management and support for operational decisions [7]. Complementarily, platforms for monitoring alternating current parameters have recorded voltage, current, power, and energy for consumption analysis [8]. These precedents demonstrate the feasibility of remote electrical acquisition, but they do not, by themselves, resolve the relationship between the aggregated power of a lighting circuit and the likely

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number of luminaires that remain in operation. This relationship becomes operationally relevant when load loss can be associated with deficiencies observable in the field. Peruvian PL supervision regulations consider, among other categories, DT1, corresponding to an inoperative lamp, and DT3, associated with the absence of a PL unit [9, 10]. Both conditions can reduce the active power demanded by the circuit when the number of connected or operating luminaires decreases. Aggregated measurement cannot differentiate which of these deficiencies is present. Voltage variation, power tolerance, luminaire aging, and electrical losses affect the recorded power measurement. It can, however, provide an early electrical alert to facilitate scheduling the physical inspection.

The reviewed literature mostly addresses solutions for individual luminaire control, adjustable lighting levels, and distributed fault detection [3-6]. Less attention has been given to circuit-level aggregated electrical supervision that combines electrical variable acquisition, embedded processing, cellular communication, estimation of the number of operating luminaires, and historical load analysis within a single architecture. Most energy-monitoring systems provide access to components of the electrical system but cannot interpret or act on aggregated circuit measurements in terms relevant to PL [7, 8]. This defines the area of interest regarding the system developed in this research.

A new system was developed and is fully functional for real-time monitoring of PL circuits in electrical distribution networks using IoT technology. This system integrates the PZEM-004T v3.0, ESP32, and A9G modules and reads the circuit's electrical parameters. The microcontroller processes the readings and sends them via GSM/GPRS to a SCADA-type web-based platform for real-time monitoring and historical querying. Active power is then related to the configured average power per luminaire to estimate the probable number of units in operation. The same supervision process retains on- and off events, time profiles, and alerts generated when the measured load departs from the configured circuit condition.

The study's contribution is the circuit-level use of active-power measurements for three linked functions within a single remote supervision architecture: estimating the number of operating luminaires, generating load-deviation alerts, and preserving historical operating profiles. The experimental scope is restricted to functional validation of the prototype; metrological accuracy was not quantified because the electrical measurements were not compared with certified instrumentation at this stage. This paper describes the technological and regulatory foundations of the supervision approach, presents the IoT architecture and experimental methodology, and reports the functional validation results, including the system's operational domain and technical limitations.

2. Technical and Regulatory Foundations

2.1. Electrical Supervision of PL Circuits

The node at the circuit supply point captures readings for voltage, current, active power, accumulated energy, frequency, and power factor. Voltage and frequency are recorded as supply conditions; current is recorded as instantaneous demand; active power represents the connected load; accumulated energy represents consumption during operation; and power factor describes the relationship between active and reactive power. The record also captures other supervisory variables, such as a rough estimate of the number of active luminaires, the number of luminaires that are not working, the strength of the GSM signal, and the status of the node connection.

The primary variable for correlating the aggregated electrical behavior of connected luminaires at the circuit's supply point is active power. For a circuit containing N_{inst} light fixtures with an average power of P_{lum}, the estimated power is equal to:

$$P_{exp} = N_{inst} \cdot P_{lum} \quad (1)$$

In (1), P_{exp} denotes the active-power reference associated with the configured circuit. Using the measured circuit power P_{meas}It is possible to determine the probable number of luminaires in operation, such as:

$$N_{est} = \frac{P_{meas}}{P_{lum}} \quad (2)$$

Because luminaire power can differ among installations, P_{lum} remains a configurable parameter rather than a fixed value. The resulting N_{est} provides a circuit-level approximation and therefore cannot identify the specific luminaire that is out of service.

The estimated number of non-operating luminaires is calculated by the difference between installed and estimated counts:

$$N_{fault} = N_{inst} - N_{est} \quad (3)$$

This indicator is used to trigger the logical chain based on excessive load reduction, as defined by the configuration. The interpretation of the alert is restricted by variables that can also affect it. P_{meas}. A change in measured power might occur due to supply/line voltage variation, luminaire aging, manufacturing tolerances, conductor losses, and operating conditions, even when no lamp is inoperative.

2.2. Operational Deficiencies in PL

PL deficiencies in Peru are grouped into DT1-DT5. DT1 is a defective light, while DT3 is a missing lighting unit. The other groups are for lights and brackets that are broken or

missing, for cases of tree intrusion, and for cases of broken or missing diffusers. The intervention logic for these conditions is based on a complete electrical system equivalent to DT1 and DT3. In both cases, a decrease in connected or energized luminaires may reduce the circuit's active power. The comparison between N_{inst} and N_{est} generates a warning if the estimated load reduction exceeds the circuit's configured limit.

This warning should be considered a service advisory rather than a diagnostic warning. A decrease in aggregate power may indicate a defective light or a missing PL unit, but at the circuit level, the measurement cannot differentiate between these cases or pinpoint the affected location. Tree interference, broken diffusers, or even lighting units oriented incorrectly are outside this electrical criterion; they may be the main manifestation of the problem without a significant change in the circuit load.

2.3. Electrical Criterion for Luminaire Supervision

During the lighting service period, P_{meas} is compared with the estimated circuit condition using N_{inst} and P_{lum}. A sustained decrease in measured active power. N_{est} and increases N_{fault}. For the configuration used in the experimental tests, the alert is triggered if the estimated reduction exceeds that of a single non-operating luminaire.

