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Microcontroller-Based Arc Fault Detection and Protection System

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Abstract -

Conventional protective devices Miniature Circuit Breakers (MCBs) and Residual Current Devices (RCDs) fail to detect hazardous arc faults, which are a primary cause of electrical fires. This paper presents the design and implementation of a low-cost, microcontroller-based Arc Fault Circuit Interrupter (AFCI) prototype capable of detecting series arc faults through the analysis of DC bias and harmonic content in the load current waveform. The system employs an Arduino Uno microcontroller, an ACS712 Hall-effect current sensor, and a ZMPT101B voltage sensor to continuously monitor the AC circuit. Upon detection of anomalous waveform characteristics specifically an elevated DC bias component or increased harmonic distortion indicative of arcing — the system instantly actuates an electromagnetic relay to isolate the load. Real-time status and fault information are provided via a 16×2 LCD display. Experimental results demonstrate three operational modes: metering-only mode, active protection mode with fault latch, and trip-and-alarm action upon threshold exceedance. The prototype validates the hardware architecture and the sense-process-act framework, while identifying the need for full FFT-based harmonic analysis in future iterations.

Keywords - Arc Fault Circuit Interrupter (AFCI), arc fault detection, DC bias, harmonic analysis, ACS712, Arduino Uno, electrical safety, relay protection.

I. INTRODUCTION -

Electrical safety is a foundational requirement of modern power engineering. Historically, circuit protection has relied on two primary device types: Miniature Circuit Breakers (MCBs) for overcurrent protection, and Residual Current Devices (RCDs) for ground-fault leakage detection. While these devices are effective for their respective fault categories, they share a critical blind spot arc faults.

An arc fault is a high-temperature electrical discharge that occurs between energized conductors due to damaged insulation, loose connections, or aging wiring. The plasma channel of such an arc can sustain temperatures exceeding 5,000°C, providing a concentrated ignition source capable of igniting surrounding insulation and building materials. Critically, series arc faults occurring in a break within a single conductor do not draw sufficient current to trip an MCB and produce no leakage path to ground to activate an RCD.

This recognition prompted the development of Arc Fault Circuit Interrupters (AFCIs), which analyze waveform characteristics to distinguish hazardous arcing from normal load operation. This paper presents a prototype AFCI system built on the Arduino Uno platform, detecting arc signatures through DC bias measurement and harmonic content analysis of the load current. The system implements the complete sense-process-act-display chain, providing a foundation for future refinement into a commercially viable protection device.

II. PROBLEM FORMULATION -

A conventional AC circuit operating under normal conditions carries a sinusoidal current waveform at the fundamental frequency (50 Hz or 60 Hz). This waveform is characterised by symmetry about the zero axis and minimal energy content at frequencies above the fundamental.

When an arc fault occurs, the erratic, non-linear nature of the arc plasma introduces two measurable anomalies into the current waveform:

- DC Bias: The asymmetric "rectifying" behaviour of the arc distorts the waveform symmetry, shifting the time-averaged value of the signal from zero to a measurable non-zero DC component.
- Harmonic Content: The rapid, unstable ignition and extinction of the arc with each half-cycle generates broadband high-frequency energy. Mathematically, this energy is expressed as harmonics integer multiples of the fundamental frequency — superimposed on the 50/60 Hz sine wave.

The challenge lies in distinguishing these arc-generated signatures from the operational "noise" produced by legitimate non-linear loads such as variable-speed motor drives, electronic ballasts, and switched-mode power supplies. A reliable arc detection algorithm must minimise both missed detections (Type II errors) and nuisance trips (Type I errors) .

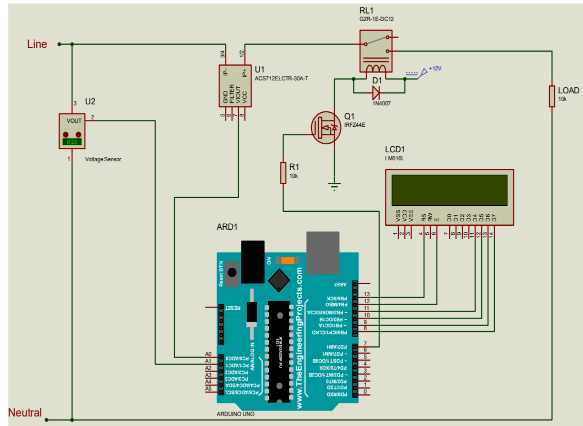
III.SYSTEM DESIGN AND METHODOLOGY

The proposed system adopts a Sense–Process–Act–Display (SPAD) architecture. Each stage is described below.

