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Design and Implementation of Digital Leakage Current Circuit Breaker with Overcurrent Protection

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Abstract:
One of the main issues is how to protect people and electrical equipment from the dangers of electricity. Common defective current types that harm both consumers and electrical equipment include leakage, overload, and short-circuit currents. Both of these faults have the potential to start fires or electrocute people. The employment of traditional electrical protection devices is common in electrical systems to mitigate the impact of defective currents. Many conventional electrical protection devices lack accurate fault detection techniques and quick trip times. In this work, we introduce a digital leakage current circuit breaker with overcurrent protection and a digital device for electrical fault prevention for users and equipment. The goal of this project is to use a microcontroller to computerize the fault detection procedure of a traditional breaker. This fully automated device's settings can be changed according to user needs while keeping flexibility and safety. The experimental results show that the system was able to detect errors in the electrical current and stop them while clarifying the type of error (leakage or overload currents).

Keywords: Arduino, Current Transformer, Earth Leakage, Overload Protection

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تصميم وتنفيذ دائرة رقمية للحماية من تسريب التيار الكهربائي والتحميل الزائد

هيثم علي علي[1*]، أبوبكر بلحسن زرقون[2]، أنور مسعود الغرايب[3]، إبراهيم عبد الناصر الساكت[4]
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الملخص
تعتبر حماية المستخدمين والأجهزة الكهربائية من مخاطر الكهرباء مصدر قلق كبير. تعتبر تيارات التسريب والحمل الزائد وقصر الدائرة أنواعًا شائعة من التيارات المعيبة التي تسبب تأثيرات مدمرة على المستخدمين وكذلك على الأجهزة الكهربائية. قد تسبب الصعق بالكهرباء أو يمكن أن تكون مصدرًا للحريق. لمنع آثار التيارات المعيبة، تستخدم أجهزة الحماية الكهربائية التقليدية على نطاق واسع في الأنظمة الكهربائية. لا تحتوي بعض أجهزة الحماية الكهربائية التقليدية على طرق مناسبة للكشف عن الأعطال وسرعة فصل الدائرة لحماية المستخدمين والأجهزة المنزلية.
نقدم في هذه الدراسة قاطع دارة رقمي للتيار مع حماية ضد التيار الزائد، وهو جهاز رقمي لحماية المستخدمين والأجهزة الكهربائية من الأعطال الكهربائية. الغرض من هذا المشروع هو حوسبة الكشف عن أخطاء الفواصل التقليدية على أساس متحكم دقيق. هذا

الجهاز آلي بالكامل وله إعدادات قابلة للتعديل لضمان السلامة مع السماح بمرونة متزايدة لمطابقة احتياجات المستخدمين بشكل أفضل. النتائج العملية تظهر بأن النظام كان قادر على اكتشاف الأخطاء في التيار الكهربائي وإيقافها مع توضيح نوع الخطأ (التسريب الكهربائي والتحميل الزائد).

الكلمات المفتاحية: اردوينو، حساس التيار الكهربائي، التسريب الأرضي، حماية التحميل الزائد.

Introduction

The primary concern in electrical systems is human safety against electrical faults. Consuming electricity raises the possibility of faulty currents and puts users and electrical equipment in danger. Faulty currents frequently cause electrocution and electrical fires. The three primary categories of defective currents are leakage current, overload, and short-circuit. Leakage current has the potential to damage organs and cause an electrical shock to a person. In the meantime, electrical circuits may catch fire due to overload and short-circuit currents. The quantity of current on the phase and the neutral are the same in normal conditions. When the quantity of current on the neutral is lower than that on the phase, a problem occurs. Leakage current is the difference between phase and neutral currents. Leakage current can travel through non-conductive materials' surfaces as well as through conductive materials' cores. Leakage current is directed to the ground system via the earth wire in order to stop transmission of the leakage current.

Figure 1 [1], shows how the human body responds to leakage current. According to the study, leakage currents of any size have the potential to seriously harm users' health. The majority of leakage protection devices have a detection time delay, which is the issue. The tripping times of protection devices typically need to decrease as defective current increases in order to lower the risk of injury.

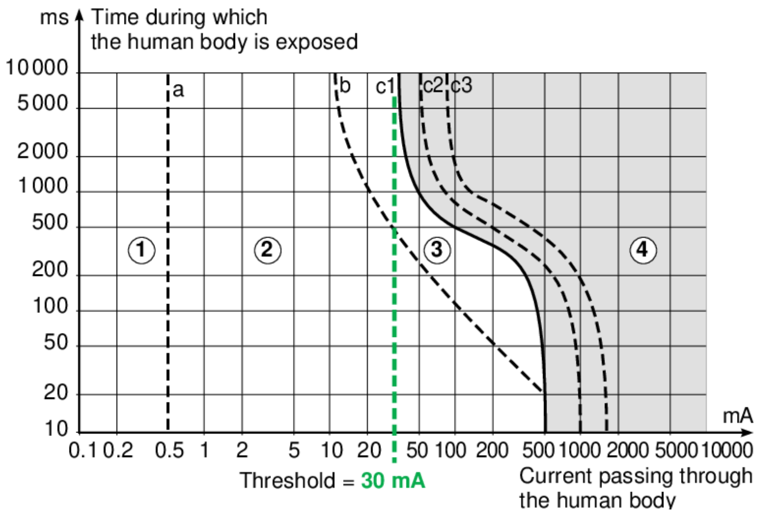

Figure 1: Time - current zones for effects of AC current [1]

The safety buffer is represented by area ① in Figure 1. At the maximum current of 0.5 mA, users are not at risk of any major health problems. Area ② does, however, have certain health problems. The threshold current in this instance is 30 mA, which the typical human body can withstand for 200 ms before breathing becomes difficult. The effects on the human body that are most dangerous are in areas ③ and ④. For instance, the risk of ventricular fibrillation rises with any current greater than 500 mA [1].