Table 1 defines the boundary of this supervision criterion. A deviation in aggregated active power is treated as electrical evidence consistent with a reduction in the number of luminaires in operation, but it does not establish the regulatory deficiency itself. Field verification is required for classification, since circuit-level measurements do not provide the diagnostic capability needed to identify the specific cause.Historical records place each instantaneous estimate within the daily operating cycle. Power rises from near zero at startup, remains near the expected operating level during service, and decreases again at shutdown. Repetition of a service pattern with slight variations can represent those patterns of disconnects or loads that are unpredictable or partial. The time record allows the actual on- and off-times of a device to be identified and correlated with the circuit's total consumption.

Table 1. Relationship between the supervised deficiencies and the electrical criterion used

Code	Deficiency considered	Electrical manifestation used by the system	Supervision response
DT1	Inoperative lamp	Reduction of aggregated AP with respect to the expected condition	Decrease in $\boldsymbol{N_{est}}$ and alert generation when the configured criterion is exceeded
DT3	Missing PL unit	Reduction of the load corresponding to the expected number of luminaires	Decrease in $\boldsymbol{N_{est}}$ and alert generation when the configured criterion is exceeded

3. Materials and Methods

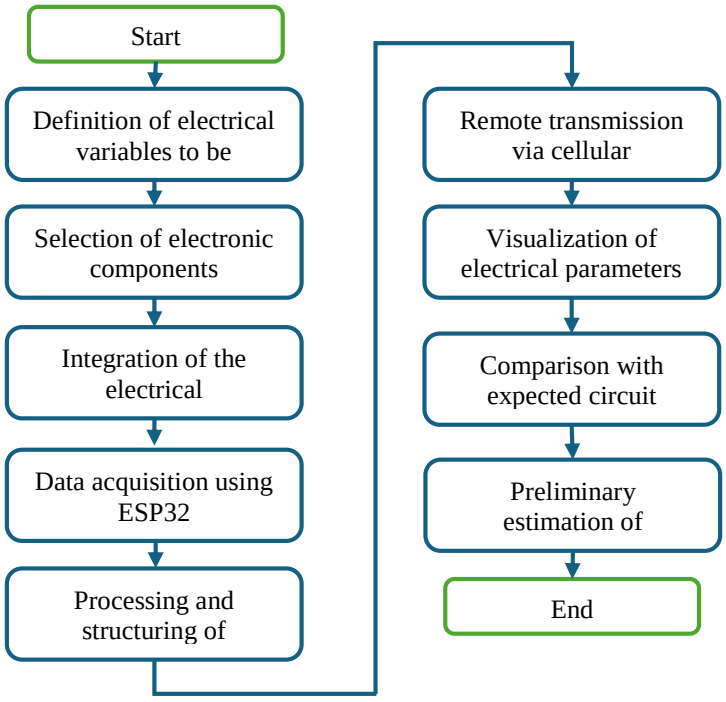


Fig. 1 Methodological workflow of the proposed IoT system for public lighting energy supervision

The experiment was developed by defining the electrical variables and functionally verifying the supervision platform. The process included the selection and integration of electronic components, measurement acquisition and processing, luminaire estimation, cellular data transmission, data storage and display, alert generation, and time-domain power analysis. The steps for implementing and evaluating the system are presented in Figure 1.

3.1. IoT System Architecture

The architecture separates electrical measurement, embedded processing, cellular communication, and remote monitoring into different layers. In the PZEM-004T v3.0, the electrical measurements are acquired, and the data are sent to the ESP32 to be structured and the operational metrics calculated [11]. The A9G module is used to establish GSM/GPRS communication with the remote server for saving and querying data through the IoT-SCADA web platform.

The PZEM-004T v3.0 measures voltage, current, active power, active energy, frequency, and power factor. The measurement module and the ESP32 communicate over UART [12]. One UART channel is connected to the A9G, which allows the electrical measurement and external communication functions to remain separated within the node.Each record sent to the server is identified and contains voltage, current, AP, active energy, frequency, PF, RSSI, operating time, and the number of luminaires. Communication is achieved by HTTP commands over the GPRS link.

The IoT-SCADA platform allows electrical variables to be displayed, historical records to be retrieved, and node status to be checked. The acquired active power is used to determine the number of luminaires and to activate the alert system when power and/or voltage are outside the predefined operating limits. Figure 2 shows the system architecture and the information flow for remote supervision of the PL circuit.

