Smart Electrical Outlet with Integrated Circuit Breaker Protection

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Abstract: ***This study presents the development of a smart electrical outlet system designed to mitigate household risks such as fire and electrocution caused by electrical overloads. The system integrates an SCT-013-020 current sensor, an ATmega328P microcontroller, and solid-state relays to monitor and control current flow. Using an OLED display, it provides real-time information on power usage and alerts when the current exceeds a defined 15-ampere limit. The control algorithm autonomously disconnects high-demand outlets during overload conditions, ensuring localized protection. Experimental validation using household appliances demonstrates the system's effectiveness in providing independent, reliable overcurrent protection compliant with national safety standards.***

Keywords: smart electrical outlets, circuit breaker, overload protection

1. Introduction

Electrical wall and floor outlets can pose significant hazards to the public when they are not properly inspected, installed, or operated [1]. According to the Electrical Safety Foundation International (ESFI), 2,220 electrical injuries and 126 fatalities were reported in 2020 [2]. The U.S. Consumer Product Safety Commission (CPSC) also estimates that electrical receptacles are involved in approximately 5,300 fires each year, resulting in an average of 40 deaths and 100 injuries annually. Consequently, the agency recommends replacing outdated outlets with modern devices that incorporate built-in safety features [3].

The 2023 Annual Report of the Heroic Fire Department of Mexico City recorded 769 service calls related to short circuits [4]. Likewise, authorities report that at least 50% of the nearly 30,000 fires that occurred in Mexico City between 2019 and 2024 took place during the winter season. Of these incidents, 53% occurred in residential buildings and were often linked to electrical short circuits [5].

These data indicate that improper use of electricity such as connecting holiday decorations and space heaters incorrectly, as illustrated in Fig. 1, is a leading cause of residential fires, with a marked increase during December and January. Due to the growing number of accidents and fires caused by electrical outlets, the need for improved residential electrical safety has become increasingly urgent. Recent incident reports highlight the risks associated with overloaded or improperly used outlets [6], it is necessary to implement a system capable of preventing or reducing such incidents, which pose serious risks including property loss, infrastructure damage, and, most critically, loss of life.

Furthermore, these hazardous events are often accompanied by increases in household electricity tariffs caused by user generated overloads on receptacle circuits. Therefore, a system is needed that not only provides overload protection but also alerts users when the maximum allowable current of the outlet is being approached. Additionally, installations must comply with the electrical standards established in NOM-001-SEDE-2012, which defines safety requirements for electrical installations in Mexico [7].

Figure 1: Improper use of an electrical outlet

A wide variety of electrical receptacles is currently available on the market, many of which are now classified as "smart" due to the way their protection mechanisms operate. Some receptacles incorporate internal switches that are engaged when the plug is inserted, thereby enabling the power supply only upon physical activation. This feature helps reduce the risk of electric shock [8]. Other designs prevent receptacle-related fires by integrating temperature and EMI sensors that, depending on the operating condition, can activate an extinguishing-material cartridge to suppress ignition [9]. Additional models rely on external heat and smoke sensors which, when reaching hazardous levels, trigger the shutdown of the receptacle [10].

There also exist receptacles in which the power line is not continuously energized. Instead, current is enabled only after verifying the presence of a proper plug, either through physical proximity detection or a wireless verification signal [11]. Some receptacles not only support wireless remote control, but also incorporate semiconductor-based technologies that allow them to function as multifunctional safety devices capable of protecting the connected load from a wide range of electrical faults [12]. Other designs operate solely as remote switches and serve as active energy management systems that optimize power consumption at the receptacle level [13].

It is worth noting that modern smart receptacles now leverage the Internet of Things (IoT) to enhance home automation through remote control; therefore, safety features and intelligent energy-management capabilities are accessed via smartphone interfaces [14]-[17]. However, many WiFi-controlled receptacles do not provide protection against wiring degradation or damage [18]. Additionally, power strips with receptacles offering features similar to wall-mounted smart outlets are also available on the market [19]. Therefore, it is essential to develop a receptacle primarily focused on preventing insulation degradation caused by overheating of internal wiring due to excessive electrical load—one of the leading sources of residential fires and electrical hazards. In addition, to enhance user safety, the receptacle should remain de-energized until a load is physically connected, ensuring that no live contacts are exposed. The system should also allow the user to visualize, directly at the receptacle and without relying on a smartphone, the operational status and electrical conditions when multiple appliances or electronic devices are connected and exceed the allowable limits of the outlet.

