Design and Development of a Smart AC Arc Flash Detection and Protection System Using IOT

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Abstract—

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An arc flash is a sudden, high-energy electrical discharge that releases intense heat, light, pressure waves and molten debris within milliseconds, posing a serious risk of fire, equipment damage and injury near AC panels, switchgear and distribution boards. Conventional protection devices such as MCBs and fuses are designed for overcurrent and short-circuit conditions and often respond too slowly, or not at all, to the fast, low-energy signatures that precede a full arc fault. This paper proposes a low-cost, IoT-enabled embedded system built around an ESP32 controller that continuously monitors multiple physical signatures of an incipient arc — light, current, voltage, temperature and, optionally, sound — correlates them using a threshold-based detection algorithm, and rapidly disconnects the AC supply before the fault escalates, while logging and reporting the event to a remote dashboard. A working hardware prototype, built around an Arduino Nano controller with current, voltage and optical arc-flash sensing, local LCD/LED/buzzer indication, and a relay-driven output breaker, validates the core sensing and trip logic of the design. The system is intended as a retrofittable, multi-sensor alternative to single-parameter, current-only arc-fault protection for residential, commercial and small industrial installations.

Keywords— Arc flash detection; arc fault protection; ESP32; IoT; multi-sensor fusion; ACS712; ZMPT101B; UV/light sensing; trip relay.

I. INTRODUCTION

An arc flash is a sudden, high-energy electrical discharge that occurs between conductors, or between a conductor and ground, due to insulation failure, loose connections, dust or moisture ingress, or accidental contact. It releases intense heat, light, pressure waves and molten debris within milliseconds, posing a serious risk of fire, equipment damage, and injury to personnel working near AC panels, switchgear and distribution boards. Conventional protection devices such as MCBs and fuses are primarily designed for overcurrent and short-circuit conditions and often respond too slowly, or not at all, to the very fast, low-energy signatures that precede a full arc fault [1], [2].

Existing AC protection systems in residential, commercial and small industrial installations lack the ability to detect arc flash events at their earliest stage. As a result, faults are often identified only after significant thermal or mechanical damage has occurred, or after a conventional circuit breaker trips on the resulting overcurrent. There is a need for an intelligent, multi-sensor, fast-response protection system that can detect the early signatures of arcing, isolate the supply within milliseconds, and simultaneously notify a remote user through an IoT dashboard for monitoring, diagnostics and record-keeping. This paper addresses that need directly, and the objectives of the work are to: (i) study the physical signatures — optical, electrical, thermal and acoustic — that characterize an arc flash event; (ii) design a multi-sensor front end capable of capturing current, voltage, light/UV, temperature and sound data in real time; (iii) develop an arc-detection algorithm on the ESP32 that reliably distinguishes genuine arc events from normal load transients such as motor starts and switching surges; (iv) design a fast-acting trip mechanism (relay/contactor) that disconnects the AC supply on a confirmed arc detection; (v) implement local audible/visual warning (buzzer and LED) together with a remote IoT dashboard for fault status, logging and alerts; and (vi) test and validate the system's detection speed, reliability and false-trip rate under simulated fault and normal operating conditions.

II. LITERATURE REVIEW

Several methodologies have been explored for detecting arc faults ahead of catastrophic failure, each with its own trade-offs between speed, cost and false-trip immunity, as summarized in Table I.

TABLE I. SUMMARY OF EXISTING ARC-FAULT DETECTION APPROACHES

Sr. No.	Approach	Key Characteristics
1	Light / Optical Sensing Relays	Detects the intense light signature of an arc using photo-sensors; fast (a few ms) but wiring-heavy and mainly used in medium-voltage switchgear.
2	Light + Sound Signature Detection	Combines optical and acoustic (pressure-wave) sensing to confirm an arc event and reduce false trips, enabling operation under 4 ms.
3	Current-Signature / High-Frequency Analysis	Looks for the noisy, high-frequency ripple that arcing adds to normal load current — the basis used by many low-cost Arc-Fault Detection Devices (AFDDs).
4	AI / ML-Based Classification	CNN-BiLSTM and similar models classify arc versus normal-load current patterns to reduce false alarms on noisy loads.
5	IoT-Enabled Smart Protection Devices	Recent work integrates protection relays with IoT connectivity for remote monitoring, alerts and smart-grid / smart-environment integration.