Other defective current types that result in overcurrent issues include overload and short circuits. They have negative impacts on electrical appliances and wiring. When numerous electrical loads are connected to an electrical circuit, an excessive quantity of current known as overload current flows through the circuit. In this instance, there is more electricity flowing through the wires than is typical. Excessive heating from the overload current erodes wire insulation and raises the risk of an electrical fire. Overload current can range from 1.36 to 6 times the electrical circuit's nominal current [2]. Under certain situations, a short connection between the phase and null wires results in a short-circuit current. This indicates that the current manages to get around the electrical loads briefly. Short-circuit current can seriously harm electrical circuits and is orders many times higher than the nominal current [3].

To protect people and electrical appliances from common faults of electric current. We must use a protection device capable of detecting these errors and working to disconnect the electrical current in the shortest time. Conventional breaker is one of these devices that are widely used. However, the architecture of conventional breakers may cause some delays to trip the electrical faults. Another issue related to the usage of conventional protection systems is overheating. The plastic container that surrounds the internal components of a conventional breaker can break or burst if overload or short-circuit currents cause sudden heating. The breaker will be tripped in this case. That means we have to replace the entire equipment. One level is present in a conventional breaker to identify electrical problems. In this instance, installing numerous breakers in an electrical system is necessary to accommodate varying degrees of faults. As a result, there are more protection devices, cables, and electrical panels overall. The price of electrical protection systems will rise as a result of each of these considerations.

Therefore, a new digital device that performs better than traditional breakers is designed and put into use as a solution to these problems. The microcontroller-based digital breaker is a computerized electrical protection device that quickly detects short-circuit, overload, and leakage current issues. Each component of the digital breaker is separate. Therefore, a form of thermal isolation is provided by this characteristic. Due to the high temperature of the overload or short circuit faults, just a part of the digital breaker may be damaged in this situation. With various levels of fault detection, the digital breaker is a multifunctional protection tool. With this capability, customers can adjust the digital breaker to the desired level of fault detection. The digital breaker can decrease the quantity of protective devices in electrical panels by utilizing this capability. In the existing literature, there are many research papers for different systems and ways working on protect people and electrical appliances from common faults of electric current. We studied several papers and here few of important contributions are presented.

One of the papers that has been published discusses the design an automated electrical protection system. The objective of this study is to develop a mechanism that able to auto switch ON and OFF the Residual Current Breaker (RCB) and Miniature Circuit Breaker (MCB) with capability to detect and isolate the fault. The main problem is when the Electric Leakage Circuit Breaker (ELCB) will turn ON again manually if the occupant were not aware with this problem and not turn up to the house within a time. Thus, an automated protection system was developed to overcome an electricity trip problem. The Arduino board was used to detect the fault; the idea is to compare the value of current at live wire and neutral wire [4].

Haries B. R. designed an automated electrical protection for three-phase system on 2012. The project's goal is to automatically reset the fault. It uses an Arduino board attached to a few MCBs and current sensors to monitor the current in each MCB. If the current is abnormal, the Arduino displays the problem location. Following that, the servomotors will be turned by the system to reset the MCB. [5].

Martin M. designed a smart residual current circuit breaker with overcurrent protection on 2022. The aim of the project is to design a digital protection system that addresses the slowness of the traditional protection system. The system was designed to detect common types of electrical faults (leakage, overloading and short-circuit currents). The system focused on quickly detecting errors, correcting them, and comparing results with the traditional system [6].

We conclude through previous studies that all research papers were intended to protect humans and electrical machines from damage, as various models and technologies were used to reach the desired goal. In this paper, a system will be built to discover specific electrical errors (leakage and overload currents). The structure of the system is considered completely similar to the system mentioned in [6], as the system will be tested in detecting common electrical faults and measuring the time for the system to detect the presence of an electrical fault in the circuit and stop it to protect humans and electrical machines. The system's efficiency is determined by how quickly the electrical current is removed from the circuit to protect people and electrical equipment, since a longer reaction time may compromise people. This system's actual performance will be contrasted with that of the system in [6].

This work is arranged as follows: Section 2, which is devoted to the block diagram of the system with a brief explanation about the system components. Section 3, covers results and discussion of this work and section 4 of this paper presents the conclusion of the performed work.

System block diagram

Figure 2, shows the complete system diagram of the digital leakage current circuit breaker with overcurrent protection (DLCBOP) and its controller board with three inputs (two current sensor and pushbutton) and four outputs (relay, buzzer and Liquid Crystal Display (LCD)). The Arduino board was used as the main brain of the whole system; it receives data from the input devices and updates the output devices. The goal of the system is to protect the people and electrical devices from electric shocks; so that the current sensor used to feed the controller by the current consumption from the main supply. Furthermore, Arduino board proposed to complete the protection system to read from current sensor then take the best decision in a short time. The figure 3 shows the prototype of the digital leakage current circuit breaker with overcurrent protection.

