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Design of a educational electrical energy consumption meter for residential use

Diseño de un medidor didáctico de consumo de energía eléctrica para uso residencial

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Abstract

This study presents the design and implementation of an interactive, user-friendly electronic meter for energy consumption measurement. The proposed system serves as an educational tool for teaching electrical installations, offering a practical and hands-on learning experience. The primary objective is to develop an interactive meter tailored for residential use, capable of providing real-time feedback on energy consumption. Its deployment in educational institutions enhances the comprehension of technical concepts, while also proving beneficial in community outreach workshops focused on residential electrical systems. The system consists of a battery-powered setup featuring an ESP32 module for voltage and current data acquisition, an SPI-connected LCD screen for local data visualization, and a WiFi module for real-time data transmission to a cloud-based database. Designed to be reproducible, cost-effective, and open source, the system represents an accessible and versatile solution for energy monitoring applications. Validation tests were conducted over five months in both laboratory and residential environments. The results demonstrated high measurement accuracy, with error margins below 5% for voltage, current, energy consumption, and estimated costs. These findings confirm that the developed interactive energy meter is a reliable and effective tool for monitoring residential energy usage while fostering educational and community-based learning experiences.

Keywords: database, consumption, energy, electric energy meter, residential

Resumen

Este trabajo presenta el diseño e implementación de un sistema de medición de consumo de energía eléctrica mediante un medidor electrónico interactivo y amigable para el usuario. Este sistema constituye una herramienta didáctica para la enseñanza de instalaciones eléctricas, ofreciendo una experiencia práctica y educativa. El objetivo principal es desarrollar un medidor interactivo para uso residencial que proporcione retroalimentación en tiempo real sobre el consumo energético. Su implementación en instituciones educativas no solo facilita la comprensión de conceptos técnicos, sino que también resulta valiosa en talleres prácticos de vinculación social enfocados en instalaciones eléctricas residenciales. El sistema consta de una batería, un módulo ESP32 para adquirir datos de voltaje y corriente, una pantalla LCD conectada por SPI para visualización local y un módulo wifi que transmite los datos a una base de datos en la nube. Su diseño es reproducible, económico y de código abierto, lo que lo convierte en una solución accesible y versátil. Pruebas realizadas durante cinco meses en laboratorios y domicilios validaron su precisión, con márgenes de error menores al 5% en voltaje, corriente, energía y costos estimados. Los resultados confirman que este medidor interactivo es una herramienta eficaz, viable e interactiva para el monitoreo energético en entornos residenciales.

Palabras clave: base de datos, consumo, energía, medidor de energía eléctrica, residencial

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1. Introduction

Promoting the efficient use of electricity is a fundamental component of a country's development plans. Achieving this goal requires effective demand management, which relies on accurately measuring and monitoring electricity consumption by end users [1].

In Ecuador, energy savings in the residential sector remain low. Although some energy efficiency plans have been implemented, there are no permanent or long-term initiatives in place [2]. Nonetheless, a significant portion of the population recognizes the importance of energy efficiency [3], particularly due to its potential for reducing electricity costs and achieving economic savings [4].

Energy-saving practices are often hindered by the misinterpretation of utility bills [5]. Moreover, these bills typically lack real-time feedback mechanisms that enable consumers to evaluate the effectiveness of their energy-saving efforts [6]. Consequently, even conscientious consumers are unable to receive immediate feedback to fully recognize and appreciate the benefits of adopting improved electricity consumption habits [7].

Technological advances in the design and construction of energy measurement systems have significantly progressed. These advancements have led to the development of electronic meters that record energy consumption exclusively in kilowatt-hours (kWh). However, such meters often present challenges for consumers to interpret and fail to effectively raise awareness of electricity usage [8].

Currently, smart meters provide more detailed data than conventional meters [9]. This enhanced information enables consumers to develop better energy consumption habits and facilitates the implementation of effective energy-saving techniques [10].

Measurement based on continuous monitoring and data recording provides users with comprehensive insights into energy consumption, including details on usage quantities, patterns, and associated electricity costs. This approach facilitates optimal resource management, identifies system losses, and enables targeted actions to improve household energy efficiency [11].

In response to these challenges, an interactive electric energy meter is being developed for the residential sector. The meter is designed to provide real-time information to users through a graphical interface displayed on an LCD screen. The presented data include energy consumption, voltage levels, electric current, power, and estimated monthly billing costs, with a maximum measurement error of 5%. Furthermore, the system incorporates a cloud-based database that stores hourly historical data on electric energy consumption.

This meter is an essential educational tool for promoting knowledge of residential electrical installations. It facilitates the development of more advanced prototypes with enhanced functionalities, ultimately contributing to the efficient use of electrical energy.

1.1. State of the art

Estrada [12] designed and developed a prototype for measuring energy consumption, which was validated in a laboratory setting by collecting data at 3-minute intervals over a 4-hour period. The study highlighted the significance of providing households with dynamic and interactive energy consumption data. Additionally, it emphasized the limitations of current residential meters, which require manual readings by an operator. This process often introduces accuracy errors, leads to suboptimal service quality, and results in dissatisfaction among residential users.

Samaniego and Velesaca [13] implemented an electronic energy meter for residential use, noting that a significant percentage of users paying for electricity services each month are unaware of the rates charged by the distribution company. The proposed meter addresses this issue by sending text messages to users, ensuring they remain consistently informed about their energy consumption and associated costs.

Vashist and Tripathi [14] developed and implemented a smart energy meter integrated with real-time pricing in an Android-based web application. However, the system lacks daily or monthly measurement capabilities, which limits the assessment of the device's accuracy. Similarly, Patel et al. [15] designed and deployed a smart meter with load-forecasting capabilities for residential customers. The system utilizes GSM communication and transmits AT commands via a microcontroller. However, the operators noted that this approach may incur higher costs due to the transmission of messages.

In [16], the design and implementation of an electronic meter are described, enabling real-time monitoring of electricity consumption. The system allows users to visualize both current and historical consumption through a graphical interface on a computer. However, this study focuses on more generalized residential solutions, in contrast to the device presented in this article, which employs specific technologies such as ESP32 and Firebase for cloud-based data logging.

