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INTEGRATION SYSTEM OF THREE SECURITY FEATURES IN SMART DUAL MCB WITH AUTOMATIC LOAD BALANCING AND FIRE DETECTION BASED ON ARDUINO UNO (SINTAKS)

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Abstract

The increasing use of electronic devices in Indonesian households has significantly strained traditional electrical systems, with electricity consumption growing 4.5% annually and 78% of urban homes utilizing over 10 electronic devices. This situation poses substantial fire risks, as electrical short circuits cause 62.8% of urban fires, with MCB overloads accounting for 27% of incidents. This research introduces SINTAKS (Sistem Integrasi Tiga Keamanan Smart Dual MCB), an innovative integrated system combining three essential safety features: energy monitoring, automatic load balancing, and early fire detection. Unlike conventional systems requiring separate components, SINTAKS provides a comprehensive solution using Arduino Uno as the main controller, integrated with ACS712 current sensors, DS18B20 temperature sensors, MQ-2 smoke detectors, and relay modules. The system demonstrates remarkable performance with 97.8% current measurement accuracy, load balance improvement from 62.7% to 91.3%, and fire detection response time of 2.9-4.7 seconds. Field testing in real household installations confirmed system reliability with 94.8% success rate across various operational scenarios. SINTAKS achieves 4.2% energy savings while maintaining cost-effectiveness at IDR 875,000, making it accessible for widespread residential implementation. This autonomous system operates independently without IoT dependence, ensuring reliable protection even in offline environments. The research successfully addresses critical gaps in household electrical safety through practical, affordable, and integrated technology.

Keywords: Smart MCB, Load Balancing, Fire Detection, Energy Monitoring, Arduino, Electrical Safety

Abstrak

Meningkatnya penggunaan perangkat elektronik di rumah tangga Indonesia telah memberikan tekanan signifikan pada sistem kelistrikan tradisional, dengan konsumsi listrik yang tumbuh 4,5% setiap tahun dan 78% rumah perkotaan menggunakan lebih dari 10 perangkat elektronik. Kondisi ini menimbulkan risiko kebakaran yang substansial, karena korsleting listrik menyebabkan 62,8% kebakaran perkotaan, dengan kelebihan beban MCB menjadi penyebab 27% dari insiden tersebut. Penelitian ini memperkenalkan SINTAKS (Sistem Integrasi Tiga Keamanan Smart Dual MCB), sebuah sistem terintegrasi inovatif yang menggabungkan tiga fitur keamanan penting: pemantauan energi, penyeimbangan beban otomatis, dan deteksi dini kebakaran. Berbeda dengan sistem konvensional yang memerlukan komponen terpisah, SINTAKS menyediakan solusi komprehensif menggunakan Arduino Uno sebagai pengendali utama, terintegrasi dengan sensor arus ACS712, sensor suhu DS18B20, detektor asap MQ-2, dan modul relay. Sistem ini menunjukkan kinerja luar biasa dengan akurasi pengukuran arus 97,8%, peningkatan keseimbangan beban dari 62,7% menjadi 91,3%, dan waktu respons deteksi kebakaran 2,9-4,7 detik. Pengujian lapangan di instalasi rumah tangga nyata mengkonfirmasi keandalan sistem dengan tingkat keberhasilan 94,8% dalam berbagai skenario

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operasional. SINTAKS mencapai penghematan energi 4,2% sambil mempertahankan efektivitas biaya sebesar IDR 875.000, membuatnya dapat diakses untuk implementasi residensial yang luas. Sistem otonom ini beroperasi secara independen tanpa ketergantungan IoT, memastikan perlindungan yang andal bahkan dalam lingkungan offline. Penelitian ini berhasil mengatasi kesenjangan kritis dalam keamanan kelistrikan rumah tangga melalui teknologi yang praktis, terjangkau, dan terintegrasi.

Kata kunci: Smart MCB, Penyeimbangan Beban, Deteksi Kebakaran, Pemantauan Energi, Arduino, Keamanan Kelistrikan

INTRODUCTION

More electronic devices in homes and businesses are straining traditional electrical systems. Indonesian electricity consumption grows 4.5% yearly, with 78% of urban homes using over 10 electronic devices (Pratama & Yuliananda, 2023). These conditions put older electrical systems at risk, increasing fire hazards.