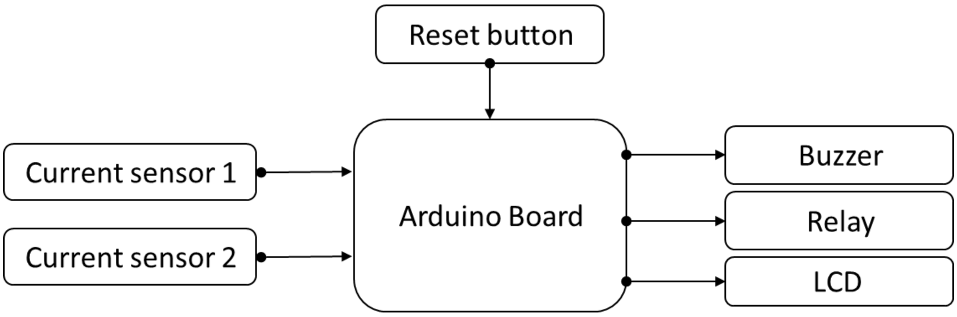

Figure 2: Block diagram of digital leakage current circuit breaker with overcurrent protection

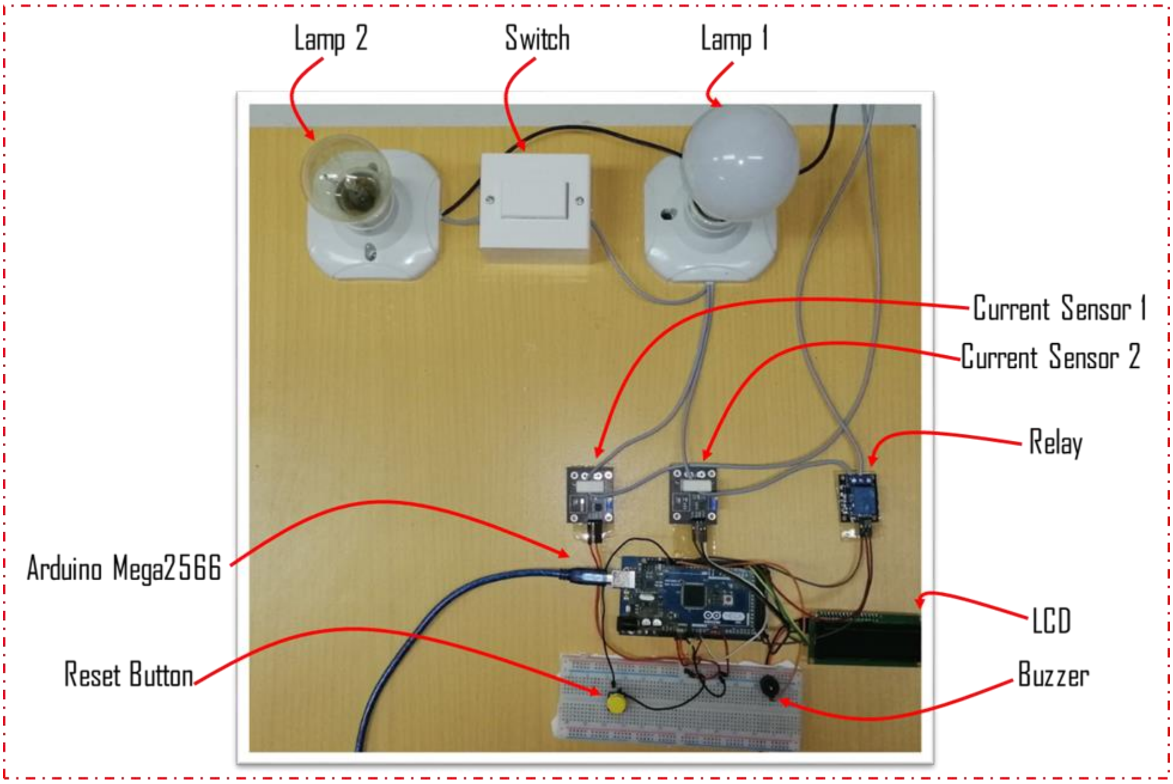

Figure 3: Prototype of digital leakage current circuit breaker with overcurrent protection.

1) **System Hardware**

The physical parts of a system are referred to as the hardware. Any component of the system that we can touch is referred to as system hardware. These are the main mechanical, electrical, and electronic components that make up the system. Hardware in this system includes, for instance, the Arduino board, current sensor, relay, LCD, etc.

- **Arduino Mega 2560**

As seen in figure 4, the Arduino Mega 2560 is a microcontroller board based on the ATmega2560. It contains 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, 54 digital input/output pins (14 of which can be utilized as PWM outputs), a USB connector, a power jack, an ICSP header, and a reset button. It comes with everything required to support the microcontroller; all you need to do is power it with a battery or an AC-to-DC adapter or connect it to a computer via a USB cable to get going. [7].