The study conducted by Muñoz et al. [17] focuses on the design and implementation of an integrated system for both local and remote monitoring of electricity consumption across various areas of a household. This system also measures the current consumed at one-minute intervals by different loads connected to the domestic electrical grid. In contrast, the prototype presented in this work employs open-source technology and is portable, cost-effective, and easier to replicate in educational laboratories. Moreover, studies presented in [18] and [19] examine the implementation of advanced metering systems, commonly referred to as smart meters, and address the challenges associated with promoting responsible electricity consumption. These findings align with the objectives of this study, underscoring the importance of accurate measurement as a fundamental tool for optimizing energy consumption and fostering energy-saving practices through historical data analysis.

Morales and Peña [20] present the design and implementation of a Home Energy Management (HEM) system within the energy sector in Colombia. The system monitors the energy consumption of typical household devices, allowing users to analyze individual device usage and develop strategies to reduce energy consumption at home. While both the HEM system and the prototype proposed in this work promote the adoption of monitoring technologies to encourage energy savings, the interactive meter presented here offers notable advantages: it is cost-effective, user-friendly, and easy to build. Additionally, its integration of internet connectivity enhances its applicability in social and educational contexts, significantly contributing to the academic and practical development of both students and end users.

The studies reviewed above emphasize the importance of household energy consumption measurement systems. However, none propose the design and implementation of a cost-effective system that incorporates energy backup, is easy to replicate, and is simple to operate, while offering real-time data access both locally (via a touchscreen interface) and digitally (through a database). The system developed in this work is intended for academic purposes and has been tested and validated in a real household over a five-month period. It aims to serve as a foundation for community outreach projects and practical workshops, enabling participants to understand system operation, gain insight into how electricity services are billed in Ecuador, and adopt measures to promote energy efficiency and savings. Furthermore, this study provides the complete technical documentation required to build the meter, underscoring its contribution to the field of residential electrical installations.

The system developed in this research can be utilized in classrooms as an educational tool to teach students about residential electrical installations, serving as a practical example of a didactic monitoring system.

Table 1 presents several studies on electricity consumption meters, examining the methods, error correction techniques, costs, platforms, and technologies employed. These studies highlight the importance of implementing such meters in households, even with basic functionalities, such as real-time reporting of consumption and cost data, to encourage energy-saving behaviors and promote the rational use of energy by consumers.

Table 1. Related studies on electricity consumption meters in the residential sector

Article	Analyzed characteristic
[21]	Connectivity
[22]	Monitoring method
[23]	Platforms
[24]	Technology
[25]	Evolution

Arévalo et al. [26] highlight that limited research has focused on analyzing the energy consumption habits of residential users using digital meters that provide real-time access to historical consumption data. This capability enables users to take informed actions to effectively reduce their electricity consumption. Similarly, Alahmad et al. [27] emphasize that altering consumer behavior plays a critical role in reducing residential energy usage. Their study examines the impact of digital meters on residential energy consumption rates in a metropolitan area, raising awareness among residents about their electricity consumption patterns and the environmental benefits of energy savings.

Building on these findings, this research aims to design, develop, and validate a cost-effective and easily replicable didactic system for measuring and recording voltage, current, energy consumption, and electricity billing costs in households. The system is designed to facilitate knowledge dissemination in the field of residential electrical installations. To achieve this, low-cost sensors are employed to monitor the household electrical system, enabling the acquisition of accurate energy consumption data. The obtained values are compared with those recorded by conventional meters and measurement instruments, such as multimeters, to verify the margin of error and ensure the system's accuracy and reliability. The system developed in this study can be further enhanced to improve data accessibility and reduce costs in similar projects [12–17]. Additionally, it holds significant educational potential as a practical tool in university laboratories and educational centers for teaching residential electrical installations. By enabling students to understand the operation of interactive, user-friendly energy consumption meters, the system fosters the development of strategies to promote energy efficiency in households.

2. Materials and methods

This section outlines the stages of the project development, detailing the materials and methods employed. The proposed system is divided into two main components:

1. Electrical-Electronic system

2. Data measurement and logging system

Figure 1 illustrates the primary components of the energy meter developed in this study.

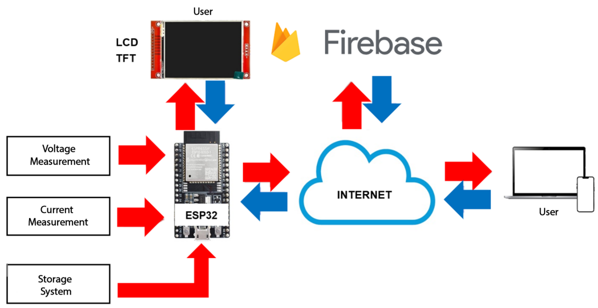

Figure 1. Primary components of the residential didactic energy meter

2.1. Electrical-Electronic system

The meter's power supply was designed with an integrated protection system utilizing a fuse. The design features a transformer that steps down the voltage from 120 VAC to 12 VAC, paired with a diode bridge for rectification and battery charging. A relay automatically selects the system's power source, seamlessly switching to the battery as the primary power supply during a power outage. Capacitors ensure a temporary voltage supply during this transition, maintaining uninterrupted system operation. Figure 2 illustrates the electrical schematic of the power supply and charging system.

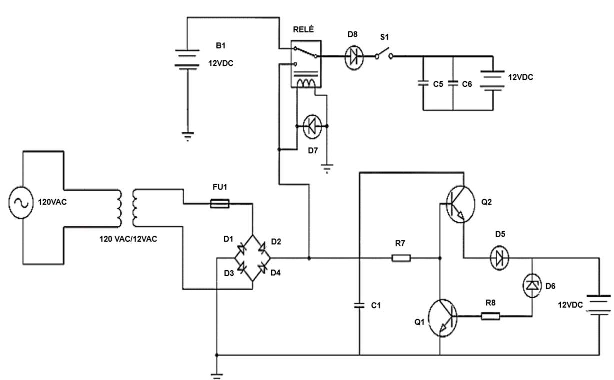

Figure 2. Power supply circuit

The design of the conditioning circuits relies on the EmonLib library [28], which computes active power, apparent power, power factor, RMS voltage, and RMS current using discrete-time equations for these parameters. Therefore, preserving the alternating signal after conditioning is essential to ensure accurate measurements.