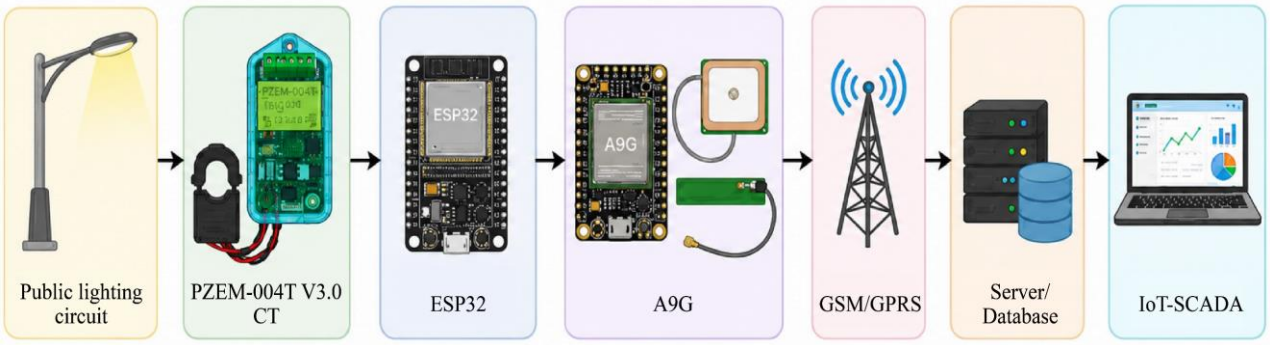


Fig. 2 Functional architecture of the IoT system for electrical supervision of public lighting circuits

3.2. Implementation of the Supervision Node

Table 2. Main components of the proposed system

Component	Main function	Communication interface
ESP32	Embedded processing, data acquisition, and communication management	UART / GPIO
PZEM-004T v3.0	Measurement of AC electrical parameters	UART TTL
A9G GSM/GPRS	Remote data transmission through a cellular network	UART / AT commands
Logic-level converter	Signal adaptation between 3.3 V and 5 V devices	Bidirectional
DC power supply	Power supply for the embedded system	--
IoT-SCADA platform	Visualization, storage, and historical analysis	HTTP

The ESP32 is the central processing unit for data acquisition and management of communication commands in the supervision node. The PZEM-004T v3.0 module measures electrical circuit variables.

The A9G provides the GSM/GPRS module for sending measurement data to the remote server. The integration of the elements includes the signaling and power supply modules to fulfill the electrical interface of the remaining modules.The firmware uses independent UART interfaces to separate measurement and communication functions. The PZEM-004T v3.0 module operates at TTL UART, while the A9G communicates with the ESP32 via AT commands. The system includes local storage on an SD card to store measured data and system events.

Each local record contains the date, time, voltage, current, AP, energy, frequency, PF, RSSI, operational time, and estimated number of lamps. The main functions of each node element integrated into the system are defined in Table 2.

All modules were positioned in an enclosure to house the acquisition and communication system. The enclosure contains the measurement, processing, storage, and transmission stages in a single node.

This reduces the connections needed to measure the circuit, power the node, and enable cellular communication. Figure 3 shows the physical arrangement as it was during the experimental tests.

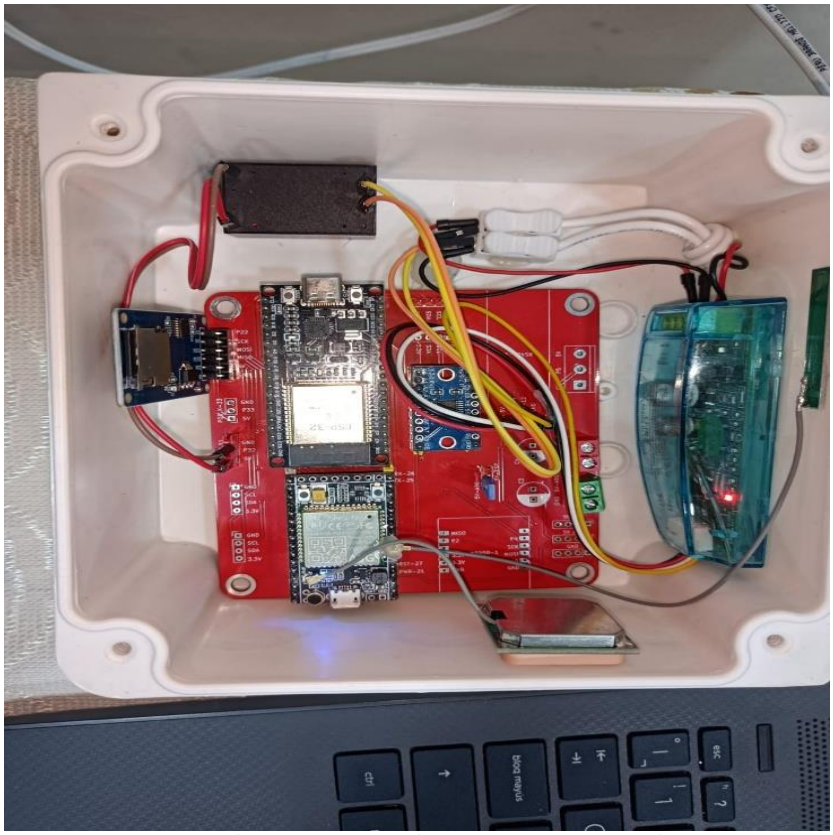


Fig. 3 Physical implementation of the IoT node used for electrical supervision of the public lighting circuit

3.3. Acquisition and Monitored Variables

Voltage, current, AP, energy, frequency, and PF can be measured electrically with the PZEM-004T v3.0. The ESP32 captures these values, performs processing, and transmits the data via the IoT. Before transmitting the data to the server, the microcontroller integrates the captured values into the node operating log.AP and accumulated energy help estimate the number of active luminaires and consumption during the effective operational period, respectively. The system also captures the GSM signal strength and the status of node connectivity. These values help distinguish an electrical condition of a circuit from a communication impairment. The electrical and operational variables used for supervision are summarized in Table 3.