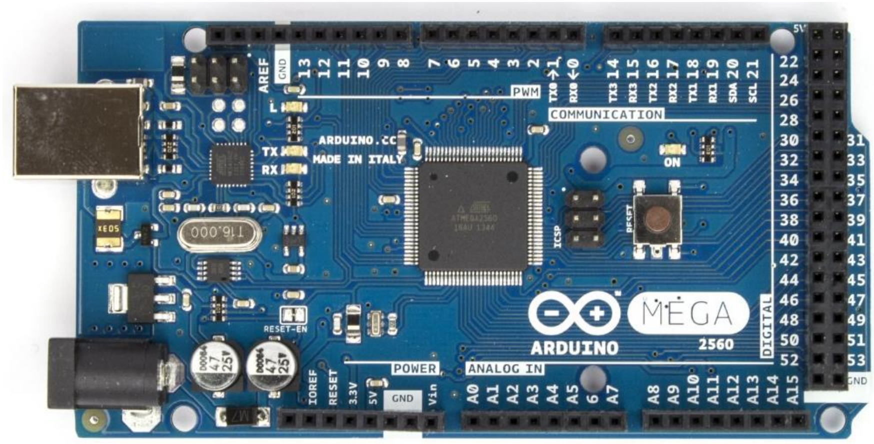

Figure 4: Arduino MEGA 2560

- **Current Sensor WCS1700**

For DC and AC current sensing in commercial, industrial, and communications systems, the Winson WCS1700 current sensor offers a cost-effective and accurate solution. The special package makes current sensing possible and allows for simple installation without interfering with the underlying system. Common uses include intelligent power management systems, motor control, load monitoring and control, and over-current fault detection. In figure 5, the WCS1700 current sensor is displayed.

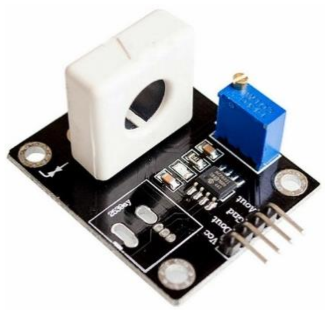

Figure 5: WCS1700 current sensor

The WCS1700 is made up of a 9.0 mm diameter through hole and a precise, low-temperature drift linear hall sensor integrated circuit with a temperature compensation circuit. To test the passing current, users can insert their electric wire via this slot in the system. System designers can monitor any current path due to this architecture, which keeps the original system layout intact. The integrated Hall IC senses the magnetic field created by any current passing through this hole and converts it into a proportionate voltage. Figure 6 and Table 1 illustrate, respectively, the relationship between the WCS1700 sensor's output voltage and primary current as well as the device's absolute maximum range [8].

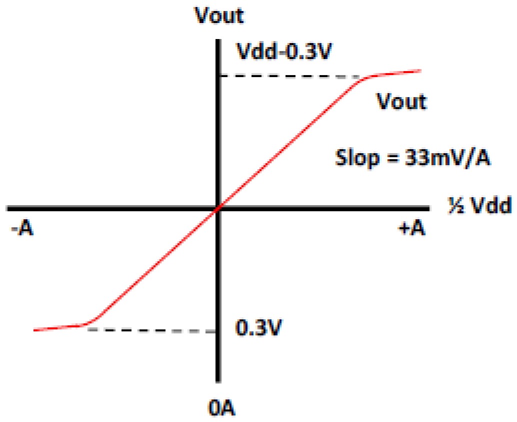

Figure 6: The output response of WCS1700 current sensor

Table 1 The absolute maximum range of WCS1700 sensor

Sensitivity	Current range
33 mV/A	DC: ±0~70A AC: rms 50A

From figure 6, the type of relationship between output voltage and primary current is linear. Therefore, the linear equation can be obtained as following:

$$y = mx + b \quad (1)$$

Where:
y: is the output voltage (measured by Arduino board).
m: is the sensor sensitivity (33 mV/A).
x: is the primary current (unknown).
b: is the voltage offset (2.5v from figure 6).
The DC primary current can be obtained directly from eq.1 as following:

$$x = \frac{y-b}{m} \quad (2)$$

The AC primary current can be obtained by calculate the current peak (I_m) and then the current can be obtained as following:

$$x_{rms} = \frac{I_m}{\sqrt{2}} \quad (3)$$

- **Liquid Crystal Display**

In embedded system applications, LCDs (Liquid Crystal Displays) are utilized to display different system characteristics and status information. Figure 7 depicts an LCD 16x2, a 16-pin device with two rows that each have space for 16 characters.

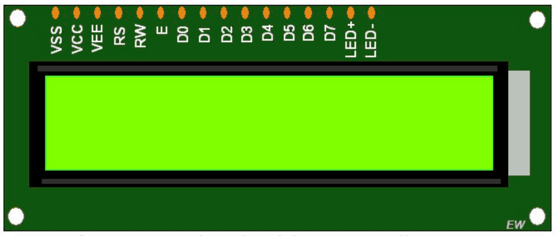

Figure 7: The liquid crystal displays.

This LCD was used in this project to display electrical current values on the phase and neutral lines.