The alternating voltage and current signals are sampled by the microcontroller, with both signals obtained through transformers. The conditioning circuits for these signals share a similar design. For the voltage signal, a voltage divider is used to scale it within the limits permitted by the analog-to-digital converter (ADC) inputs of the microcontroller. A second voltage divider introduces a 1.65 VDC offset to the scaled alternating signal to prevent negative values during voltage measurement. This offset corresponds to half of the maximum voltage allowed by the ADC inputs. Figure 3 illustrates the schematic of the voltage signal conditioning circuit.

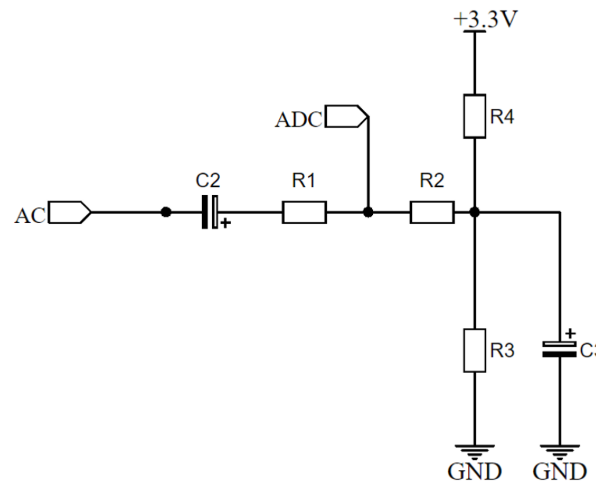

Figure 3. Voltage conditioning circuit

To determine the resistor values for the first voltage divider, Equation (1) is applied. The maximum output voltage of the divider (V_0) must remain within the allowable maximum limits of the ADC inputs while accounting for variations in the grid voltage (V_s).

$$V_0 = V_S \left(\frac{R_2}{R_1 + R_2} \right) \tag{1}$$

Where, V_s is the voltage on the secondary side of the transformer; R1 is the fixed resistor of the voltage divider, V_0 is the output voltage of the divider, and R_2 is the resistor to be determined.

This circuit ensures that when the grid voltage reaches its maximum of 129.60 VAC, the microcontroller receives an alternating voltage ranging between 2.40 V (maximum) and 0.80 V (minimum). This design prevents negative voltages while preserving the integrity of the alternating signal.

For the current conditioning circuit shown in Figure 4, a load resistor is required on the secondary side of the current transformer to generate a voltage signal suitable for sampling. The value of this resistance is determined using Equation (2).

$$R_L = \frac{(N_{CT})(V_{CT})}{1} \tag{2}$$

Where, V_{CT} is the required voltage on the secondary side of the current transformer; I is the maximum current to be measured; N_{CT} is the transformation ratio; and R_L is the load resistance.

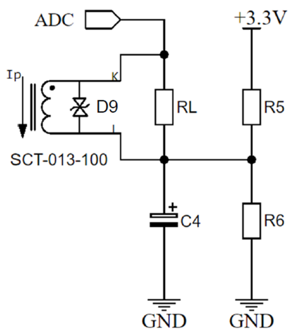

Figure 4. Current conditioning circuit

This voltage signal obtained across the load resistor is offset by 1.65 VDC using a voltage divider circuit, where resistors R_5 and R_6 each have a value of 30 $k\Omega$. This configuration ensures that the voltage provided by the divider is half of the microcontroller's supply voltage.

The capacitor C_4 provides a low-impedance path, allowing the AC signal current to flow to ground (GND)without passing through R_6. For a capacitance of 10 μF and a frequency of 60 Hz, the impedance is calculated as 265.26 Ω, which is significantly lower than the resistance of R_6.

With the selected resistors and capacitors, the microcontroller is ensured to receive an alternating voltage ranging from a maximum of 2.65 V to a minimum of 0.65 V when measuring the peak current of 66.72 A obtained from the load study.

A 32-bit microcontroller, specifically the ESP32 development board, is employed due to its analog input and digital output capabilities, which enable seamless integration with various components. Additionally, the ESP32 features an integrated circuit for internet connectivity. This microcontroller processes the voltage and current signals, performs the necessary calculations to determine the corresponding electrical parameters, and controls the LCD screen to display the relevant data. Furthermore, it transmits the information to a cloud database via WiFi. As a 32-bit system, the ESP32 provides enhanced precision for floating-point calculations and includes a 12-bit analog-to-digital converter, offering improved resolution during the sampling of voltage signals.

With the circuit designs completed, the printed circuit board (PCB) design, shown in Figure 5, was created using Easy EDA design software. The design incorporates several considerations, including connections for the TFT screen, a ground plane to minimize electromagnetic interference (EMI), the avoidance of 90° bends in traces, and adherence to standard sizes for electronic components. It is important to note that, due to the type of connection required for the LCD screen and its touch functionality, the same SPI port of the microcontroller was utilized. Consequently, cable bridges were implemented on the top layer, indicated in red in the PCB design.

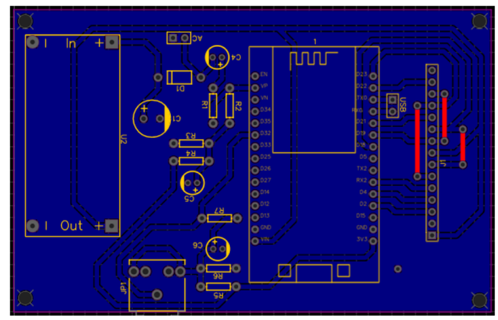

Figure 5. PCB Design

The design of the meter case was developed considering the dimensions and arrangement of all required components, including the transformer, battery, electronic board, power button, relay, screen, and holes for screws and wires. A suitable design was selected to meet the functional requirements of the meter and was created using 3D modeling in Fusion 360 software. Figure 6 illustrates the design of the meter case.

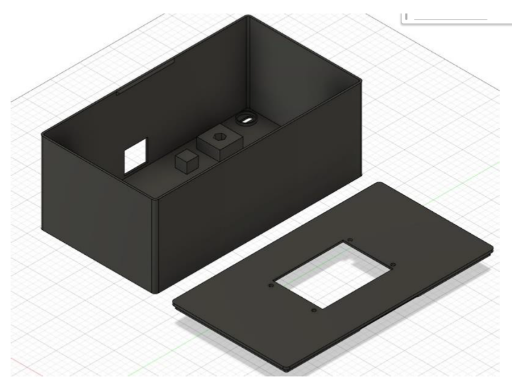

Figure 6. Design of the meter case

2.2. Data measurement and recording system

The measurement programming code was developed using the Arduino IDE, using multiple libraries essential for various processes, such as the calculation of electrical parameters, control of the TFT screen with touch functionality, internet connectivity, and connection to the Firebase database.