Table 3. Electrical and operational variables recorded by the IoT system

Variable	Symbol	Unit	Technical purpose
Voltage	V	V	Evaluate supply level
Current	I	A	Analyze instantaneous circuit demand
Measured AP	P_{meas}	W	Determine operating electrical load.
Accumulated energy	E	Wh / kWh	Register consumption during operation
Frequency	f	Hz	Verify the AC supply condition
PF	PF	--	Characterize load behavior
Average luminaire power	P_{lum}	W	Configurable parameter for luminaire estimation
Installed luminaires	N_{inst}	unit	Expected number of luminaires in the circuit
Estimated luminaires	N_{est}	unit	Probable number of operating luminaires
Estimated non-operating luminaires	N_{fault}	unit	Difference between installed and estimated luminaires
GSM signal intensity	$RSSI$	--	Assess remote communication availability.
Node status	--	--	Verify monitoring-node connectivity

3.4. Data Processing and Transmission

The ESP32 processes the measurements from the PZEM-004T v3.0 by adding a record to each measurement that includes the date, time, and node status. The ESP32 processes the measurements of the electrical variables V, I, P, E, f, and PF; RSSI; operating time; and an estimation of the number of luminaires. This combination of measurements allows the ESP32 to store all electrical measurements and variables needed by the supervision platform in a single record. The A9G module is used for remote communication. The ESP32 uses AT commands to establish the transceiver connection and configure the GPRS connection before sending records to the server via HTTP. The record includes the node ID along with the measurements.

Measurements are stored on the SD card before they are sent. All measurements are time-stamped and include voltage, current, AP, reactive power, active energy, reactive energy, frequency, PF, and RSSI, along with the operating time and an estimation of the number of luminaires. All system events and alarms are stored in a separate record, which is used to distinguish operational data from incident data. Firmware verifies the server response for each transmission. A good server response resets the communication failure counter, while a bad server response increases the counter. Once the communication failure counter reaches 5, the recovery routine for the A9G module is executed, which consists of a reset and connection to the cellular network. Should the module fail to connect to the cellular network, the ESP32 automatically resets to run the node. The information received on the server is processed by the IoT-SCADA platform to help visualize and support historical data queries. Separation between local and remote processes helps the node perform data acquisition and operational logic on site, while the platform performs data storage, temporal presentation of data, and logging of events.

3.5. Luminaire Estimation and Alert Logic

The estimation of the number of luminaires in operation is based on the relationship between the active power measured in the circuit and the average power configured for each luminaire. The value of P_{lum} is kept as an adjustable parameter, so that the same architecture can be used in circuits with different nominal or average power per unit. The expected circuit condition is defined by N_{inst}, while N_{est} is obtained from the power recorded during the operating period. The supervision logic compares. N_{est} with N_{inst}. When the difference corresponds to more than one switched-off luminaire, the system generates an alert for possible load reduction.

The event is recorded on the platform, along with the expected and estimated numbers of luminaires, thereby preserving traceability of the detected condition. The alert is interpreted as a warning of an electrical deviation in the circuit. A decrease in power may be compatible with an inoperative lamp or with the absence of a PL unit, but aggregated measurement cannot by itself establish the cause or the physical location of the deficiency. Confirmation of a DT1 or DT3 condition requires field inspection. In addition to load reduction, the system records circuit on- and off-events. The accumulated consumption for each operating period is retained along with the corresponding time, enabling the energy used to be related to the effective operating interval. This information is subsequently used to reconstruct the daily power profile and review deviations associated with intermittency or unforeseen load changes.

3.6. Historical Record and Operational Events

The IoT-SCADA platform preserves the received measurements to enable restoration and analysis of the circuit's overall behavior. This allows for the reconstruction of historical records for measurement data and the associated consumption. This information is retained along with electrical data and the status of the operating node.

In analyzing the daily consumption profile, it is necessary to include the operating states: startup, operation, and shutdown. When a node is started up, there is a transition from a state of almost zero consumption to a state of consumption corresponding to the lighting load. During a node's operation, power consumption is constant and proportional to the number of lights on. During a node shutdown, power consumption drops to nearly zero. The operating states can be identified by reconstructing the records for each cycle.

Measurements and records are maintained internally in the node for each operating interval. If the profile changes, it may be due to an intermittent disconnection or an unforeseen variation in load. The interpretation is based on the complete history and not on an instantaneous record. A local event log is maintained on the SD card, and each entry contains the date, time, event type, and associated message. Measurements are saved periodically to keep routine electrical records separate from those generated by the supervision logic. Once the previously defined alert criteria are exceeded, the associated event is stored on the platform and can also be sent via the selected communication channel. This means that measurements, their corresponding operating states, and alerts will be found in the same time sequence. This allows for comparison of various operating events to changes in circuit load.

3.7. Experimental Procedure

Functional validation of the integrated IoT node was carried out on the PL test circuit. Each step confirmed the acquisition of electrical variables, ESP32 processing, GSM/GPRS communication, data recording on the IoT-SCADA platform, and generation of operational indicators. The process also verified historical data storage and the recording of operational events. The variables controlled during the tests included voltage, current, AP, consumed energy, frequency, and PF.