- **Relay Module**

Since a relay is an electromagnetic switch, its electromagnet, which is driven by a little current and serves as both a lever and the switch itself, is its central component. This enables significantly bigger electrical currents to be leveraged and controlled by very tiny electrical currents. Although sensors are delicate devices that only generate little currents, they require an external source to activate larger equipment by permitting larger currents to flow. The electromagnet is energized by the little control current, which attracts the armature to it. When the armature makes contact with the other end of the circuit, the circuit is completed and current can start to flow. Numerous varieties exist for relays. There are several types of electromagnetic relays: hybrid, thermal, reed, induction, attraction, and induction type. Relays were employed as electrical insulators between large voltages (Loads) and small voltages (Arduino). In the event of an electrical malfunction (leakage or overload), the Arduino board will use the relay to isolate the main power supply [9]. In Figure 8, a single-channel relay module is displayed.

Figure 8: The relay module

- **Buzzer Module**

An audio signaling device, often known as a buzzer or beeper, can be mechanical, electromechanical, or piezoelectric (piezo for short). Buzzers and beepers are commonly used in timers, alarm clocks, and to validate user input, including as keystrokes or mouse clicks. A pleasure buzzer is an example of a purely mechanical buzzer that needs drivers to operate. Other examples of them are doorbells [9]. In this project, the buzzer serves as an alert device, sounding when the Arduino senses an electrical malfunction (leakage or overload). The buzzer utilized in this system is depicted in Figure 9.

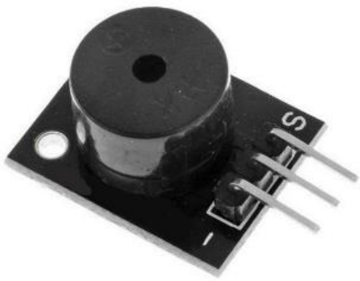

Figure 9: The buzzer module

2) **System Software**

The software is a set of guidelines, processes, and documentation that manages various tasks on a system. The Arduino IDE is the software employed in this system.

- **Integrated Development Environment**

"Integrated Development Environment" is what IDE stands for. The primary function of the open-source Arduino IDE software is to write and compile code for the Arduino Module and Node MCUs. Because it is an official Arduino program, code compilation is so simple that even a layperson with no prior technical experience may begin learning the basics. It operates on the Java Platform, which is readily available for MAC, Windows, and Linux operating systems. The Java Platform has built-in functions and commands that are essential for debugging, editing, and compiling code in an environment. There are numerous Arduino modules available, such as the Uno, Mega, Leonardo, Micro, and many more. On the board of each of them is a microcontroller that has been programmed to accept data in the form of code. The primary code, sometimes referred to as a sketch, written on the IDE platform will eventually produce a Hex File, which is uploaded and sent to the board's controller. The two primary components of the IDE environment are the Editor and Compiler, the former of which is used to write the necessary code and the latter of which is used to compile and upload the code into the specified Arduino Module. The languages C and C++ are supported in this environment [10]. Figure 10 shows the IDE software.

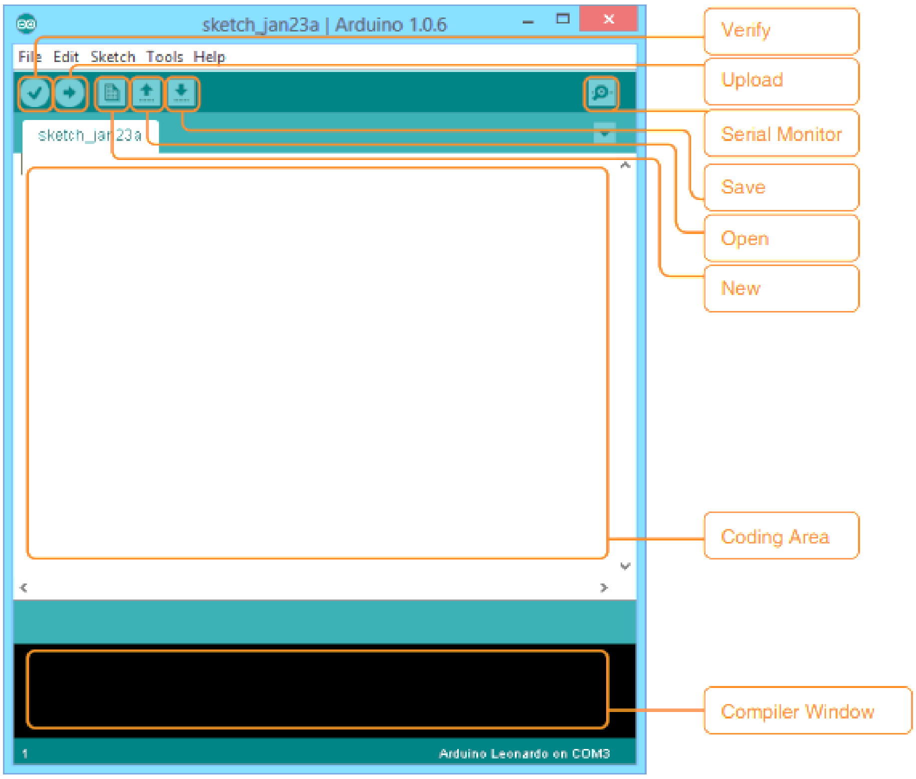

Figure 10: Integrated Development Environment of Arduino boards

3) Principle of Working the System

After reviewing the elements used for the system, they are linked together as shown in figure 11 to begin the practical testing process of the system and verify its efficiency in detecting electrical errors (leakage and overload) in the fastest time to protect humans and machines.