The microcontroller utilizes the current date and time, obtained from the internet, to record energy consumption values in the database corresponding to each hour of the day. Based on the measured energy data, the economic cost of consumption is calculated. This data is reset every 30 days and archived in the historical records. The monetary calculations are performed according to the tariff schedule by consumption range provided by Empresa Eléctrica Quito [29].

The flowcharts detailing the measurement system, signal conditioning, and data recording processes are presented in Figures 7 and 8.

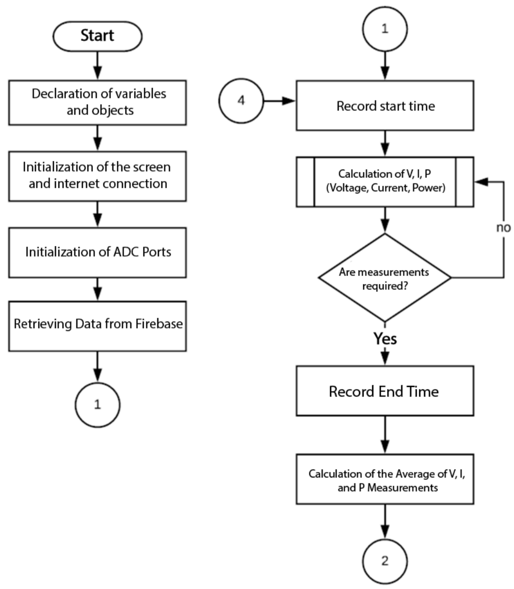

Figure 7. Flowchart for measurement and data recording system - Part 1

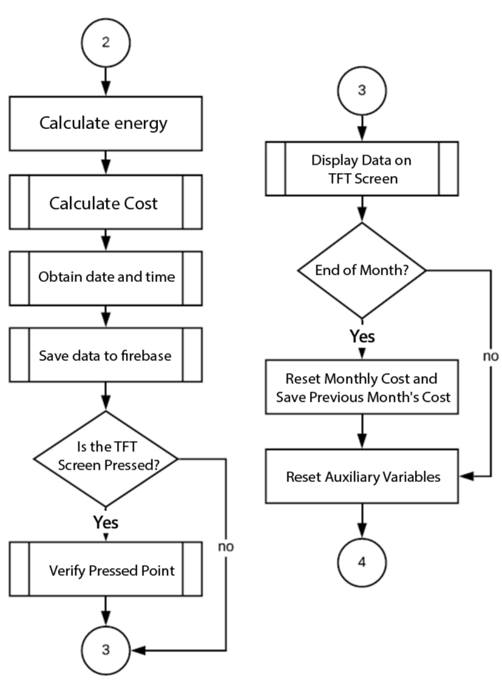

Figure 8. Flowchart for measurement and data recording system - Part 2.

Wi-Fi connectivity enables the meter to store recorded energy consumption data in a database. Key parameters relevant to the user, including power, voltage, current, consumed energy, and energy cost, are logged and stored. In addition to providing real-time feedback on electrical variables, the database remains accessible to users at any time from any internet-connected device. The primary advantage of using wireless communication, particularly Wi-Fi, is the ability to monitor measurements in real time. To access the database, users must have a Gmail account, which allows them to be added as viewers in the Firebase project. Once registered, a unique URL is provided, granting access to the real-time database via any web browser on a mobile device or computer, enabling users to monitor their energy consumption conveniently.

3. Results and discussion

Considering the design parameters and characteristics of the energy meter for residential use, a didactic, cost-effective, and easily reproducible system was developed. The system interactively displays real-time consumption data to the user, both on a local TFT screen and through an online data log accessible from any internet-connected device.

The printed circuit board (PCB) was fabricated using the CNC method on fiberglass material, while the meter case was constructed via 3D printing.

Once all components were prepared, the final assembly of the meter was carried out, integrating all elements within the case. A data bus was implemented for the TFT screen connection, ensuring quick and efficient assembly and disassembly. Figure 9 presents the completed meter, including its screen, which displays the corresponding real-time data.

Figure 9. Educational meter for residential energy consumption

To ensure the accurate measurement of electrical variables, the meter was installed near the load center of the residential home under study, as illustrated in Figure 10. This location centralizes energy distribution to the various circuits of the house, minimizing losses and ensuring representative measurements. The current transformer was connected in series with the main power phase to acquire a signal proportional to the total system current. Meanwhile, the voltage transformer was connected between the phase and neutral terminals, providing a reduced and representative signal of the line voltage. Both signals were conditioned through circuits designed to adjust their amplitude and introduce an offset, ensuring they remain within the acceptable range of the microcontroller's analog-to-digital converter (ADC) inputs. This configuration ensures accurate data acquisition and enables subsequent processing for the calculation of power, energy, and other relevant parameters.

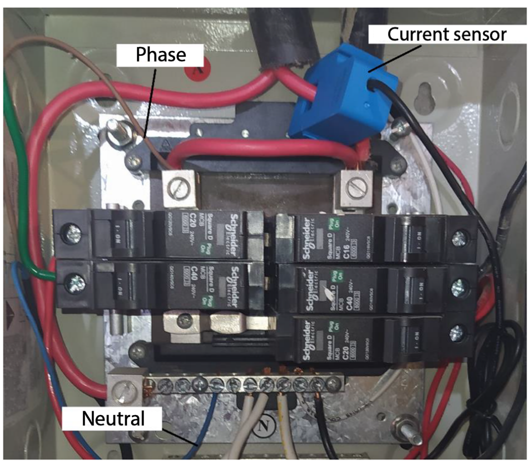

Figure 10. Electrical connections at the load center

For the calibration of the voltage and current sensors, measurements were performed using a multimeter as the reference for the residential grid voltage and a clamp ammeter for current measurements.

The calibration constants were iteratively adjusted within the measurement algorithm to minimize deviations between the meter readings and the reference instrument measurements.

Multiple voltage and current measurements were conducted at various times throughout the day. When discrepancies were identified between the readings from the multimeter and those from the meter, the voltage and current calibration constants were adjusted using Equation (3).

$$K_n = K_a \left(\frac{M_p}{M_m} \right) \quad (3)$$

Where, K_n is the new calibration constant, K_a is the previous calibration constant, M_p is the reading from the multimeter, and M_m is the reading from the meter.