The purpose of this study is to design, implement, and evaluate a smart outlet system that autonomously provides overcurrent protection in residential environments by monitoring electrical load conditions using embedded control and sensing technology.

This system contributes to reducing electrical hazards in homes, addressing gaps in conventional outlet safety mechanisms while promoting the integration of accessible embedded solutions for domestic use.

2. Materials and Methods

Figure 2 shows the blocks that comprise the electrical overload protection system, mounted on a conventional household outlet. The system consists of three functional blocks. Its operation is based on overload protection for electrical receptacles in accordance with the NOM-J-412-ANCE-2008 standard [20]. A brief description of each system block is provided below.

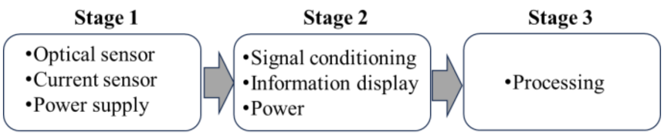

Figure 2: Block diagram of the system

- ***Stage 1***

The system includes a power supply that provides 12 V at 400 mA to the prototype. The SCT-013-020 sensor, shown in Fig. 3(a), is a non-invasive current sensor that delivers a voltage proportional to the current drawn from the electrical network. Since the sensor output is analog, the signal must be properly conditioned before it can be processed by the digital control system. Additionally, the design incorporates an optical sensor, shown in Fig. 3(b), which functions as a switch. When a plug is inserted into the outlet, the sensor generates a signal that notifies the control unit of the connection event.

(a) (b)

Figure 3: Sensors (a) Current sensor, (b) Optical sensor

- ***Stage 2***

The signal conditioning stage converts the sinusoidal waveform obtained from the current sensor into a digital signal that can be interpreted by the control system. This conversion is performed using a precision rectifier circuit, shown in Figure 4, which is implemented with LM358 operational amplifiers. These op-amps are selected because the sensor output has a very small amplitude, making it unsuitable for rectification with conventional diode-based circuits. After rectification, the signal is amplified to ensure proper processing by the control circuitry. It is important to note that this conditioning stage corresponds to a single outlet channel.

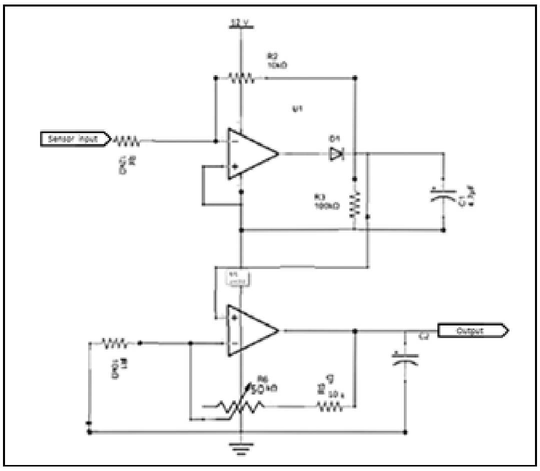

Figure 4. Signal conditioning circuit

The system's visual interface is implemented using a 128 × 64 OLED display, as shown in Figure 5. This display presents the current consumption of each outlet, as well as the total power drawn by the receptacle. Each measured value is accompanied by an identifying label: **A1** for the upper outlet, **A2** for the lower outlet, and **WT** to indicate the total power consumed by both outlets. The total power value is displayed at the top of the OLED screen, ensuring clear and immediate interpretation.

Figure 5: 0.96-inch I2C OLED display

Figure 6 shows the solid-state relays used in the power stage, which control the switching on and off of the electrical outlets.

Figure 6: FOTEK SSR-25DA solid-state relays

- ***Stage 3***

It consists of a control system implemented on an acquisition board based on an ATmega328P processor, as shown in Fig. 7. This processor coordinates the different functional blocks of the system and ensures proper operation. It runs at a clock frequency of 16 MHz and includes the required peripherals to interface with all system components. Additionally, it provides reduce prototype implementation time. The embedded algorithm within the controller is responsible for identifying and distinguishing the electrical loads associated with each outlet.