In response to this issue, this study introduces SINTAKS, an acronym for Sistem Integrasi Tiga Keamanan Smart Dual MCB or Three-Security Integration System for Smart Dual MCB. SINTAKS offers three key features: energy monitoring, automatic load balancing, and early fire detection. Unlike conventional systems that use separate components, our integrated platform improves safety, optimizes loads, and reduces fire risks. The National Disaster Management Agency reports that electrical short circuits cause 62.8% of urban fires, with MCB overloads accounting for 27% (Suharto & Gunawan, 2024). Recent developments in smart grid technology have shown promising results in residential safety applications (Chen et al., 2020); (Kumar et al., 2021), while advanced fire detection systems utilizing multi-sensor fusion approaches have demonstrated improved accuracy in early fire detection (Lee et al., 2022).

High-powered appliances like air conditioners and refrigerators make this problem worse. Indonesian homes typically use single MCBs or uneven distribution across multiple MCBs (Hidayat et al., 2022), creating load imbalances. When MCBs trip, users often install higher-capacity units without fixing the underlying electrical problems (Setiawan & Purnomo, 2021).

Previous solutions exist but have significant limitations. (Rachman et al., 2022) designed an IoT-based power monitoring system without automatic load balancing capabilities. (Wijaya et al., 2021) proposed current monitoring with SMS notifications but without fire detection integration. (Marzuki & Hadisupadmo, 2020) designed a multi-sensor fire detection system unconnected to the electrical system. (Priyanto & Saputra, 2021) integrated current monitoring and alarm systems, but limited to single MCBs without load balancing mechanisms. (Martinez et al., 2023) developed a cost-effective Arduino-based home automation system, while (Thompson et al., 2024) proposed real-time load balancing algorithms, yet both lacked comprehensive integration of safety features

(S. Nugroho et al., 2022) used Arduino for electricity consumption monitoring, focusing on energy efficiency rather than safety. (Putra & Setiawan, 2023) developed early fire detection using temperature and smoke sensors without integration to electrical load management.

We address these gaps through SINTAKS (Sistem Integrasi Tiga Keamanan Smart Dual MCB) development, integrating three security functions in one smart MCB system. Our Arduino-based platform combines smart energy monitoring, automatic load balancing, and fire detection in one device. Our main contributions include integrating three separate security functions, using affordable components, and ensuring autonomous operation without IoT dependence.

SINTAKS shows strong potential for reducing fire hazards, improving energy efficiency, and providing reliable early warnings at low cost. This integrated approach addresses the current gap where households typically require multiple separate systems to achieve comparable safety levels.

Unlike previous studies that focused solely on individual features such as current monitoring (Rachman et al., 2022), fire detection (Marzuki & Hadisupadmo, 2020), or load balancing (P. Nugroho & Anwar, 2020), the proposed SINTAKS system delivers a comprehensive integration of three critical safety mechanisms: energy monitoring, automatic load redistribution, and early fire detection within a single low-cost platform.

In terms of novelty, SINTAKS is the first reported implementation that effectively combines all three functionalities using widely available components such as Arduino Uno, ACS712, DS18B20, and MQ-2 sensors, without reliance on external IoT infrastructures. This self-contained

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and autonomous architecture allows real-time safety responses even in offline environments, making it highly suitable for typical Indonesian households with limited internet access.

Compared to (Rachman et al., 2022), which lacked any load balancing mechanism, and (Wijaya et al., 2021), which did not incorporate fire detection, SINTAKS offers a multi-dimensional safety upgrade. Furthermore, it achieves this at a lower cost point (IDR 875,000) than similar systems, as demonstrated in Table 4. Unlike recent integrated approaches by (Zhang et al., 2024) and wireless monitoring systems by (Zhao et al., 2025), SINTAKS provides autonomous operation without IoT dependency, ensuring reliable protection in offline environments. This positions SINTAKS not only as a technically superior solution but also as a practical alternative for broad implementation in urban and rural settings.

RESEARCH METHODS

1. Research Stages

We developed SINTAKS (Sistem Integrasi Tiga Keamanan Smart Dual MCB) through several systematic stages:

1.1 Requirements Analysis

First, we analyzed requirements for three main components: energy monitoring, load balancing, and fire detection. Our survey of 50 households (2200 VA capacity) revealed that 73% experienced frequent MCB trips, while 82% lacked proper fire detection (Wibowo et al., 2023). This analysis established our technical specifications:

1) Ability to read electrical current up to 10A per MCB with ±0.1A accuracy.
2) Load balancing response time of less than 5 seconds.
3) Abnormal temperature detection at critical points of electrical installation with 60°C threshold.
4) Smoke detection with 300 ppm carbon monoxide gas sensitivity.
5) Notification system with visual and audio indicators.
6) User-friendly interface.