The NTE INEN-IEC 62053-21 standard [30] specifies that, for residential systems, meters must conform to Class 1 or Class 2 requirements. These include a nominal operating frequency of 60 Hz, an LCD display with the number of integer digits determined by the requirements of the distribution companies, and an admissible error limit of 5% of the nominal values.

In the test household, daily measurements recorded by the conventional meter were documented. Additionally, an analysis of electricity bills from the past five months was conducted. Using this data, along with a load study, the average daily and monthly consumption was determined.

As presented in Table 2, the consumption values obtained from the three studies—load study, daily measurements, and electricity bills—are consistent, thereby validating the data and confirming the functionality of the constructed meter.

Table 2. Average electricity consumption of the test household

Type of consumption	Load Study (kWh)	Daily Measurement (kWh)	Electricity Bills (kWh)
Daily	6.84	6.62	6.32
Monthly	202.32	198.57	189.60

With the household's average energy consumption levels established, an analysis was conducted to determine the voltage and current levels the meter must measure. For voltage, the permitted variations in the residential sector, as specified bythe Energy and Natural Resources Regulatory and Control Agency (ARCERNNR), are ±8% [31].Given the standard residential voltage of 120 VAC, the permissible range extends from a maximum of 129.60 VAC to a minimum of 110.40 VAC. The maximum current, on the other hand, depends on the household's total power demand at full load.

For the system configuration in complex residential environments, the following aspects are considered:

- **Robust design for electrical variations**

  The device is engineered to withstand voltage fluctuations and measure peak currents up to 66.72 A. This design incorporates transformers paired with calibrated voltage dividers to ensure input signals remain within the microcontroller's operational limits. Conditioning circuits with offset adjustments are employed to prevent distortion of alternating signals. Additionally, the system includes a current transformer with a load resistance specificallycalculated using equations based on the expected maximum power.

- **Modularity for different residential configurations**

  The system is designed to be adaptable to standard single-phase residential systems and can be expanded to accommodate biphasic or triphasic configurations by adjusting the current and voltage sensors. Its compact design facilitates the integration of additional components, enabling the inclusion of more sensors or functions as needed.

- **Advanced sensor calibration**

  In environments with frequent fluctuations, the system supports recalibration of voltage and current constants using adjustment formulas derived from reference measurements, ensuring long-term accuracy. Furthermore, continuous testing can be conducted under varying conditions to correct deviations by applying absolute and relative percentage error calculations, with acceptable limits set below 5%.

- **Real-time interaction and feedback**

  The LCD screen provides real-time data on voltage, current, power, and costs, which is essential in residential environments where constant monitoring is required. Additionally, remote access to the database enables users to identify consumption patterns and detectanomalies from any internet-connected device.

- **Resilience to electrical interruptions**

  The system is designed to remain operational during power outages, ensuring uninterrupted monitoring and data recording. The design incorporates a relay that automatically switchesthe battery and the main power supply.

- **Adaptability to regulations and standards**

  The error limits, consumption rates, and recording frequencies can be adjusted to comply with regulatory requirements or to meet the specific-needs of the residential area.

- **Scalability for complex residences**

  The system offers the potential for implementing a network of interconnected meters to monitor entire residential buildings or areas with multiple housing units. Integration with IoT systems could enhance compatibility with home automation platforms, optimizing energy usage in conjunction with smart devices such as thermostats and solar panels. Furthermore, additional sensors could be incorporated to monitor variables such as electrical frequency and power quality, including harmonic distortion and voltage fluctuations.

3.1. Tests

Voltage and current tests were conducted by recording hourly measurements over a day (24 measurements). Figure 11 presents the measured voltage data. The comparison between the multimeter and the meter readings reveals an absolute and relative percentage error close to zero, with a mean absolute error (MAE) of 0.520. The mean absolute percentage error (MAPE) is also significant, with a value of 0.433%, well within the error tolerance of 5%. These results validate the accuracy of the system's voltage measurements during the conducted tests.

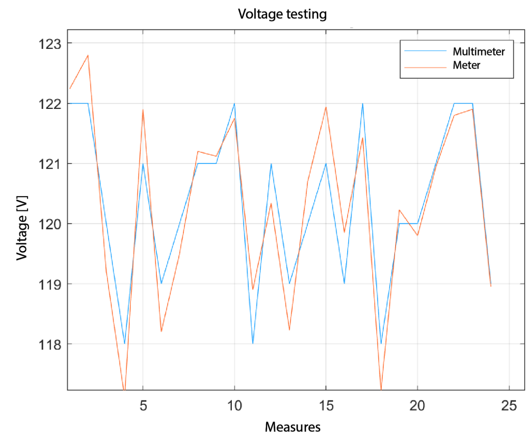

Figure 11. Voltage comparison between the multimeter and the proposed system

Figure 12 illustrates the measured current data. The comparison between the clamp meter and the system's meter readings reveals a mean absolute error (MAE) of 0.180. Additionally, the mean absolute percentage error (MAPE) is significant, with a value of 1.90%, which is well within the error tolerance of 5% as established by national regulations. These results confirm the accuracy of the system's current measurements during the conducted tests.

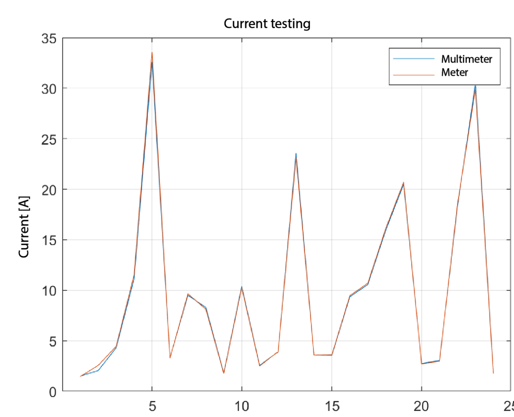

Figure 12. Current comparison between the clamp meter and the proposed system

After verifying the current and voltage measurements, the data storage process in the database was reviewed. It was confirmed that the information is stored daily in the desired format (DD-MM-YYYY) and that each record includes the corresponding hourly sub records (00:00–23:00). Additionally, it was verified that consumption values are updated hourly and reset at the start of each new day. The results are presented in Figures 13 and 14.