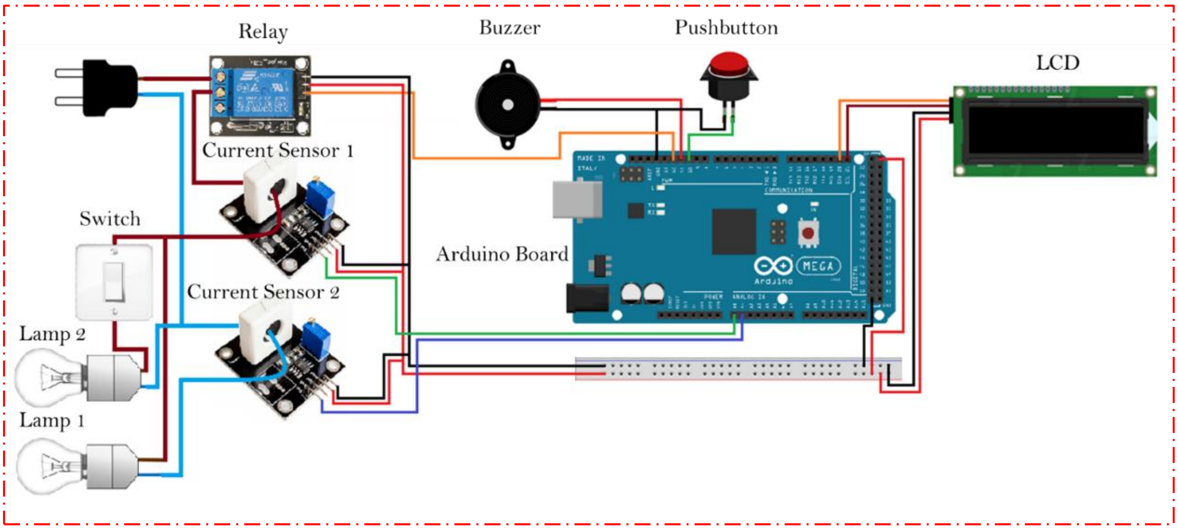

Figure 11: Circuit wiring of digital leakage current circuit breaker with overcurrent protection

From the previous form, the Arduino board is the main device in the system, as it works to read the values of electrical currents and make the decision to stop or operate the system. Software lines have been written to make the right decision in the event of an electrical error, these lines were written based on theoretical methods to detect these errors.

- **Leakage Current Protection**

The mechanism of the algorithm for detecting an electrical leak is simple. The Arduino board reads the electrical current on the phase line through the first electrical current sensor, and then reads the electrical current value on the neutral line through the second electrical current sensor. After that, the Arduino board compares the values of currents with each other, when there is no electrical leakage, the values are identical and the difference between them is zero. In the event that the values of electrical currents are inconsistent with these lines, it indicates the presence of an electrical leakage in one of the lines. The Arduino compares this leakage with the maximum value of the leakage entered by the user, after which it turns off the electrical circuit in the event of an increase in the electrical leak from the permissible limit.

- **Overload Current Protection**

The mechanism of overloading detection of electric current is not much different from the mechanism for making the electric leaks detection. The Arduino board makes the steps to detect on the presence of an electrical leak, and in the absence of any leaks, the Arduino applies the steps to detect to the presence of an overload. Where the Arduino board monitors the value of the phase line continuously and in the event that it exceeds the maximum value entered by the user, the Arduino stops the circuit and alerts the user to the excessive electrical load.
The summary of these tests is that the user gives the maximum value of electrical leakage and the maximum value of electrical loading and the system will periodically do the tests. We advise users not to write random values and the necessity of referring to the values mentioned in figure 1 to emphasize the survival of these values within the scope of the safe area to ensure the work of this system in protecting humans and machines.

Results and discussion

Before reviewing the results obtained practically, we mention the task of each element within the system as follows:

- Arduino board: is used as the main brain of the whole system; it receives the data from the input devices and then updates the output devices.
- Current sensor: is used to measure the quantity of the current in the conductors.
- LCD: is used to display the type of current fault if occurred.
- Buzzer: is used to make an alarm when a current fault is detected.
- Relay module: is used to trip the electrical circuits in the case of electrical faults.
- Reset button: is used to reset the system.

Figure 12 shows the flowchart of the digital leakage current circuit breaker with overcurrent protection. When the system is turned on, the Arduino board reads several current samples to calculate the maximum current (Im). Then the actual current value (Irms) can be calculated by equations (3). After calculating the value of the actual current, its value is classified to decide to disconnect or continue to connect the electrical circuit.

To start the process of testing the system in its final form, all electronic components are connected to each other as shown in the system wiring in in figure 11. After that, by uploading the code into Arduino board the project can be tested successfully. Under typical conditions, the load practically plugged in uses about 20mA. To provide real faults, we simulated the leakage current fault by split the neutral wire from the sensor to decrease the level of current on this sensor in order for the Arduino board to detect an imbalance in the reading of the sensors; it then disconnects the electrical circuit due to the presence of an electrical leak. Furthermore, by adding additional loads to the electrical circuit, we simulated overload situation. In the event of leakage current and overload faults, the device operated in accordance with the predetermined scenario and successfully disconnected the electrical circuit, as demonstrated in figure 13 and figure 14.