Figure 7: Data acquisition board

- ***System Operation***

The purpose of the system is to provide overload protection for electrical outlets in residential buildings through continuous monitoring of their operating conditions. The device integrates two independent outlets, both protected by the control system.

When a plug is inserted, the optical sensors detect its presence and enable power delivery to the corresponding receptacle. The system then measures the current drawn by the connected load. Using this information, the control algorithm determines whether the outlet exceeds the allowable current limit specified by the standard (15 A). If this threshold is surpassed, the system disconnects the power, and the OLED display presents an “OVERLOAD” message. When both outlets are active, the system also evaluates the total current consumption. If the combined load exceeds 15 A, the algorithm disconnects the outlet with the higher current demand while maintaining operation of the outlet with the lower load. The OLED display indicates which receptacle has been disabled by showing the corresponding “OVERLOAD” notification.

To restore operation after an overload event, the user only needs to remove the plug from the affected outlet, which resets its control status. It is important to highlight that overload protection is applied independently to each outlet, ensuring localized and reliable fault handling.

Figure 8 shows the complete electrical diagram of the system.

Figure 9 shows the household appliances used to test the system. These devices have the following power consumption:
Black & Decker iron = 1200 W
Practik coffee maker = 1100 W

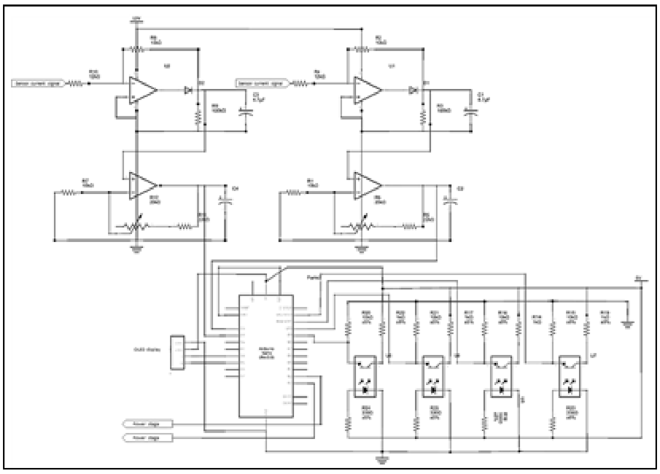

Figure 8: Electrical circuit of the control system

Figure 9: Household appliances used for prototype testing.

Equation (1) shows the calculated current for the 1200 watt iron using a 127 volt AC supply, and Equation (2) shows the current obtained for the 1100-watt iron under the same supply voltage.

$$I = \frac{W}{V} = \frac{1200\ W}{127\ V} = 9.44\ A \quad (1)$$

$$I = \frac{W}{V} = \frac{1100\ W}{127\ V} = 8.66\ A \quad (2)$$

2.1 Control Algorithm Flowchart

The control algorithm flowchart integrates all functional stages of the system in a structured manner. The program uses measurements from both optical and current sensors. Upon execution, the system initializes the required variables, inputs, and outputs. Figure 10 presents the flowchart of the control algorithm.

The first operation consists of reading the status of the optical sensors, each of which can exhibit two logical levels: high or low. When the level is high, the program proceeds with the acquisition of current measurements. Conversely, if either optical sensor (1 or 2) reports a low level, the system enables the solid-state relay associated with the corresponding outlet either the upper (1) or lower (2) and then performs the current measurement. Using these data, the algorithm computes the electrical parameters for each outlet and displays the results.

Subsequently, the system calculates the sum of the currents from both outlets. If the resulting value does not exceed 15 A, the system returns to the initial state and restarts the monitoring cycle. If the threshold is exceeded, the algorithm determines which outlet exhibits the higher load. If the current drawn by outlet 1 is greater than or equal to that of outlet 2, the system selects the output to be disabled, displays the corresponding notification, and restarts the process.

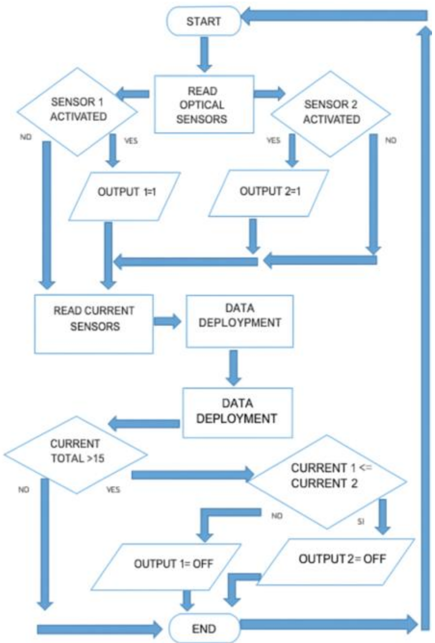

Figure 10: Control algorithm flowchart of the smart power outlet.