Figure 13. Daily records in Firebase

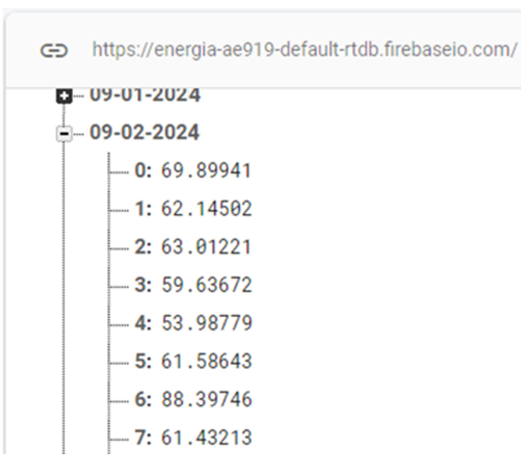

Figure 14. Hourly sub records in Firebase

Additionally, the accuracy of electrical energy measurement and cost calculation was validated. A comparison was conducted between the measurements obtained from the developed meter and those from a conventional meter, as well as between the energy costs calculated by the system and the economic values recorded on electricity bills over a five-month period.

Figure 15 presents the daily energy data measured by both the interactive meter and the conventional meter over a month, with measurements taken at the same time each day. Notably, unlike the developed interactive meter, the conventional meter does not report decimal values. Absolute and relative percentage errors were generally close to zero, with a mean absolute error (MAE) of 0.127 and a mean absolute percentage error (MAPE) of 1.90%. These results fall within the 5% error margin permitted by regulatory standards.

These results validate the performance of the developed meter, demonstrating its accuracy and precision in comparison with conventional instruments across various measurement parameters.

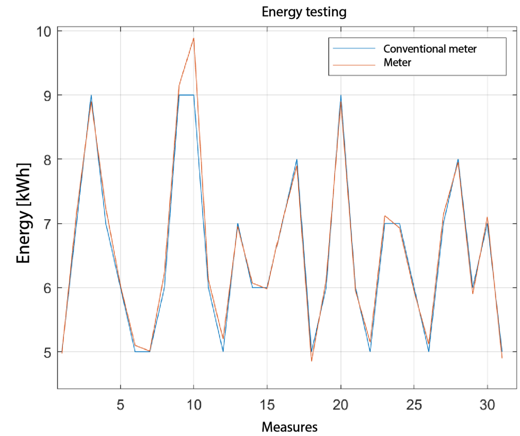

Figure 15. Daily energy comparison between the conventional meter and the proposed system

To verify the final operation of the interactive meter, energy consumption measurements recorded over 29 days in February 2024 were compared with the corresponding calculated economic values, as illustrated in Figure 16. These results were then contrasted with the data from the electricity bill for the same month, as shown in Figure 17.

Figure 16. Monthly record of the meter

Consumo Total	Unit of measure	Amount ($)
201,00	kWh	17,11

Figure 17. Values provided on the electricity bill

The user interface includes a touch-enabled button that allows navigation between two information windows. The first window displays the monthly energy consumption in kilowatt-hours (kWh) and the corresponding cost in US dollars. The second window presents real-time voltage, current, power, and the monetary value associated with the previous month's consumption.

Finally, measurements were conducted over approximately five months (from March to July 2024) to verify the reliability of the developed meter. The monthly energy data recorded by the meter, along with the corresponding values from the electricity bills, are presented in Figure 18 and Table 3.

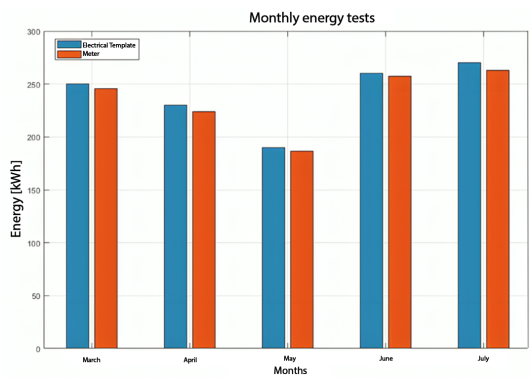

Figure 18. Monthly energy comparison between the electricity bill and the proposed system

Table 3. Comparison of monthly energy consumption

Months	Electricity bill (kWh)	Meter (kWh)	Absolute error (kWh)	Relative (error %)
March	250	247.8	2.2	0.88
April	230	228.8	1.2	0.52
May	190	188.4	1.6	0.84
June	260	257.6	2.4	0.92
July	270	267.3	2.7	1.00

Figure 19 and Table 4 present the monthly energy cost data calculated by the constructed meter alongside the values obtained from the electricity bills.

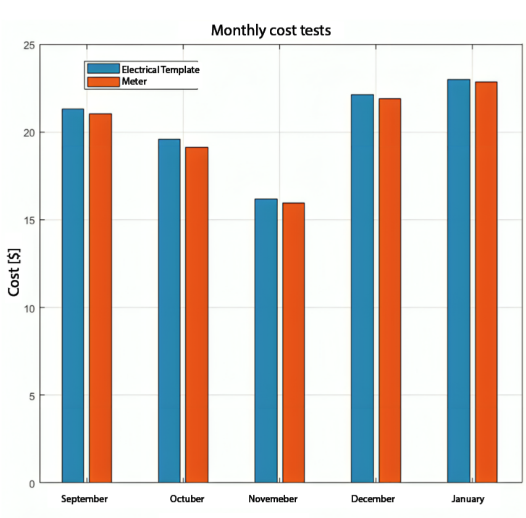

Figure 19. Monthly economic cost comparison between the electricity bill and the proposed system

Table 4. Comparison of energy consumption monetary cost

Months	Electricity bill ($)	Constructed meter ($)
March	21.28	21.02
April	19.57	19.12
May	16.17	15.96
June	22.13	21.90
July	22.98	22.85

The various tests conducted validate the proper functioning of the constructed meter for residential use, demonstrating its ability to provide accurate data and securely store it in the cloud. This ensures reliable information regarding electricity consumption and its associated economic cost.