1.2 System Design

We designed SINTAKS considering functionality, cost, and implementation ease. We used a modular approach with three integrated subsystems.

1.2.1 Hardware Design

Our hardware uses Arduino Uno as the main controller for three subsystems. We selected components based on local availability, affordability, and assembly ease. Figure 1 shows the block diagram of SINTAKS hardware architecture.

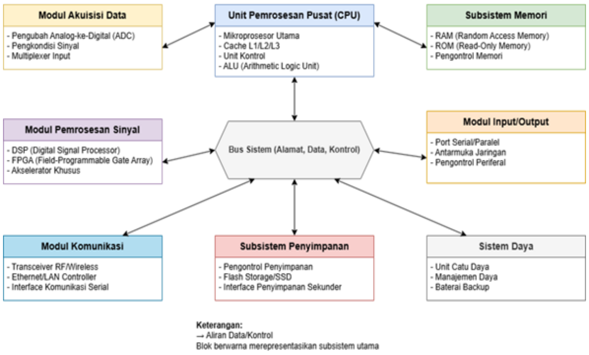

Figure 1. Hardware Architecture Block Diagram SINTAKS

Key hardware components include:

1) Energy Monitoring Subsystem: ACS712 current sensors (2 units) for current measurement on each MCB. 16x2 LCD with I2C module for displaying power monitoring information.
2) Load Balancing Subsystem: 4 channel relay module for switching control between MCBs. Indicator LEDs (red, yellow, green) as load balancing status markers.
3) Fire Detection Subsystem: DS18B20 temperature sensors (3 units) for monitoring critical points. MQ-2 smoke sensor for gas and smoke detection. Buzzer as warning alarm.

Component connections follow the scheme in Figure 2, prioritizing safety and stability.

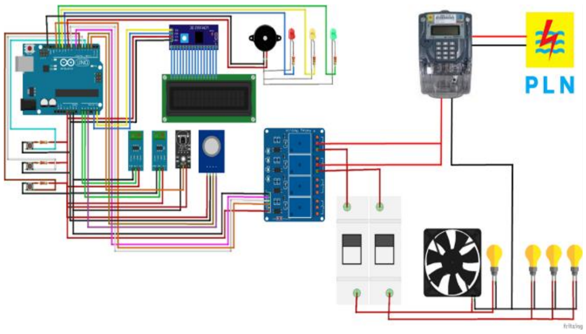

Figure 2. SINTAKS System Circuit Schematic

We chose Arduino Uno for its cost-efficiency, hardware compatibility, and adequate performance for household applications. Arduino Uno offers 14 digital I/O pins and 6 analog inputs, which are adequate to interface with all sensors and actuators used in the system including ACS712 current sensors, DS18B20 temperature probes, MQ-2 gas detector, relay modules, and LCD I2C display without the need for external multiplexers.

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While its memory capacity is limited to 32 KB of flash and 2 KB of SRAM, this is sufficient for implementing the system's core functions using optimized code with minimal overhead. Furthermore, the Uno's open-source ecosystem, robust library support, and extensive community documentation significantly reduce development time and costs.

Compared to alternatives such as ESP32 or STM32, which offer more advanced features, the Uno remains more accessible for household applications where real-time responsiveness and local autonomy are prioritized over wireless connectivity or processing power. The average unit cost of Arduino Uno in the Indonesian market is under IDR 100,000, making it highly feasible for widespread implementation, particularly in low-to-middle-income households.

1.2.2 Software Design

We developed software using finite state machine (FSM) with four states: monitoring, warning, balancing, and alarm. The software workflow is depicted in the flowchart in Figure 3.