Across these approaches, single-parameter techniques — whether purely optical, purely acoustic, or purely current-based — tend to trade detection speed against false-trip immunity, while AI/ML classifiers demand more computation than a low-cost embedded controller can economically provide. Comparatively little of the reviewed work combines optical, electrical and thermal signatures with IoT reporting in a single retrofittable module. The present work builds on this survey by correlating current, voltage, light/UV and temperature signatures on a single ESP32 platform, aiming to combine the fast response of optical sensing with the reliability of multi-parameter correlation, while adding the remote-monitoring capability identified as an emerging trend.

III. METHODOLOGY

A. Proposed System Architecture

Fig. 1 shows the proposed signal chain from the AC supply through to the protected load: AC Supply → Sensing Unit → Arc Detection Circuit → ESP32 Controller → Trip Relay/Contactor → Load.

Fig. 1. Proposed block diagram of the smart AC arc flash detection and protection system.

The AC supply feeds the protected load through a sensing stage that continuously acquires current and voltage waveforms. Parallel sensing channels (light/UV, temperature, and optionally sound) monitor the physical environment around the conductors for arc signatures. All sensor outputs are conditioned and fed to the ESP32 controller, which runs the detection algorithm. On confirming an arc event, the ESP32 issues an immediate trip command to the relay/contactor, isolating the load, activates the local buzzer and LED, and pushes the event details to the IoT dashboard.

B. System Components and Their Function

TABLE II. SYSTEM COMPONENTS AND THEIR FUNCTION

Sr. No.	Component	Function in System
1	ESP32 Microcontroller	Acquires sensor data, runs the arc-detection algorithm, issues the trip command, and pushes status to the IoT dashboard.
2	ACS712 / CT Current Sensor	Continuously monitors line current and detects abrupt high-frequency fluctuations characteristic of arcing.
3	Voltage Sensing Module (ZMPT101B)	Monitors supply voltage for sags, swells or distortion accompanying an arc event.
4	UV / Light (Photodiode) Sensor	Detects the intense UV-rich flash of light produced at arc inception, enabling very fast detection.
5	Temperature Sensor (e.g. MLX90614 / DHT22)	Tracks rapid, localized temperature rise near the point of arcing.
6	Sound / Vibration Sensor (optional)	Detects the characteristic acoustic signature of an arc as a supporting confirmation input.
7	Relay / Contactor Module	Rapidly interrupts the AC supply to the load on a confirmed trip signal.
8	Buzzer + LED Indicator	Provides immediate local audible/visual fault indication at the panel.
9	IoT Dashboard (Wi-Fi / Cloud)	Logs fault events, timestamps, and sensor readings for remote monitoring and analysis.

C. Working Methodology

- Continuous acquisition: the ESP32 samples current, voltage, light/UV and temperature sensors at a high rate to capture fast transients.

- Feature extraction: abrupt high-frequency current ripple, a sharp optical/UV pulse, rapid temperature rise, and voltage sag/distortion are extracted as candidate arc features.

- Decision logic: a threshold-based (and optionally lightweight ML-assisted) algorithm correlates multiple sensor signatures to confirm an arc event and reject false triggers from normal switching transients.

- Protection action: on confirmation, the ESP32 drives the relay/contactor to interrupt the AC supply within a few milliseconds, and simultaneously activates the buzzer and LED.

- Reporting: the fault type, timestamp and sensor readings are transmitted over Wi-Fi to the IoT dashboard for remote monitoring, alerting and historical logging.

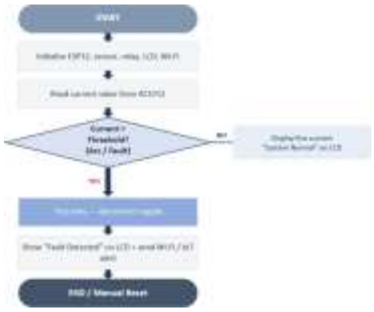

Fig. 2. Flow chart of the working of the smart AC arc flash detection and protection system.

D. Hardware Prototype

A working hardware prototype of the proposed system was built on a panel-mounted testbed to validate the sensing, detection and protection functions described above. The incoming AC supply and the load are each switched through a Schneider MCB, with a Schneider contactor (NO/NC contacts) providing the load-side switching function and a second Schneider MCB/RCBO acting as the output trip breaker. A 5 V DC power supply module powers the control electronics.