The recorded AP was used to estimate the number of working light fixtures from the average power of each fixture. This assessment was compared with the expected value, and the control threshold was set.The process considered the circuit's behavior over time. The recorded data enabled the determination of the circuit state, identification of operating-period consumption, and observation of daily variations in power consumption. The profiles obtained were used to distinguish stable operation from repetitive variations of unknown origin. Figure 4 shows the functional test bench with the supervision node, platform-access computer, and test verification equipment.



Fig. 4 Experimental setup used for functional validation of the IoT public lighting supervision system

The evaluation was limited to checking the integration and functional response of the measurement, processing, communication, visualization, luminaire estimation, alert generation, and historical record stages. At this stage, no metrological comparison with a certified instrument was performed to determine the error of the measured variables, in accordance with the need for reference-based assessment procedures in electrical measurement and power-quality evaluation [13, 14].

4. Results

4.1. IoT-SCADA Monitoring Interface

The IoT-SCADA platform received and displayed the variables acquired by the node during circuit operation. Under a representative functional-test condition, 218.5 V, 5.844 A, 892.3 W of AP, 82658 Wh of accumulated energy, and a PF of 0.7 were recorded. For that same record, the system estimated 13 luminaires in operation and kept the node status as ONLINE.

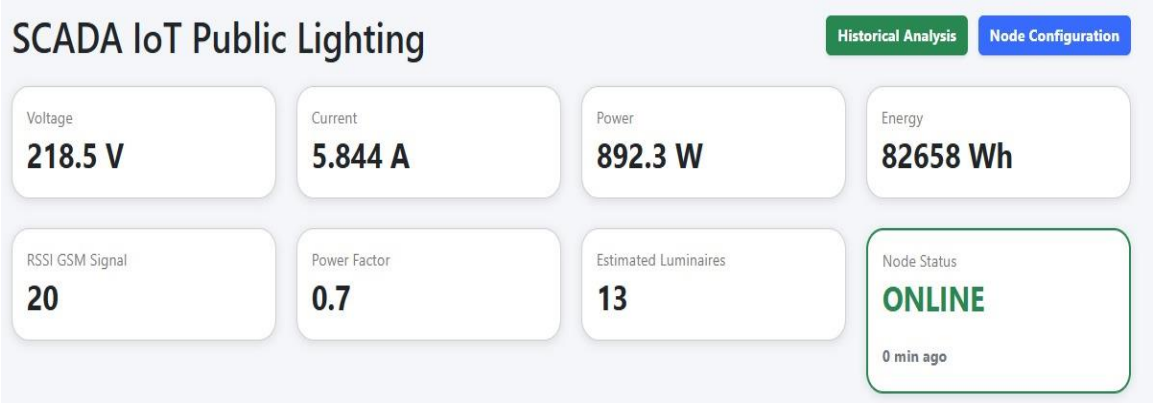


Fig. 5 IoT-SCADA interface during real-time supervision of the public lighting circuit

Figure 5 presents the interface that consolidates the electrical variables, GSM signal strength, estimated number of luminaires, and node communication status on a single screen.

4.2. Luminaire Estimation and Alert Recording

The operational estimate was obtained from the measured AP and the average power configured per luminaire. For a reference condition of 14 luminaires, the system recorded an estimate of 11.9 units in operation.

The difference from the expected value triggered the alarm logic for a load reduction exceeding the configured criterion. The generated event simultaneously preserved the expected number of luminaires and the estimated value. At another stage of the operating cycle, the system recorded a circuit shutdown with an accumulated consumption of 12103.0 Wh and a deviation of -0.1%. Figure 6 brings together both events recorded by the platform.

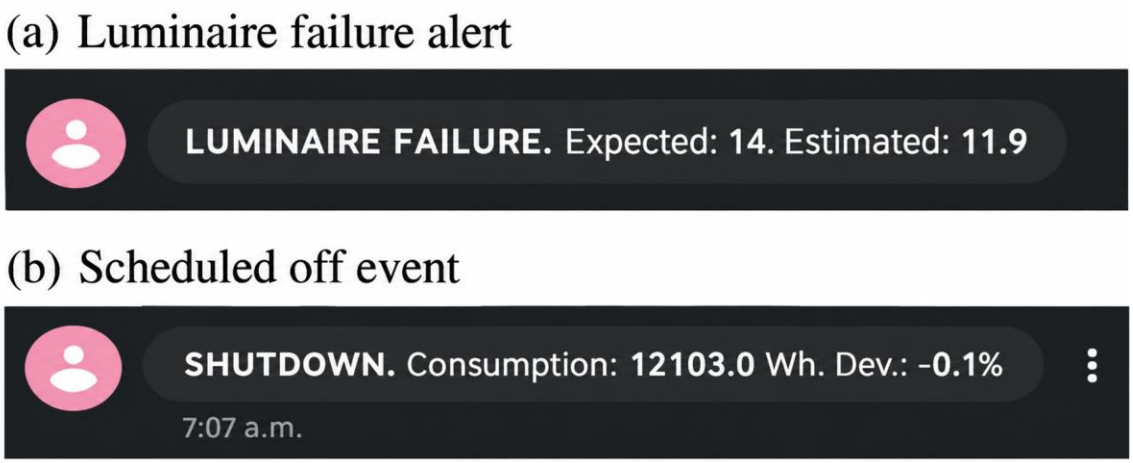


Fig. 6 Events recorded by the IoT system, (a) alert due to the difference between expected and estimated luminaires, and (b) shutdown event with accumulated consumption and deviation from the expected condition.