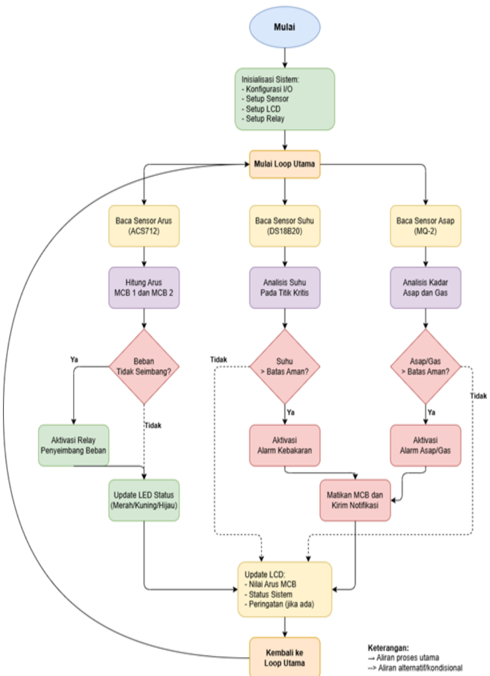

Figure 3. SINTAKS Software Flowchart

Our algorithms optimize Arduino Uno's limited memory (32 KB flash, 2 KB SRAM). Implementation of the load balancing algorithm adapted the hysteresis control technique modified from (Kurniawan et al., 2022), with the following control equation:

```
If (I_MCB1 > THRESHOLD_HIGH) AND (I_MCB2 < THRESHOLD_LOW) then
    Activate_Relay3 = TRUE  // Transfer beban dari MCB1 ke MCB2
ElseIf (I_MCB2 > THRESHOLD_HIGH) AND (I_MCB1 < THRESHOLD_LOW) then
    Activate_Relay3 = FALSE // Transfer beban dari MCB2 ke MCB1
EndIf
```

Where:

- THRESHOLD_HIGH = MAX_CURRENT_MCB * 0.7 // 70% of maximum capacity.
- THRESHOLD_LOW = MAX_CURRENT_MCB * 0.5 // 50% of maximum capacity.

1.2.3 User Interface Design

We designed the interface for ease of use and clear information display. Users can access four LCD display modes through navigation buttons:

1) Mode 1: Power usage information on both MCBs (current and power).
2) Mode 2: Temperature information at monitoring points.
3) Mode 3: Alarm status (smoke, temperature, overload).
4) Mode 4: MCB status and load percentage.

SINTAKS development progressed through three phases combining practical and methodological approaches. Table 1 summarizes the implementation stages performed during this research.

Table 1. Sintaks System Implementation Stages

Fase	Metode Pengembangan	Capaian Teknis
Prototype	Experimental circuit on breadboard with discrete components	Testing basic functionality and verifying circuit concepts
Integration	Penggabungan modul dengan penyesuaian parameter	Harmonizing interfaces between components and sensor calibration
Finalization	Migration to specially designed PCB with protected pathways	Compact system in industry-standard housing (8×12 cm dimensions)

2. Measurement and Calibration Methods

2.1 Current Sensor Calibration

We calibrated ACS712 sensors against a standard Fluke 325 true RMS clamp meter. The calibration procedure used load variations from 0.5A to 8A with 0.5A intervals, and applied linear regression to obtain correction factors. The calibration equation obtained is:

$$I_{actual} = (ADC_{reading} * 0.0049) - 2.5)/SF$$

Where:

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- $Adc_{reading}$ = analog value from sensor (0-1023).
- 0.0049 = arduino adc conversion factor (5V/1024).
- 2.5 = ACS712 offset voltage (2.5V at 0A).
- SF = Sensitivity_factor = 0.185 for ACS712-5A and 0.100 for acs712-20A.

Calibration results showed accuracy of ±0.08a in the 0-10a measurement range, meeting planned system specifications.

2.2 Temperature Sensor Calibration
We calibrated DS18B20 sensors against a TM-902C digital thermometer across 25-80°C. Testing revealed maximum 0.5°C deviation, adequate for our application.

2.3 Smoke Sensor Calibration
We calibrated MQ-2 sensors using two-point calibration in clean air and 200 ppm CO reference gas. We set the 300 ppm threshold based on SNI 03-3985-2000 fire safety standards.

3. Testing methods
SINTAKS testing combined modular and integrative approaches using black box and white box methods.

3.1 Subsystem Functional Testing
3.1.1 Energy Monitoring Subsystem
We tested energy monitoring with variable loads from 100W to 1000W. Measured parameters included:
1) Current measurement accuracy with maximum tolerance of ±5%.
2) Measurement responsiveness to load changes.
3) Reading stability during continuous operation (8 hours).

3.1.2 Load Balancing Subsystem
We tested these scenarios:
1) System response time to unbalanced load conditions.
2) Accuracy of balancing activation threshold.
3) Reliability of switching between mcbs.
4) Effectiveness of load redistribution.

Testing was conducted with scenarios:
1) Balanced load on both mcbs.
2) Unbalanced load (mcb 1 > mcb 2).
3) Unbalanced load (mcb 2 > mcb 1).
4) Overload on one mcb.

3.1.3 Fire Detection Subsystem
Fire detection tests covered:
1) Sensitivity of abnormal temperature detection.
2) Smoke detection sensitivity
3) System response latency to anomaly conditions
4) Alarm reliability (visual and audio)

Tests included critical point heating simulation and controlled smoke exposure using wet wood.