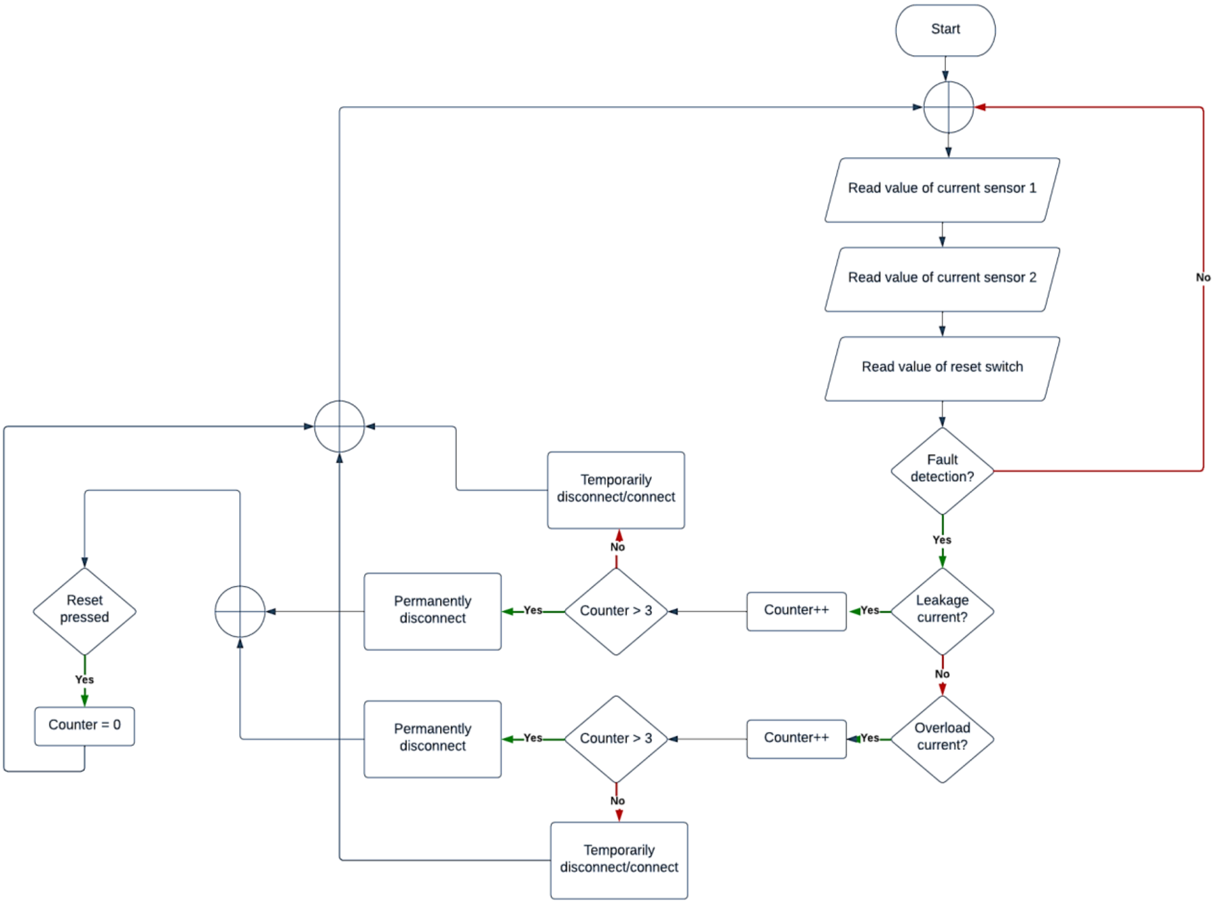

Figure 12: The flow chart of digital leakage current circuit breaker with overcurrent protection