A. Sensing Subsystem

Current sensing is performed by the ACS712-30A Hall-effect sensor connected in series with the AC load. The sensor outputs an analog voltage proportional to the line current with a sensitivity of 100 mV/A and a bandwidth of approximately 80 kHz, sufficient to capture relevant harmonic frequencies. The quiescent output voltage is 2.5 V, and the measurement range is ±30 A.

Voltage sensing is accomplished by the ZMPT101B precision transformer-based module, which steps down the 230 V mains to a safe, Arduino-compatible analog level. The module operates over a supply range of 5–30 V and supports measurement of voltages up to 250 V AC. Its onboard operational amplifier buffers and biases the transformer secondary output to the mid-rail of the Arduino ADC reference.



B. Processing Subsystem

The Arduino Uno (ATmega328P, 16 MHz, 10-bit ADC) serves as the central processing unit. Both sensor outputs are sampled via the Arduino's analog input pins. For each AC cycle, the microcontroller acquires a window of N samples and computes the following metrics:

- DC Bias (V_DC): Calculated as the arithmetic mean of the sampled current values over a complete integer number of cycles. Under normal sinusoidal conditions, $V\_DC \approx 0$. A statistically significant departure from zero flags a potential arc.
- Harmonic Index (H): A simplified measure of the high-frequency energy content relative to the fundamental, derived from the deviation of the waveform from an ideal sinusoid. A full Fast Fourier Transform (FFT) implementation is identified as the recommended upgrade path.

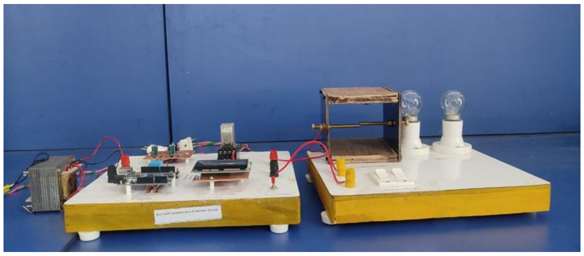
The controller compares V_DC and H against calibrated threshold values derived during a baseline commissioning phase. The detection decision logic is:

$$\text{Fault} \leftarrow \text{TRUE} \quad \text{if} \quad (|V\_DC| > \theta\_DC) \quad \text{OR} \quad (H > \theta\_H)$$

where θ_DC and θ_H are the DC bias and harmonic thresholds, respectively.

C. Actuation Subsystem

The 12 V OMRON MY-4 electromagnetic relay (contact rating: 10 A, 400 V) is driven by the Arduino's digital output through a transistor-based driver circuit, ensuring galvanic isolation between the 5 V logic domain and the 230 V AC mains. Upon a fault decision, the relay contacts open, de-energising the load circuit. The relay remains latched in the tripped state until a deliberate manual reset, preventing automatic re-energisation in a faulted condition.



D. Display Subsystem

A 16×2 HD44780-compatible LCD display provides real-time operational awareness. During normal operation, the display alternates between a measurement screen (showing RMS voltage and AC current) and a status screen (showing the protection mode). Upon a fault event, the display immediately presents a fault alarm message, identifying the nature of the detected condition.

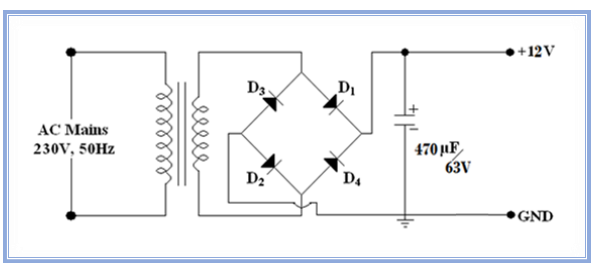
E. Power Supply Design

A regulated 12 V DC bus is derived from the 230 V mains via a 230 V/15 V step-down transformer (1 A), a full-wave bridge rectifier (four 1N4007 diodes, PIV > 44 V), and a 470 µF electrolytic filter capacitor. The Arduino's onboard 5 V regulator subsequently provides the logic-level supply for the sensors and display. The power supply design is governed by:

$$V\_m = (V\_dc \times \pi) / 2 = (14 \times 3.14) / 2 \approx 21.98\ V$$

$$C = (I \times \Delta T) / \Delta V = (1 \times 0.01) / 26 \approx 384\ \mu F \rightarrow$$