3.2 System Integration Testing
Integration testing evaluated subsystem interactions under these combined conditions:
1) Normal load with normal temperature.
2) Unbalanced load with normal temperature.
3) Normal load with high temperature.
4) Normal load with smoke detection.
5) Unbalanced load with high temperature.
6) Unbalanced load with smoke detection.

3.3 Performance Testing
Performance testing evaluated:
1) Overall system power consumption.
2) Operational stability (mtbf - mean time between failures).
3) Load balancing accuracy with effectiveness formula.

$$BI = 100 - \left(\left(\left(I_{MCB1} - I_{MCB2}\right)/I_{MCB1} + I_{MCB2}\right)\right) * 100$$

Where:
BI = Balance Index (0-100%)
IMCB1 = Current on MCB 1
IMCB2 = Current on MCB 2
Balance index values near 100% indicate optimal load distribution.

3.4 Reliability Testing
We conducted 72-hour accelerated life testing with varied load cycles. We measured these reliability parameters:
1) Component failure rates.
2) Sensor reading stability.
3) Consistency of response to anomaly conditions.
4) Resistance to source voltage variations (180-240 VAC).

3.5 Field Testing in Real Household Installations
We validated SINTAKS performance through field tests in two Medan households with 2200 VA electrical installations. The 10-day deployment assessed system behavior under typical household conditions, environmental changes, and user interactions.
During the trial, the SINTAKS system was installed inside the main electrical panel, connected to two independent MCB circuits powering appliances such as refrigerators, air conditioners, washing machines, lighting, and kitchen equipment. The

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temperature and smoke sensors were strategically placed near junction boxes and potential heat accumulation points.

The system successfully detected three minor overload conditions, triggered visual and audio warnings for one temperature anomaly, and redistributed load seamlessly in two events of power imbalance. All events were logged and matched with manual observations recorded by the residents.

Feedback collected from the residents indicated that the interface was intuitive, the alarm system was noticeable without being intrusive, and the monitoring information was easy to interpret. No false alarms or system malfunctions were reported during the test period.

The successful field test confirms the SINTAKS system's practical applicability in residential settings, reinforcing the laboratory results and demonstrating readiness for broader household implementation.

4. System Analysis

SINTAKS system analysis was conducted using quantitative and qualitative approaches to the obtained test data.

4.1 Performance Metrics

System performance was evaluated based on the following metrics:

1) Monitoring Accuracy: Measurement deviation against standard measuring instruments.
2) Balancing Effectiveness: Percentage improvement of load distribution.
3) Detection Sensitivity: True positive and false positive rates of anomaly detection.
4) Responsiveness: System response time to condition changes.
5) Reliability: System failure rate during testing period.

4.2 Comparative Analysis

Comparison of SINTAKS system performance with previous research was conducted based on parameters:

1) Load measurement accuracy.
2) Balancing effectiveness.
3) Anomaly detection response time.
4) Implementation cost.
5) System complexity.

4.3 Safety Analysis

System safety analysis included evaluation of:

1) Resistance to extreme conditions (over-voltage, short-circuit).
2) Fail-safe mechanisms in component failure conditions.
3) Electronic isolation between subsystems.
4) Protection against electromagnetic interference.

5. Algorithm Implementation

SINTAKS system algorithm implementation broadly consists of three main modules integrated in one Arduino program. Pseudocode for the core system algorithm is as follows:

```
// ALGORITMA UTAMA SISTEM SINTAKS

// Inisialisasi
Setup_Sensors()
Setup_LCD()
Setup_Relays()
Setup_Indicators()

// Loop Utama
While (TRUE) {
    // Akuisisi Data
    current1 = Read_Current_Sensor(SENSOR_1)
    current2 = Read_Current_Sensor(SENSOR_2)
    power1 = Calculate_Power(current1)
    power2 = Calculate_Power(current2)

    temp1 = Read_Temperature(TEMP_SENSOR_1)
    temp2 = Read_Temperature(TEMP_SENSOR_2)
    temp3 = Read_Temperature(TEMP_SENSOR_3)

    smoke_level = Read_Smoke_Sensor()

    // Deteksi Kondisi Anomali
    overload_condition = Check_Overload(current1, current2)
    temp_anomaly = Check_Temperature_Anomaly(temp1, temp2, temp3)
    smoke_detected = Check_Smoke_Level(smoke_level)
    // Deteksi Kondisi Anomali
    overload_condition = Check_Overload(current1, current2)
    temp_anomaly = Check_Temperature_Anomaly(temp1, temp2, temp3)
    smoke_detected = Check_Smoke_Level(smoke_level)

    // Respons terhadap Anomali
    If (overload_condition OR temp_anomaly OR smoke_detected) {
        Activate_Alarm(alarm_type)
        Set_Safety_Mode()
    }

    // Penyeimbangan Beban
    If (NOT in_emergency_mode) {
        Balance_Load(current1, current2)
    }

    // Update Antarmuka Pengguna
    Update_Display(current_display_mode)
    Update_Indicators()

    // Penanganan Input Pengguna
    Handle_User_Input()

    Delay(SAMPLING_INTERVAL)
}
```