The results obtained from tests conducted in households and at the Industrial Technology Laboratory of the ESFOT Technologist Training School at the National Polytechnic School demonstrate the effectiveness of the residential energy consumption meter. Its primary objective is to support the academic development and practical training of Electromechanics students. Figure 20 illustrates a technical workshop led by ESFOT students on residential electrical installations for young people from vulnerable communities, conducted as part of the outreach project with the 'Río Verde' Foundation. The meter (1) is used alongside the training teaching panels (2) to facilitate these workshops.

Figure 20. Students participating in technical workshops on residential electrical installations as part of outreach projects

4. Conclusions

An interactive electric energy meter for residential use was successfully developed and implemented, designed to deliver accurate measurements with an error margin of less than 5%, in compliance with national regulations. The device provides users with real-time information on their energy consumption, including estimated monthly costs, and maintains a historical record stored in the cloud. Equipped with a TFT LCD touchscreen, the meter displays essential data such as voltage levels, current, power, energy consumption (kWh), and costs (USD), all of which are simultaneously recorded in an online database.

To extend historical records beyond those typically maintained by electricity distribution companies, the system incorporates an hourly consumption logging feature that requires an internet connection and synchronization with precise time and date data. The database stores daily energy consumption resets the counter monthly, and updates backup data to ensure accuracy. Firebase Real-Time Database was selected as the primary tool for its ability to store data in a simple, nested, and customizable manner, as well as being cost-free during the project's development. The collected data provides a valuable resource for analyzing residential consumption habits and detecting anomalies, thereby facilitating the adoption of energy-saving practices.

The developed meter offers enhanced functionalities compared to conventional meters by providing real-time data that enables users to monitor their energy consumption and design tailored strategies for cost reduction. While currently equipped with basic functions targeted at residential consumers, the system is flexible, adaptable, and cost-effective, with an approximate production cost of $80 (USD). Its portability and ease of replication further increase its potential for widespread adoption. Future enhancements could include advanced features such as prepaid and postpaid modes, remote access for energy provider management, and fault detection capabilities.

This interactive residential energy meter significantly contributes to fostering sustainability by addressing issues related to efficient electricity use and waste reduction. Its ability to provide real-time data on energy consumption, estimated costs, and historical records empowers users to make informed decisions, optimize consumption habits, and reduce greenhouse gas emissions associated with energy waste. Additionally, its application in educational environments enhances technical knowledge of electrical installations and raises awareness about the importance of energy conservation in achieving environmental sustainability.

The designed and implemented device represents a significant advancement in the field of residential electrical installations and energy savings. It promotes learning and technical training through its integration into educational institutions, such as ESFOT, as part of the Applied Technology project line. This initiative addresses critical technical challenges in the country and finds practical applications in electricity laboratories and training programs for residential electrical installations. Furthermore, its incorporation into community outreach projects, such as technical workshops, fosters skill development in electricity and residential electrical systems. By being part of such projects, the device supports the adoption of sustainable consumption habits and empowers communities to actively contribute to environmental protection, serving as a model for responsible and accessible technological innovation.

References

[1] M. Poverda, *Eficiencia Energética: Recurso no Aprovechado.* OLADE, 2007. [Online]. Available: https://upsalesiana.ec/ing33ar9r1

[2] O. G. Arellano Bastidas, *Estudio y análisis de eficiencia energética del sistema eléctrico del hospital IESS-Ibarra.* Universidad de las Fuerzas Armadas, Ecuador, 2020. [Online]. Available: https://upsalesiana.ec/ing33ar9r2

[3] A. E. Pilicita-Garrido and D. C. Cevallos-Duque, "Innovación tecnológica de un sistema integral para monitorear el consumo eléctrico," *Ingenius Revista de Ciencia y Tecnología*, no. 22, pp. 9–16, 2019. [Online]. Available: https://doi.org/10.17163/ings.n22.2019.01

[4] J. I. Peña Paredes and A. P. Trujillo Gavilanes, *Monitorización, análisis y difusión del consumo energético eléctrico de modelo de vivienda del sector residencial de la ciudad de Riobamba.* Escuela Superior Politecnica del Chimborazo, Ecuador, 2014. [Online]. Available: https://upsalesiana.ec/ing33ar9r4

[5] N. Benito Marín, *Optimización de contratación de electricidad para consumidores domésticos y pymes.* Universidad CAros II de Madrid, España, 2016. [Online]. Available: https://upsalesiana.ec/ing33ar9r5

[6] M. Nieves García, *Propuesta y evaluación de tratamientos para la mejora de la eficiencia energética en el sector residencial mediante el desarrollo de experimentos económicos.* Universitat Jaume I, España, 2017. [Online]. Available: https://upsalesiana.ec/ing33ar9r6

[7] A. Costa, F. Ciniello, G. Grzybowsk, and R. C. Betini, "Development of a prototype for measurement of electricalenergy," *Brazilian Archives of Biology and Technology*, vol. 61, 2018. [Online]. Available: https://doi.org/10.1590/1678-4324-smart-2018000032

[8] C. A. Iza Calapaqui and L. J. Latacunga Pilatasig, *Diseño y construcción de un prototipo para determinar el consumo de energía eléctrica residencial.* Universidad Técnica de Cotopaxi, Ecuador, 2021. [Online]. Available: https://upsalesiana.ec/ing33ar9r8

[9] A. Pitì, G. Verticale, C. Rottondi, A. Capone, and L. Lo Schiavo, "The role of smart meters in enabling real-time energy services for households: The italian case," *Energies*, vol. 10, no. 2, 2017. [Online]. Available: https://doi.org/10.3390/en10020199

[10] T. AlSkaif, I. Lampropoulos, M. van den Broek, and W. van Sark, "Gamification-based framework for engagement of residential customers in energy applications," *Energy Research & Social Science*, vol. 44, pp. 187–195, 2018. [Online]. Available: https://doi.org/10.1016/j.erss.2018.04.043

[11] J. López, R. Luna, J. Cervantes, J. Meneses Ruiz, and J. Hernández, "Aplicación de tecnologías de medición avanzada (ami) como instrumento para reducción de pérdidas," *Boletin IIE*, vol. 39, pp. 180–191, 12 2015. [Online]. Available: https://upsalesiana.ec/ing33ar9r11

[12] L. M. Estrada Albiño, *Medidor residencial de energía eléctrica con revisión de consumo de forma inalámbrica.* Universidad Tecnica del Norte, Ecuador, 2023. [Online]. Available: https://upsalesiana.ec/ing33ar9r12