Selected: 470 µF



IV. HARDWARE SPECIFICATIONS

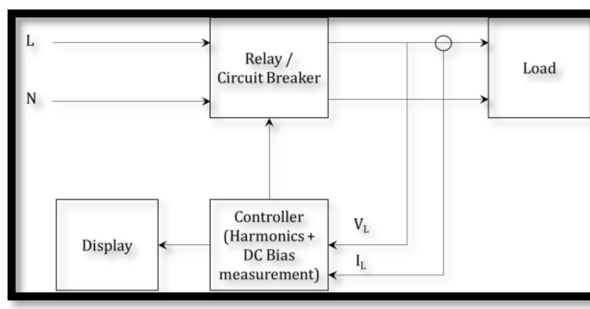
Table I summarises the key components used in the prototype.

TABLE I
SYSTEM COMPONENT SPECIFICATIONS

Component	Model / Part	Key Specifications
Microcontroller	Arduino Uno (ATmega328P)	16 MHz, 10-bit ADC, 14 DIO, 6 AI
Current Sensor	ACS712-30A	±30 A, 100 mV/A, 80 kHz BW, 5 V supply
Voltage Sensor	ZMPT101B	Up to 250 V AC, on-board op-amp, 5 V supply
Relay	OMRON MY-4 (12 V)	10 A, 400 V contacts, electromagnetic
Display	16×2 LCD (HD44780)	Alphanumeric, 5 V, 4-bit/8-bit interface
Rectifier Diodes	1N4007	1 A, 1000 V PIV
Filter Capacitor	Electrolytic	470 µF, 25 V
Transformer	Step-down	230 V / 15 V, 1 A

V. DETECTION ALGORITHM

The detection algorithm is structured as a continuous real-time loop executing on the Arduino Uno. The software flow is described below.



A. Initialisation

On power-up, the controller initialises the LCD, configures sensor analog input pins (A0, A1) and the relay digital output pin (D7), and forces the relay to the energised (closed) state, allowing normal power flow to the load.

B. Mode Selection

A mode-selection switch connected to analog pin A5 determines the operating mode. When the switch is HIGH, the system operates in Protection OFF (Metering) mode. When LOW, it enters Protection ON (Active Monitoring) mode.

C. Metering Mode (Protection OFF)

In this mode, the system functions as a digital power meter. The controller continuously samples the voltage and current sensors, calculates RMS voltage and AC/DC current magnitudes, and displays the results on the LCD. No fault evaluation is performed; the relay remains closed.

D. Active Monitoring Mode (Protection ON)

In this mode, the fault_check() function is invoked continuously. The controller analyses the sampled waveform data to compute the DC bias and harmonic index. If either computed quantity exceeds its respective threshold, the controller:

- Sets the relay control pin LOW (de-energising the relay and opening the load circuit).
- Displays "FAULT: ARC DETECTED" on the LCD with specifics of the triggering condition.
- Enters a latched infinite loop, preventing automatic reset. Manual Arduino reset is required to restore power.

VI. EXPERIMENTAL RESULTS

The prototype was tested under three experimental scenarios, corresponding to the two operating modes and the fault-trip sequence.

A. Result 1 — Metering Mode (Protection OFF)

With the mode switch set to HIGH, the system operated as a digital meter. The ACS712 and ZMPT101B sensors correctly acquired instantaneous current and voltage waveforms. The Arduino ADC digitised these signals, and the firmware computed RMS voltage and AC/DC current magnitudes. The LCD alternated between displaying:

- Measurement Screen: "Voltage = [V] V" / "Current = [I] A"
- Status Screen: "Arc Fault" / "Protection OFF"

No relay trip was initiated in this mode, confirming correct metering functionality independent of protection logic.

B. Result 2 — Active Protection Mode (Protection ON)

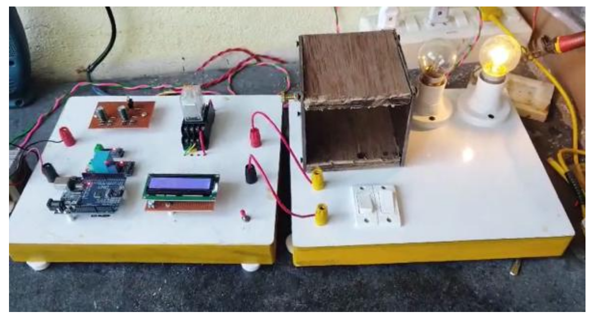
With the mode switch set to LOW, the system transitioned to continuous active monitoring. The LCD displayed "Arc Fault / Protection ON." The fault_check() function executed in a polling loop. Under normal resistive load conditions (100 W lamp), no threshold was exceeded and the relay remained closed. The system maintained stable continuous operation without nuisance tripping during this phase.