4.3. Time Profile of Power During Normal Operation

The historical record made it possible to reconstruct the circuit operating cycle from AP. The profile showed a transition from values close to zero to the operating level, followed by a prolonged interval with power between approximately 800 and 920 W. After the service period, power returned to values near zero. Overall, the effects of the control function are shown in Figure 7.

The startup, ordinary operation, and shutdown stages can be discerned in a single time series. After the initial startup, which caused sudden fluctuations, the system stabilized to a relatively even load. The final drop of power to near zero marks the end of the recorded operating cycle. Its time profile with repetitive load variations provided a reference for the temporary nature of profile variations throughout the operation phase.

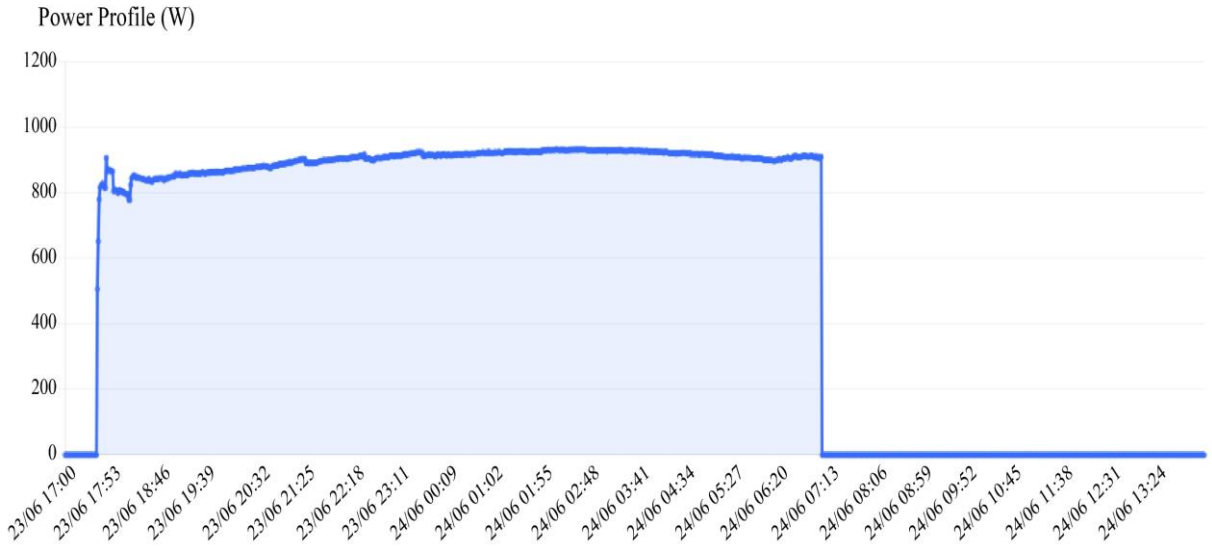


Fig. 7 Historical power profile during startup, operation, and shutdown of the public lighting circuit

4.4. Time Profile with Repetitive Load Variations

A second historical record exhibited repetitive variations in the operating power. After startup, the signal cycled between two load levels, neither of which reached the near-zero level associated with a complete circuit shutoff. Figure 8 illustrates the behavior and shows the circuit remains energized; however, it repetitively decreases from the upper power level.

The profile of the recorded oscillations differs from the behavior shown in Figure 7. The reference condition has a stable power band during service, whereas the second record shows superimposed load changes within the same operating interval. The system records these changes so they can be retrieved later for analysis of intermittency, partial disconnection, or unpredictable load changes.

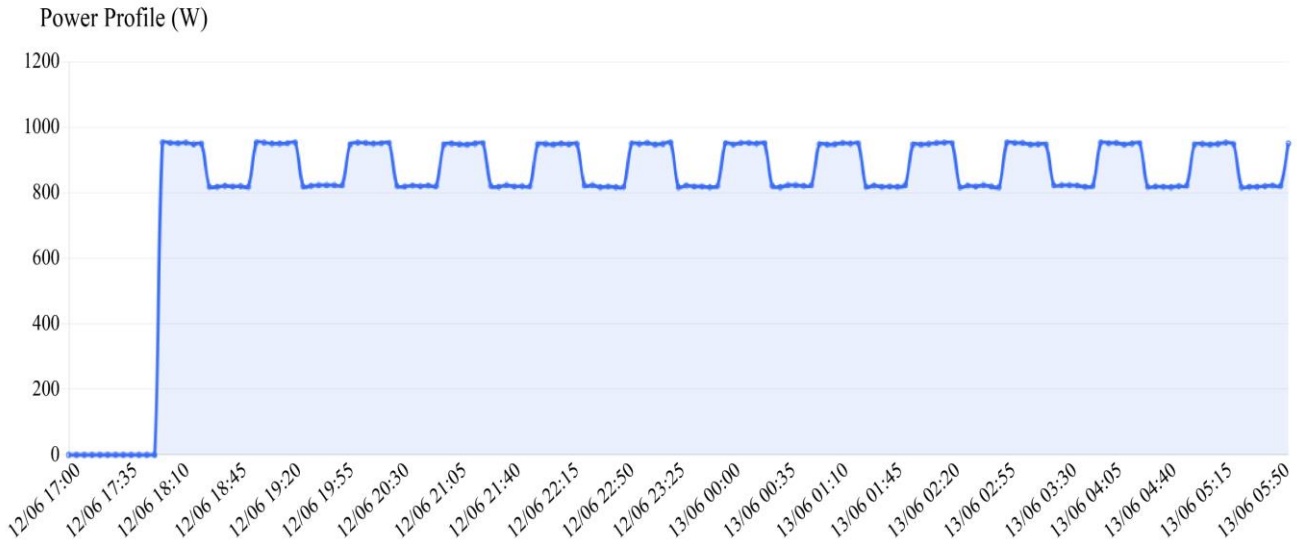


Fig. 8 Historical power profile with repetitive variations during the operating period of the public lighting circuit