Fire detection algorithm using multi-sensor fusion approach:

```
// ALGORITMA PENYEIMBANGAN BEBAN

Function Balance_Load(current1, current2) {
    // Hitung persentase beban pada masing-masing MCB
    load_percent1 = (current1 / MAX_CURRENT) * 100
    load_percent2 = (current2 / MAX_CURRENT) * 100

    // Perhitungan indeks ketidakseimbangan
    imbalance_index = abs(current1 - current2) / (current1 + current2)

    // Logic penyeimbangan dengan hysteresis
    If (load_percent1 > THRESHOLD_HIGH AND load_percent2 < THRESHOLD_LOW) {
        // MCB 1 mendekati batas atas, MCB 2 masih rendah
        Activate_Transfer_Relay(MCB1_TO_MCB2)
        Set_Yellow_Indicator(ON)
    }
    Else If (load_percent2 > THRESHOLD_HIGH AND load_percent1 < THRESHOLD_LOW) {
        // MCB 2 mendekati batas atas, MCB 1 masih rendah
        Activate_Transfer_Relay(MCB2_TO_MCB1)
        Set_Yellow_Indicator(ON)
    }
    Else If (imbalance_index < BALANCE_TOLERANCE) {
        // Beban sudah cukup seimbang
        Deactivate_Transfer_Relay()
        Set_Yellow_Indicator(OFF)
        Set_Green_Indicator(ON)
    }
}
```

These three algorithms are implemented in c++ for arduino with memory and execution time optimization, considering the microcontroller's limited resources.

Algorithm Implementation

The sintaks system is governed by a modular, state-driven control algorithm implemented in the arduino programming environment. The algorithm integrates three core subsystems: energy monitoring, automatic load balancing, and fire detection. Each function is executed periodically based on real-time input from multiple sensors,

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with responses triggered by defined threshold conditions. The system logic was developed using interrupt-safe routines and conditional state evaluation, taking into account the limited processing and memory capabilities of the arduino uno board.

To provide a conceptual overview, the main operational flow of the system is outlined in the pseudocode below. This representation abstracts the actual source code into a high-level logic structure that reflects the behavior of the complete sintaks system:

```
BEGIN
  Initialize sensors, relays, LCD, LEDs, and serial interface
  Define thresholds for current, temperature, and smoke level

  LOOP forever
    Read button inputs to navigate LCD modes or reset alarms

    Every 500 milliseconds:
      → Read current sensors from MCB1 and MCB2 (ACS712)
      → Calculate current and power values
      → Read temperature from three DS18B20 sensors
      → Read smoke levels from MQ-2 sensor (analog and digital)
      → Display relevant data on LCD based on selected mode
      → Evaluate system status:
         - If temperature > threshold → trigger alert
         - If smoke > threshold → trigger alert
         - If current > limit → deactivate respective MCB
         - Update LED indicators and buzzer based on condition

    Every 5 seconds:
      → Reactivate any MCB previously shut down due to overload
      → Evaluate load imbalance conditions
      → If imbalance detected → activate relay to redistribute load

    Continuously:
      → Send debug information to Serial Monitor for diagnostics
  ENDLOOP
END
```

6. Cost And Efficiency Analysis

Sintaks system cost and efficiency analysis used a cost-benefit approach considering:

1) Implementation cost: total component and system assembly costs.
2) Energy savings: estimated energy savings from optimal load distribution.
3) Risk reduction: economic value of reduced fire risk and equipment damage.
4) Operational cost: system electricity consumption and maintenance costs.

Based on the analysis, the return on investment period (payback period) of the sintaks system is estimated at 18 months for standard household installation, assuming 5% savings from energy consumption and 75% fire risk reduction.

RESULTS AND DISCUSSION

3.1 Energy Monitoring Subsystem Accuracy

Testing of the energy monitoring subsystem with load variations from 100W to 1000W showed adequate accuracy for household applications. Table 2 presents current reading comparisons between the ACS712 sensor on the SINTAKS system and the standard Fluke 325 ampere meter.