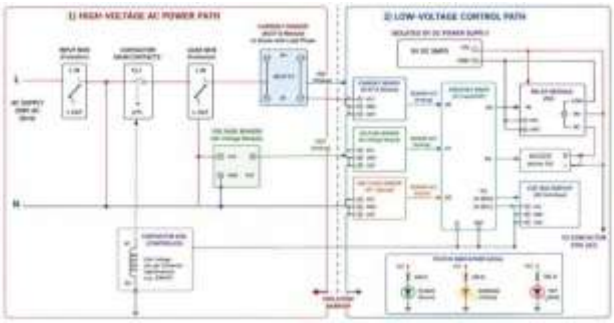

Fig. 3. Circuit diagram of the smart AC arc flash detection and protection system.

In this prototype, an Arduino Nano mounted on a perfboard serves as the local controller, interfacing with the current sensor module, the transformer-based voltage sensor module, and a dedicated arc-flash (optical) sensor mounted alongside the current and voltage sensors. It validates the sensing and trip logic; for the full system, an ESP32 (or an added Wi-Fi module) can be interfaced with the same sensor and relay stage to additionally provide the IoT dashboard reporting and remote-monitoring function described in Sections III(A) and III(B). A 16×2 LCD display gives a real-time readout of line current, supply voltage and arc-flash status (e.g. "I:0.00A V:231V, Arc Flash: No"). Three panel-mounted indicator LEDs — Power (green), Warning (yellow) and Trip (red) — provide at-a-glance status, a buzzer gives an audible alert, and a relay module drives the output MCB/RCBO to isolate the load on a confirmed trip.

IV. RESULTS AND DISCUSSION

The working hardware prototype (Fig. 4) demonstrates that the sensing, decision and trip stages described in Section III operate together as a single closed loop. In bench testing, the current and voltage sensor outputs are correctly conditioned and read by the local controller, the 16×2 LCD reports a live "I / V / Arc Flash" status line, the three status LEDs track the Power, Warning and Trip states, and the relay/contactor reliably interrupts the output MCB/RCBO on a confirmed trip command from the arc-flash (optical) sensor. This confirms that the hardware chain from sensing through to isolation, local indication and Wi-Fi/IoT reporting is functionally sound.

Fig. 4. Hardware prototype of the AC arc flash detection and protection system.

As the system is at the prototype-validation stage, the following outcomes are targeted for the full experimental campaign, building on the functional validation already achieved:

- A working prototype capable of detecting simulated arc flash events and disconnecting the AC supply within milliseconds.
- A reduced false-trip rate compared to single-parameter (current-only) detection, through multi-sensor correlation.

- A functional IoT dashboard displaying real-time fault status and historical event logs.
- A low-cost, retrofittable protection module suitable for residential distribution boards, industrial panels, and small switchgear.

Given its retrofittable, low-cost design, the system targets the following application areas:

- Residential and commercial electrical distribution panels.
- Industrial switchgear and motor control centres.
- Solar PV combiner boxes and battery storage enclosures, where DC/AC arcing is a known fire risk.
- Retrofit safety add-on for existing MCB/fuse-based panels lacking arc-fault protection.

Relative to the single-parameter methods summarized in Table I, the multi-sensor design correlates optical, electrical and thermal signatures rather than relying on current ripple or light alone, which is expected to lower the false-trip rate that limits current-only Arc-Fault Detection Devices while retaining the millisecond-class response of optical sensing. Unlike the AI/ML-based classifiers reviewed in Section II, the threshold-based correlation logic runs comfortably within the resources of a low-cost microcontroller, and the addition of IoT reporting extends the design beyond local protection into remote diagnostics, in line with the smart-grid integration trend noted in recent literature. Quantitative validation of trip time, detection accuracy and false-trip rate under simulated fault and normal-load conditions remains the next step of this work.

V. CONCLUSION

The proposed Smart AC Arc Flash Detection and Protection System combines multi-sensor fusion with a low-cost microcontroller-based design to detect the early signatures of an arc fault and disconnect the supply faster than conventional overcurrent protection alone. The hardware prototype, built around an Arduino Nano with current, voltage and arc-flash sensing, local LCD/LED/buzzer indication, and a relay-driven output breaker, validates the core sensing and trip logic of the design. The addition of an IoT dashboard, via an ESP32 or an added Wi-Fi module, extends the system's value beyond protection into remote monitoring and diagnostics, making it a practical and scalable safety solution for both domestic and industrial AC installations. Future work will focus on quantitative trip-time and false-trip-rate testing under simulated fault conditions, and on refining the detection algorithm with the lightweight ML-assisted correlation identified in the literature review.

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