4.5. Functional Validation Summary

Table 4. Summary of the functional validation of the IoT system

Evaluated function	Observed evidence	Functional result
Acquisition and visualization	Recording of voltage, current, AP, energy, and PF in IoT-SCADA	Electrical variables received and displayed
Node connectivity	ONLINE status during acquisition	Active remote communication
Luminaire estimation	Conversion of measured power into the estimated number of operating units	Estimate available on the platform
Alert generation	Event with 14 expected luminaires and 11.9 estimated luminaires	Alert recorded for load reduction
Shutdown record	Event with 12103.0 Wh and a deviation of -0.1 %	Stored operating cycle
Historical analysis	Profiles of normal operation and repetitive variations	Recorded temporal behavior

The validation integrated the following functions: electrical acquisition, transmission, visualization, luminaire estimation, alert generation, and historical storage. As shown in Table 4, the functions integrated during validation and the evidence obtained from the tests are summarized.

The test sequence confirmed the functional integration among measurement, processing, communication, and remote supervision. The validation performed did not quantify the metrological error of the electrical variables against a certified instrument; therefore, the results characterize system operation and not its accuracy class.

5. Discussion

5.1. Scope of Electrical Supervision at the Circuit Level

The implemented architecture supervises PL from the aggregated behavior of the load, not from the individual status of each luminaire. This decision establishes the system's utility and range. At the supply point, the AP can be converted to an estimate of working units and can be kept as a time series to

detect service period variation. The information in Figures 5 to 8 relates to these two levels of analysis: instantaneous circuit condition and evolution of the load. Previously reported IoT-based PL systems have concentrated an important part of their functions on remote control, lighting regulation, automation, and energy efficiency. The evaluated system adopts a different function: it uses aggregated electrical variables as input to interpret the operating status of the circuit. This approach avoids installing an independent supervision unit at each lighting point, although it loses the ability to directly locate which luminaire produces a deviation.

The integration of electrical measurement and remote supervision also aligns with IoT applications for electrical networks and the monitoring of alternating-current parameters, in which voltage, current, power, and energy are used to characterize the load and support operational management [7, 8]. In this work, the difference lies in the subsequent use of active power: the measured value is not limited to the energy record but is related to N_{inst} and P_{lum} to obtain N_{est}.

5.2. Scope of Luminaire Estimation and Relationship with DT1 and DT3

The usefulness of N_{est} depends on the aggregated active power, maintaining a sufficiently stable relationship with the number of luminaires that remain energized. Under that condition, a reduction in P_{meas} with respect to P_{exp} translates into a decrease in the estimated number of operating units. The event recorded with 14 configured luminaires and 11.9 estimated luminaires constitutes a case of that relationship, but by itself, it does not identify which unit produced the reduction or establish the physical nature of the deficiency.

The connection between DT1 and DT3 is based on the expected effect of these deficiencies on the circuit's active load. In the case of an inoperative lamp or a missing PL unit, the total load in the circuit decreases. Other types of defects, such as incorrect orientation, tree interference, or diffuser damage, may not significantly affect the measured power and may therefore be overlooked. The architecture proposed in this paper is thus more adequate for identifying defects associated with the absence of a load than for addressing the full range of shortcomings in PL. The evaluation also depends on the value assigned to P_{lum}. A "typical" average power value that does not reflect the luminaires' behavior results in differences in N_{est}, even though all components remain active.

Changes in operating voltage, aging of luminaires, manufacturing tolerances, conductor losses, or power factor may affect. P_{meas}, even in the absence of incipient faults. Thus, the circuit's electrical characteristics must be considered when setting the alert threshold, rather than treating it as an acceptable threshold for an installation. Unlike individual supervision schemes, this architecture uses the collective electrical response for the overall circuit. This reduces the overall instrumentation needed, but also decreases the spatial resolution for the supervision.

A departure from the set reference can be detected at the circuit level; however, identifying the specific circuit or component and the nature of the issue is only possible through on-site inspection. The real value of the method lies in knowing which circuits to review to determine whether they require user engagement beyond scheduled maintenance or inspections. This scope of operation is aligned with the research funding, and it should not be expanded to identify DT1 or DT3 automatically.

5.3. Operational Usefulness of Alerts and the Historical Record

With observational supervision, deviations can be identified when they occur. However, this control method does not provide information on the deviation or whether it occurs repeatedly. The historical record provides information about the operating cycle as a whole. One profile exhibited a single power cycle, including startup, service interval, and shutdown. The second profile showed repeated load variations while the circuit remained in operation.