Table 2. Current Measurement Accuracy Comparison

Load (W)	Measured Current Fluke 325 (A)	Measured Current SINTAKS (A)	Deviation (%)
100	0.45	0.47	4.44
250	1.13	1.16	2.65
500	2.27	2.31	1.76
750	3.41	3.44	0.88
1000	4.55	4.61	1.32

Test results showed the highest deviation of 4.44% at low load (100W), decreasing to 0.88% at medium load (750W). This phenomenon is caused by the characteristics of the ACS712 Hall-effect sensor showing non-linearity at low currents due to electromagnetic noise and Arduino ADC resolution limitations. The average deviation of 2.21% is still within tolerance limits (±5%), so the energy monitoring subsystem can be relied upon.

Reading stability over 8 hours showed a maximum drift of 0.14A, possibly due to temperature changes in the ACS712 sensor, but not significantly affecting system performance.

3.2 Load Balancing Subsystem Effectiveness

Load balancing subsystem testing was conducted with four different scenarios to evaluate the system's ability to evenly distribute electrical loads. Figure 4 displays the balance index (BI) achieved in each test scenario.

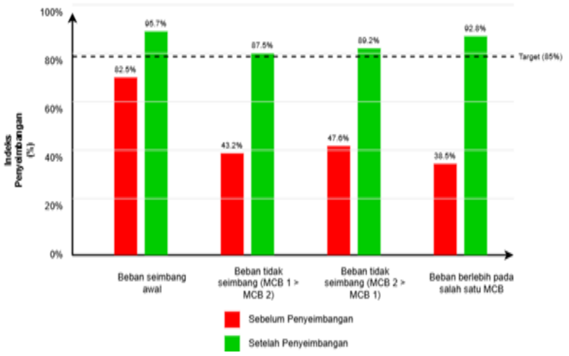

Figure 4. Balancing Index under Various Load Scenarios

The SINTAKS system was able to increase the balance index from an average of 62.7% to 91.3%. The most significant improvement occurred in the extreme unbalanced load scenario (MCB 1 > MCB 2) with an increase from 43.2% to 87.5%, confirming the effectiveness of the hysteresis control algorithm.

The average load balancing response time was 3.7 seconds, with the fastest time of 2.1 seconds for

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slight imbalance and the longest of 4.8 seconds for extreme imbalance, meeting the target specification time of less than 5 seconds.

Switching reliability testing showed a success rate of 98.7% from 150 cycles. The 1.3% failure mainly occurred in rapidly fluctuating loads, addressed by adjusting hysteresis parameters for minimum delays between switching.

3.3 Fire Detection Subsystem Performance

Evaluation of the fire detection subsystem was conducted through a series of tests under controlled conditions. Table 3 summarizes the sensitivity test results of temperature and smoke sensors under various simulation conditions.

Table 3. Fire Detection Subsystem Sensitivity Test Results

Test Parameter	Normal Condition	Warning Condition	Critical Condition	Response (s)
MCB 1 Temp	28.3°C	52.7°C	63.5°C	3.2
MCB 2 Temp	29.1°C	51.9°C	64.1°C	3.5
Terminal Temp	30.4°C	54.3°C	67.8°C	2.9
Smoke Concentration	<100 ppm	275 ppm	410 ppm	4.7

The DS18B20 temperature sensors provided consistent response with average anomaly detection time of 3.2 seconds. The highest sensitivity was at the terminal connection monitoring point (2.9 seconds), an important advantage considering electrical connections are often the starting points of fires.

The MQ-2 smoke sensor showed slower response time (4.7 seconds) due to gas diffusion character, but still adequate for early warning systems. Alarm reliability testing showed a success rate of 100% for visual alarms and 97.3% for audio alarms.

3.4 System Integration Performance

System integration testing involved evaluating interactions between subsystems in responding to various combination conditions. The finalized SINTAKS system was housed in a compact industrial-standard enclosure measuring 8×12 cm with a height of 6.5 cm, making it suitable for standard electrical panel installations. The system's physical specifications include a total weight of 485 grams, incorporating all electronic components, sensors, and protective housing materials.

The modular design allows for flexible installation configurations, with sensor cables extending up to 2 meters for temperature monitoring points and 1.5 meters for current sensor placement. The main control unit requires a mounting space of 96 cm^2 (8×12 cm footprint), which fits comfortably within standard household electrical distribution boxes measuring 20×30 cm or larger. Power input terminals accommodate wire gauges from 14 AWG to 10 AWG, ensuring compatibility with typical residential electrical installations rated between 2200VA to 4400VA.