The algorithm, in conjunction with the hardware stages of the prototype, provides protection against overcurrent conditions. Optical slot sensors are employed to detect plug insertion. Based on this information, the system energizes the outlet through the power stage. The consumed current is estimated through processing of the conditioned analog signal, and the current and power values are displayed on the OLED screen.

The system continuously monitors both currents, and if the combined or individual value exceeds the 15 A threshold, the algorithm determines which outlet must be deactivated and issues a visual disconnection alert. The affected outlet remains disabled until the plug is removed and the system detects this condition. During this period, the remaining outlet continues operating under system supervision. At the end of each cycle, the program returns to the initial state and restarts the monitoring sequence.

3. Results and Discussion

3.1 Overload-protected electrical outlet prototype

In Figure 10, the completed prototype can be seen, showing the assembly inside a plastic enclosure that houses two electrical outlets and an OLED display. Inside the enclosure, the entire system is installed in a layout optimized function. The system includes four optical sensors positioned at the outlets, two solid-state relays one for activating each outlet two SCT-013-020 current sensors for individually measuring the loads, two signal-conditioning stages to adapt the sensor outputs, and a digital control board based on an ATmega328P microcontroller.

The proposed system enables real-time monitoring and control of electrical loads under a defined maximum consumption threshold. The design is based on a standard receptacle that integrates two independently monitored outlets, allowing for individual management. Each outlet incorporates a solid-state relay responsible for controlling the power supply, operated through a digital control system.

The allowable current limit is set at 15 A, in compliance with the NOM-J-412-ANCE-2008 standard. The system ensures that this threshold is not exceeded during operation. If both outlets are used simultaneously and the total current surpasses the permitted limit, the control algorithm determines which outlet must be disabled to prevent an overcurrent condition. The disconnected outlet is automatically re-enabled only after the plug is removed.

The prototype includes a visual interface that allows users to monitor the individual consumption of each outlet in real time. When an overload occurs, the display shows a warning message indicating the specific outlet where the condition originated.

Additionally, the system integrates optical sensors in each outlet to detect plug insertion. Power is supplied only when both sensors confirm a valid connection; if only one is engaged, the system prevents energization. This mechanism enhances operational safety and help avoid failures from improper use.

(a) (b)

Figure 10: Prototype: (a) front view, (b) rear view

3.2 Current measurement of the prototype under no load condition

To assess the intrinsic power consumption of the prototype, a no-load current measurement was performed, meaning that the outlet was energized while no appliance was connected. This procedure allows verification of the system's self-consumption and ensures that no leakage currents,

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unexpected overconsumption, or faults in the conditioning and sensing stages are present. Figure 11(a) shows that the measured AC current consumption is 10 mA.

Additionally, Figure 11(b) indicates that the no-load voltage is 126.5 V. This voltage level is significant because residential supply lines often experience variations depending on grid stability and power quality.

It is also important to note that the control program uses 127 V as the reference voltage standard, from which all power calculations are derived. It can also be observed in both figures that when no appliances are connected to the receptacles, the display does not present any measurement values; it only shows the reference labels “WT,” “A1,” and “A2.”

(a) (b)

Figure 11: Measurement: (a) Current, (b) Voltage

3.3 Current measurement in the household appliances used

In Fig. 12(a), the iron is shown connected to the prototype outlet alongside the multimeter used for reference measurements. Fig. 12(b) presents the resulting power reading (WT = 1157.46 W) and the measured current at the upper outlet (A1 = 9.11 A).

It is important to note that the multimeter displays a slightly different value. This discrepancy arises from the prototype’s intrinsic current draw (10 mA), fluctuations in the residential supply voltage, and the fact that the system was not designed as a precision metering instrument but rather as a visual, informative indicator to keep the user aware of approximate power consumption levels. Additionally, the lower outlet (A2) shows no current reading, as it is not in use.