C. Result 3 — Fault Trip Action

When a fault condition was introduced (simulated by exceeding the frequency threshold during testing), the system executed the following protective sequence:

- Relay trip: The relay output pin was driven LOW, physically opening the load circuit within the relay switching time (~8 ms).
- Alarm: The LCD was immediately updated with "Fault Detected / Reset..." alert message.
- Latch: The firmware entered an infinite latch loop, sustaining the disconnected state until a deliberate manual reset.

These results validate the complete sense-process-act-display chain of the prototype.



VII. DISCUSSION

The prototype demonstrates a functional architecture for AFCI operation. However, a critical gap was identified between the stated design objective and the implemented detection logic in the current prototype:

- Detection Basis: The prototype's fault_check() function triggers solely on a line frequency threshold (frequency > 51 Hz) rather than on computed DC bias or harmonic index values, which were the originally stated indicators.
- Pin Assignment Conflict: Both the voltage sensor and the frequency-detection sensor were mapped to the same Arduino analog pin (A0), preventing simultaneous operation and requiring resolution in future revisions.
- DC Current Unused: The measured DC current magnitude (I_D) was correctly computed but not incorporated into the fault decision logic, leaving the DC bias detection goal unimplemented.
- Processing Constraints: The ATmega328P's 16 MHz clock and 10-bit ADC limit real-time FFT implementation to reduced-resolution spectral analysis, necessitating a migration to a 32-bit platform for full harmonic analysis.

These findings define a clear roadmap for the next design iteration, which should prioritise correcting the pin assignment, incorporating the DC bias metric into fault logic, and implementing a fixed-window FFT algorithm for harmonic quantification.

VIII. APPLICATIONS

The technology demonstrated in this project has broad applicability:

- Residential Buildings: Protection of branch circuits against arc faults in aging or mechanically damaged wiring.
- Data Centres and Server Rooms: Prevention of arc-induced fires in high-density power cable environments.
- Industrial Facilities: Motor control centres and control panels where vibration accelerates conductor wear.
- Healthcare Facilities: Ensuring continuity and safety of circuits supplying life-critical equipment.
- Renewable Energy Systems: Detection of DC arc faults in photovoltaic (PV) string wiring, where DC arcs are particularly hazardous.
- Aviation and Transportation: Compact wiring environments where AFCI technology is mandated for safety compliance.

The following enhancements are recommended for future iterations:

A. FFT-Based Harmonic Analysis

Implementing a fixed-window Fast Fourier Transform on the sampled current data will enable precise frequency-domain analysis, allowing threshold-based detection on the high-frequency energy band (2 kHz–100 kHz) specific to arc events.

B. 32-Bit Microcontroller Migration

Migration to an ESP32 or ARM Cortex-M (STM32) platform will provide the processing speed (>100 MHz), ADC resolution (12-bit), and memory necessary for real-time FFT and embedded machine learning inference.

C. Machine Learning Classification

Training a compact neural network or support vector machine (SVM) on a labelled dataset of arc and non-arc waveforms will improve discrimination between true arc events and nuisance sources (e.g., vacuum cleaners, dimmers), reducing Type I errors.

D. IoT and GSM Integration

Integration of a GSM module (SIM800L) or Wi-Fi (via ESP32) will enable automatic SMS and push-notification alerts upon fault detection, supporting remote monitoring of electrical health through a cloud dashboard.

E. Three-Phase Extension

Scaling the hardware to include three current and three voltage sensing channels will adapt the system for three-phase four-wire industrial and commercial installations.

X. CONCLUSION

This paper presented the design and experimental validation of a microcontroller-based arc fault detection and protection prototype. The system employs an Arduino Uno, Hall-effect current sensing, and transformer-based voltage sensing to implement a Sense Process–Act–Display protection chain. Three operational results were demonstrated: metering-only operation, active monitoring with threshold comparison, and automated relay trip with fault latching.

The work confirms the viability of the hardware architecture and identifies concrete corrective actions most critically, implementation of DC bias and FFT-based harmonic analysis in the fault detection logic necessary to achieve the full AFCI design objective. The prototype establishes a replicable, low-cost platform for further research into intelligent arc fault protection systems, with a clear path toward commercial-grade reliability through the adoption of 32-bit processing, machine learning classification, and IoT-enabled remote notification.

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