The two records exhibit differences that cannot be determined by a single observation. A single instance of a power change may be associated with a normal transition. However, multiple instances with the same variation during the service interval create a pattern that may be described as intermittency, a disconnect, or a change in an unknown load. The causality for the pattern may not be immediately apparent. Consequently, a pattern is recorded for further study and analysis. On- and off-records provide a connection to the energy consumed during the operating interval. This eliminates the need to solely analyze consumption based on the scheduled switching times. With the shutdown, a recording of both 12103.0 Wh and a deviation of -0.1% was made, along with the time the event occurred. Thus, the recorded values may be compared with the duration that the lighting was energized.

Alerts and historical records play different roles in the supervision process. An alert is defined by an exceeded deviation criterion. A historical record is the sequence of events that occurred before and after the criterion was exceeded. Considered together, these data help prioritize where to direct resources for inspection more than supervision, which is limited to the ONLINE/OFFLINE status of a node or a reading of instantaneous power, because the former incorporates the persistence, repetition, and timing of the event within the operating evaluation.

5.4. Comparison with Previous Work

Smart PL architectures have mainly used wireless networks, sensors, and distributed control units to modify the lighting level or supervise specific points. LoRa-based

systems have integrated measurement, communication, and remote regulation, while other proposals combine LED luminaires with lighting and motion sensors to adjust operation according to environmental conditions [15, 16].

Another line of work maintains the conventional infrastructure and adds connectivity for remote supervision. The adaptation of lighting controllers with high-pressure sodium lamps through web interfaces makes it possible to schedule times and query device status without completely replacing the existing installation [17]. In the system developed in this work, GSM/GPRS communication fulfills a different function: it transports electrical measurements and operational indicators from a single circuit node to the IoT-SCADA platform.

Automatic fault detection has been addressed through distributed architectures capable of identifying non-operating luminaires and transmitting information associated with the affected point [18]. Systems that combine lighting control, supervision through a cloud platform, and real-time error detection have also been proposed [19]. These approaches have luminaire-level information and can achieve greater spatial resolution. The architecture evaluated here works at the circuit level: P_{meas} is related to P_{lum} and N_{inst} to obtain N_{est}, so a load decrease can activate an alert without directly locating the unit that produced the deviation.

This difference defines a trade-off between distributed instrumentation and supervision resolution. The proposed node does not require an independent measurement unit at each luminaire to estimate the reduction in the number of operating units; instead, physical identification of the deficiency continues to depend on a subsequent inspection. This work did not compare installation costs, maintenance, or reliability with distributed architectures, so an economic advantage should not be attributed to the configuration used.

IoT systems applied to electrical networks have also used voltage, current, power, and energy to characterize loads and transmit information to remote platforms [7, 8]. In this work, the functional difference lies in the subsequent treatment of AP: the measurement is used to estimate luminaires' operating conditions, generate alerts for load deviations, and reconstruct temporal circuit profiles. The contribution depends on this functional integration and not on the individual novelty of the PZEM-004T, ESP32, A9G, or the web interface.

5.5. Limitations and Scope of the Validation

The system has been functionally validated. In this phase, the results from the PZEM-004T v3.0 were not verified with a calibrated electrical analyzer; thus, no relative error, repeatability, or metrological accuracy can be assessed. Measurement tests with different load levels and reference instruments are necessary for characterization of these parameters [13, 14]. The metrics related to detection, such as false-alarm rate and sensitivity to different load reductions and the error of N_{est} The number of known operational luminaires was also not quantified. The historical profiles confirmed the recording of stable conditions and variations, but this does not represent a statistical assessment of the alert algorithm. GSM/GPRS communication was validated from a functional perspective; however, communication behavior was not verified over extended operation time. Availability, latency, reconnection time, and reliability parameters need to be assessed to evaluate system performance when supervision is provided through a cellular network with varying coverage. The next stage will provide a metrological comparison with certified instruments, controlled tests with varying numbers of luminaires, validation of alerts, and long-term communication tests. In this stage, the goal is to move from functional validation to quantitative validation of the system's accuracy, detection capability, and availability.

6. Conclusion

The developed IoT system enabled supervision of PL circuits via aggregated electrical acquisition, embedded processing, GSM/GPRS communication, and remote visualization on an IoT-SCADA platform. The integration of the PZEM-004T v3.0, ESP32, and A9G enabled recording of voltage, current, AP, energy, frequency, and PF, while also preserving information on connectivity, operational events, and historical profiles. AP was used as a proxy for the number of luminaires. During the tests, a configuration of 14 luminaires resulted in an event with an estimated value of 11.9, triggering the load-reduction alert because the estimated reduction exceeded 1 luminaire. The system recorded the completion of an operating cycle with a total consumption of 12103.0 Wh and a deviation of -0.1 %. These records couple energy control with operational metrics without requiring individual control for each lighting point.

Temporal monitoring enabled the identification of stable power operating conditions and other conditions with periodic variations during the service period. Retaining the circuit on/off events along with the load evolution provides temporal information that cannot be obtained from a single measurement. Load-loss deviations can be treated as warnings of DT1 or DT3, but identifying the deficiency and its location still requires an inspection.

The scope of this research was restricted to assessing the system's functional operation and did not include establishing metrological accuracy using certified equipment or measuring GSM/GPRS availability and reliability parameters. Achieving the operational goals of the system requires controlled tests with known numbers of luminaires, comparison with reference equipment, confirmation of the alerts, and prolonged operation of the cellular link. These measurements will help determine the estimation error and adjust the supervision threshold to determine the availability of the system during real operation.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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