[13] D. I. Samaniego Idrovo and D. F. Velesaca Orellana, *Diseño e implementación de un medidor de energía electrónico para vivienda, con orientación a la prevención de consumo y ahorro energético.* Universidad Poltecnica Salesiana, Ecuador, 2016. [Online]. Available: https://upsalesiana.ec/ing33ar9r13

[14] P. C. Vashist and A. Tripathi, "Design and implementation of smart energy meter with real-time pricing," in *Computational and Experimental Methods in Mechanical Engineering*, V. V. Rao, A. Kumaraswamy, S. Kalra, and A. Saxena, Eds. Singapore: Springer Singapore, 2022, pp. 499–507. [Online]. Available: https://doi.org/10.1007/978-981-16-2857-3_49

[15] H. K. Patel, T. Mody, and A. Goyal, "Arduino based smart energy meter using gsm," in *2019 4th International Conference on Internet of Things: Smart Innovation and Usages (IoT-SIU)*, 2019, pp. 1–6. [Online]. Available: https://doi.org/10.1109/IoT-SIU.2019.8777490

[16] E. A. Quintero Salazar, "Medidor electrónico interactivo de consumo de energía eléctrica para uso residencial," *Prospectiva*, vol. 14, no. 1, pp. 55–70, 2016. [Online]. Available: https://doi.org/10.15665/rp.v14i1.639

[17] A. E. Pilicita-Garrido and D. C. Cevallos-Duque, "Innovación tecnológica de un sistema integral para monitorear el consumo eléctrico," *Ingenius, Revista de Ciencia y Tecnología*, no. 22, pp. 9–16, 2019. [Online]. Available: https://doi.org/10.17163/ings.n22.2019.01

[18] J. S. Echeverría, , and J. García-Echeverría, "edición avanzada inteligente, retos al consumo responsable del servicio público domiciliario de energía en Colombia," *Revista chilena de derecho y tecnología*, vol. 11, pp. 47–62, 12 2022. [Online]. Available: http://dx.doi.org/10.5354/0719-2584.2021.64167

[19] A. M. Díaz Rodríguez, J. B. Cogollos Martínez, J. Peña Acción, A. Cogollos Izaguirre, and R. González Álvarez, "Modelo matemático para predecir el consumo de energía eléctrica en la universidad de cienfuegos," *Universidad y Sociedad*, vol. 12, no. 4, pp. 45–56, 2020. [Online]. Available: https://upsalesiana.ec/ing33ar9r19

[20] Z. de la Cruz Severiche Maury, A. Fernández Vilas, and R. P. Díaz Redondo, "Low-cost hem with arduino and zigbee technologies in the energy sector in colombia," *Energies*, vol. 15, no. 10, p. 3819, May 2022. [Online]. Available: http://dx.doi.org/10.3390/en15103819

[21] W. Luan, J. Peng, M. Maras, J. Lo, and B. Harapnuk, "Smart meter data analytics for distribution network connectivity verification," *IEEE Transactions on Smart Grid*, vol. 6, no. 4, pp. 1964–1971, 2015. [Online]. Available: https://doi.org/10.1109/TSG.2015.2421304

[22] T. Hengyu, W. Huanning, H. Yan, Z. Zhihua, Y. Hejun, and L. Yuan, "Real-time monitoring method for smart meter measurement performance," in *2021 5th International Conference on Smart Grid and Smart Cities (ICSGSC)*, 2021, pp. 72–76. [Online]. Available: https://doi.org/10.1109/ICSGSC52434.2021.9490438

[23] G. Artale, A. Cataliotti, V. Cosentino, S. Guaiana, D. Di Cara, N. Panzavecchia, G. Tiné, N. Dipaola, and M. G. Sambataro, "Pq metrics implementation on low cost smart metering platforms. a case study analysis," in *2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS)*, 2018, pp. 1–6. [Online]. Available: https://doi.org/10.1109/AMPS.2018.8494866

[24] A. S. Metering, S. Visalatchi, and K. K. Sandeep, "Smart energy metering and power theft control using arduino & gsm," in *2017 2nd International Conference for Convergence in Technology (I2CT)*, 2017, pp. 858–961. [Online]. Available: https://doi.org/10.1109/I2CT.2017.8226251

[25] N. S. Živic, O. Ur-Rehman, and C. Ruland, "Evolution of smart metering systems,"

in *2015 23rd Telecommunications Forum Telfor (TELFOR)*, 2015, pp. 635–638. [Online]. Available: https://doi.org/10.1109/TELFOR.2015.7377547

[26] J. A. Arévalo-López, N. Ávila Peñuela, E. Estupiñan-Escalante, O. A. Parra-Urrego, and D. A. Cano-Tirado, "Design and implementation of an energy metering system to recognize the household electrical energy consumption pattern through an iot network," in *2021 Joint Conference - 11th International Conference on Energy Efficiency in Domestic Appliances and Lighting & 17th International Symposium on the Science and Technology of Lighting (EEDAL/LS:17)*, 2022, pp. 1–6. [Online]. Available: https://upsalesiana.ec/ing33ar9r26

[27] M. A. Alahmad, P. G. Wheeler, A. Schwer, J. Eiden, and A. Brumbaugh, "A comparative study of three feedback devices for residential real-time energy monitoring," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 4, pp. 2002–2013, 2012. [Online]. Available: https://doi.org/10.1109/TIE.2011.2165456

[28] OEM. (2023) Openenergymonitor. GitHub. [Online]. Available: https://upsalesiana.ec/ing33ar9r28

[29] ARCERNNR, *Pliego tarifario del servicio público de energía eléctrica año 2023.* Agencia de Regulación y Control de Energía y Recursos Naturales no Renovables, Ecuador, 2023. [Online]. Available: https://upsalesiana.ec/ing33ar9r29

[30] INEN, *NTE INEN-IEC 62053-21: Equipos de medida de energía eléctrica. Requisitos particulares. Parte 21: Contadores estáticos de energía activa (clases 1 y 2).* Instituto Ecuatoriano de Normalización, Ecuador, 2010. [Online]. Available: https://upsalesiana.ec/ing33ar9r30

[31] ARCERNNR, *Regulación ARCONEL 001/2020.* Agencia de Regulación y Control de Energía y Recursos Naturales no Renovables, Ecuador, 2023. [Online]. Available: https://upsalesiana.ec/ing33ar9r31