(a) (b)

Figure 12: Iron usage: (a) Connection setup, (b) Current measurement

In Figure 13(a), the coffee maker is connected to the prototype outlet along with the multimeter used for measurement. Figure 13(b) shows the resulting power measurement (WT = 1025.62 W) and the current drawn at the lower outlet (A2 = 8.00 A).

It is important to note that the multimeter displays a different measurement value, consistent with the previously explained reasons. Additionally, the upper outlet (A1) shows no current reading since it is not in use.

(a) (b)

Figure 13: Coffee maker usage: (a) Connection setup, (b) Current measurement

3.4 Prototype Overcurrent Protection Response

When testing the activation of the outlet’s overcurrent protection, both appliances the iron and the coffee maker were connected simultaneously. Based on the current measurements shown in Figures 12 and 13, these devices would reach a combined load of approximately 17 A, exceeding the 15 A protection threshold; therefore, the system should intervene.

Figure 14(a) shows both appliances connected to the prototype outlets. Figure 14(b) presents the measurements displayed on the OLED screen. Initially, the coffee maker is connected to the lower outlet (A2). When the iron is connected to the upper outlet (A1), both appliances continue operating while the iron increases its temperature. Once the iron reaches its peak heating stage, its current draw increases, and as soon as the combined load surpasses the 15 A protection limit, the control system immediately disables the corresponding outlet. This action interrupts power delivery to the iron and simultaneously displays the message “OVERLOAD” on the screen.

The lower outlet (A2) remains energized, allowing the coffee maker to continue operating. The display reports its current consumption (A2 ≈ 8.11 A) and power (WT ≈ 1028.19 W).

(a) (b)

Figure 14: Use of household appliances: (a) Connection, (b) Current measurement

In Figure 15, it can be observed that once the iron is disconnected, the prototype’s control system detects the absence of any connected load and subsequently re-enables the upper outlet (A1). The “OVERLOAD” message is cleared from the display, indicating that a new electrical load may be connected, provided that its current consumption does not exceed the 15 A protection threshold. Otherwise, the outlet will once again enter the overload protection state.

Figure 15: Prototype response after disconnecting an electrical load

Now the test is repeated using the lower outlet (A2). For this configuration, the coffee maker is connected to the upper outlet (A1), while the iron is connected to the lower outlet (A2). As shown in Figure 16, the "OVERLOAD" message now appears on the OLED display in the position corresponding to A2, indicating that the lower outlet has exceeded the allowable current limit. Meanwhile, the measurements for the upper outlet display A1: 8.06 A and WT: 1026.1 W. These results confirm that the prototype operates as specified, reliably providing independent overload protection for either of the two monitored outlets.

Figure 16. Overload Warning Displayed on the OLED Screen

4. Conclusion

Reports issued by fire departments, news agencies, and civil protection organizations underscore the urgent need to integrate effective electrical safety mechanisms in residential buildings to mitigate critical hazards such as fires and electrocution. Unlike many existing solutions that rely on external devices, network connectivity, or user dependent interfaces, the proposed system introduces a self contained and autonomous outlet architecture, specifically designed for continuous and reliable everyday operation without external dependencies. The proposed outlet uniquely combines overcurrent protection with conditional power delivery, supplying electrical energy only when a valid load is physically detected. This approach significantly reduces risks associated with wiring degradation, unintended energization, and improper handling limitations commonly observed in conventional and Wi-Fi based smart outlets. In contrast to systems focused primarily on remote control or energy management, the proposed design prioritizes intrinsic electrical safety at the point of use.

Furthermore, the integration of an embedded OLED display provides direct, local, and real-time feedback on total power consumption and the individual current drawn by each receptacle, eliminating the need for smartphones or external applications. This feature enhances user awareness and enables immediate corrective action when unsafe conditions arise. The system also generates instant visual alerts upon detecting an overcurrent condition exceeding the 15 A threshold, reinforcing its proactive and preventive nature.

Finally, the system's intrinsic power consumption of only 10 mA confirms its high energy efficiency and distinguishes it from existing smart outlet solutions that introduce additional standby losses. These characteristics position the proposed outlet as a novel, practical, and safety-oriented solution for residential environments, addressing critical gaps in current outlet technologies.

Future work will focus on improving measurement accuracy and integrating temperature monitoring to further strengthen fire prevention capabilities.

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