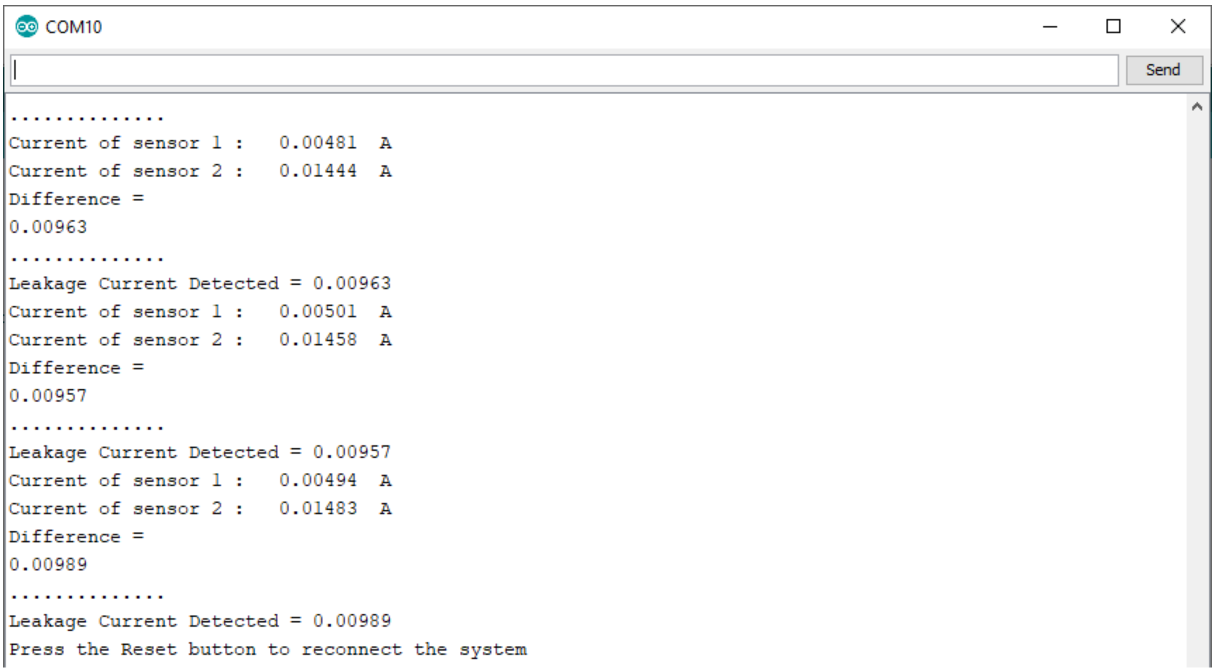

Figure 13: Leakage Current Detection Test.

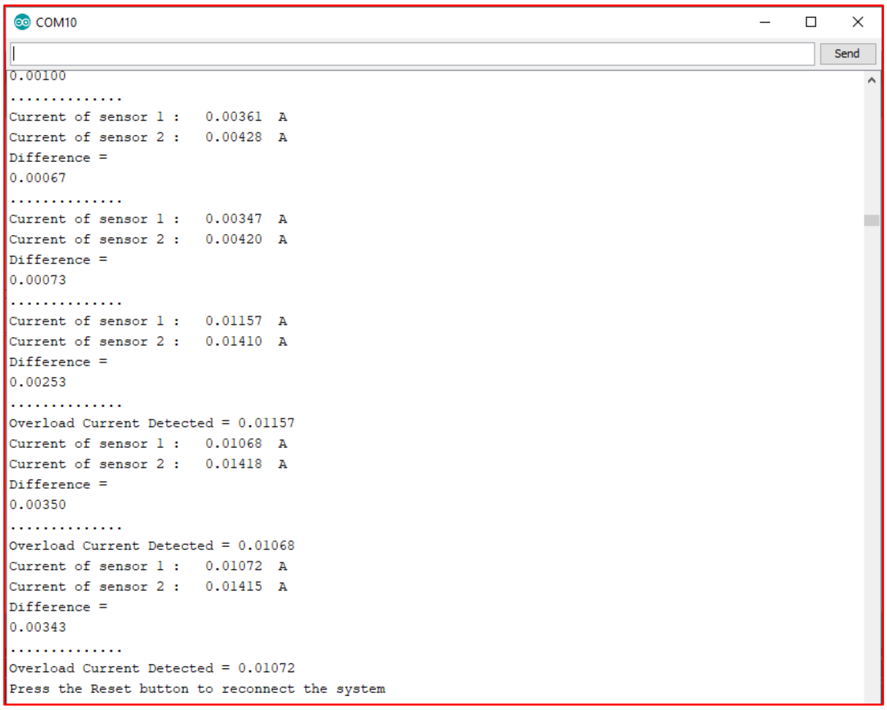

Figure 14: Overload Current Detection Test

From Figure 13 and Figure 14, the digital leakage current circuit breaker with overcurrent protection detects leakage and overload currents and automatically disconnects the electrical circuit, and then after three seconds it tries to connect the electrical circuit three times, if the current fault still exists the digital leakage current circuit breaker with overcurrent protection disconnects the electrical circuit. The system can be re-connected by pressing the reset push button. Table 2 shows the overall comparison of the systems' performance.

Table 2 The overall comparison of the RCBOs' performance**.**

Fault Type	Tripping time (ms) Our system	Tripping time (ms) Smart RCBO [6]
Leakage Current	16.6	28.5
Overload Current	15.5	31.5

As shown in Table 2, the digital leakage current circuit breaker with overcurrent protection has a shorter tripping time than the system in [6]. For example, the smart RCBO requires roughly 28.5 ms to detect the leakage current, and our system takes 16.6 ms to trip the leakage current. The system can also trip overcurrent current problems faster than the smart RCBO as shown in Table 2. The tripping time of these faults was calculated by capturing a video for all tests and then using the Camtasia Studio program that specializes in graphic design, the time was calculated accurately. The practical results show that the system was able to discover electrical errors when they occur in a short time and turn off the electrical circuit to protect people and electrical machines.

Conclusion

The digital leakage current circuit breaker with overcurrent protection has been successfully designed and implemented based on Arduino board. The digital leakage current circuit breaker with overcurrent protection contains settings that can be changed to improve the safety of users and electrical equipment. The Arduino board was used to read the values of the electric current sensors to be able to monitor the electrical loads and detect faults in quick time. The time that the system took to detect the presence of an electrical current error, was calculated by a video recording of the process and then calculating the time with graphic design programs to get high accuracy in the value of time taken instead of its manually calculated. The experimental results show that the digital leakage current circuit breaker with overcurrent protection is able to detect electrical faults in a short time. In addition, clarification the type of error that occurred with the possibility of restarting the system for the number of attempts by the user.

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