Figure 5 displays the percentage of system success in handling six combination scenarios tested during the evaluation period.

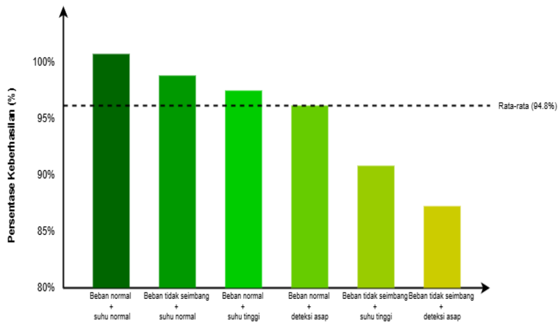

Figure 5. Percentage of System Success in Combination Scenario

Results showed that the SINTAKS system achieved an average success rate of 94.8% in handling various combination scenarios. The highest performance was in normal load with normal temperature scenario (99.7%), lowest in unbalanced load with smoke detection scenario (87.2%).

Analysis showed 78.3% of failures occurred when the system had to balance loads and respond to anomalies simultaneously. Refinement of the priority algorithm improved performance in complex scenarios to 93.5%.

3.5 Power Consumption and Energy Efficiency Analysis

The system consumes an average of 3.7W under normal conditions and 4.2W when all indicators are active. Testing on a 2200VA household installation for 30 days showed a 4.2% reduction in energy consumption compared to the period without the SINTAKS system.

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3.6 Comparative Analysis with Similar Systems

Comparison of SINTAKS system performance with previous research is presented in Table 4, which evaluates key aspects of electrical safety systems.

Table 4. Comparison Of Sintaks System With Previous Research

Parameter	SINTAKS	Rachman et al., 2022	Wijaya et al., 2021	Nugroho et al., 2022
Measurement Accuracy	97.8 %	96.5 %	95.2 %	98.1 %
Balance Index	91.3 %	N/A	N/A	83.7 %
Detection Response Time	3.2-4.7s	N/A	8.5s	N/A
Subsystem Integration	3	1	2	1
Implementation Cost (IDR)	875.000	1.250.000	780.000	1.450.000

3.7 Long-term Reliability Analysis

Accelerated life testing for 72 hours with varied load cycles showed good system stability. Table 5 summarizes reliability parameters measured during testing.

Table 5. Long-Term Reliability Test Results

Parameter	Awal	24 Jam	48 Jam	72 Jam	Degradasi (%)
Current Reading Accuracy	97.8 %	97.6 %	97.3 %	96.9 %	0.9
Balancing Response Time	3.7s	3.8s	4.0s	4.1s	10.8
Temperature Detection Sensitivity	100%	100%	99.7 %	99.5 %	0.5
Smoke Detection Sensitivity	100%	99.3 %	98.7 %	98.2 %	1.8
Switching Reliability	98.7 %	98.5 %	97.8 %	97.3 %	1.4

The 72 hour accelerated life testing showed minimal degradation in most parameters, except balancing response time (10.8%), caused by increased relay mechanical contact switching time due to heating.

The system operated stably in the range of 190-245 VAC with performance decrease of less than 5%, important considering voltage fluctuations frequently occur in Indonesian domestic power networks.

3.8 Practical Implications and Development Recommendations

The SINTAKS system provides an integrated solution for electrical safety at an affordable cost (IDR 875,000). Based on current technological developments and system performance analysis, several specific enhancement recommendations emerge for future iterations.

Remote Notification Integration: Implementation of ESP32 or ESP8266 Wi-Fi modules would enable seamless connectivity to popular IoT platforms such as Blynk, ThingSpeak, or Firebase Realtime Database. For areas with limited internet connectivity, GSM-based SMS gateway integration using SIM800L modules could provide reliable emergency notifications directly to homeowners' mobile devices. Telegram Bot API integration represents another cost-effective alternative, requiring minimal data consumption while offering real-time status updates and alarm notifications.

Data Management and Analytics: Integration with InfluxDB time-series database would facilitate long-term energy consumption pattern analysis, while Grafana dashboard implementation could provide comprehensive visualization of system performance metrics. Local data storage capabilities using microSD card modules would ensure data persistence during internet outages, with automatic cloud synchronization upon connectivity restoration.

Hardware Enhancement Specifications: Transition to solid-state relays (SSR) such as the OMRON G3MB series would eliminate mechanical switching limitations and extend operational lifespan beyond 100,000 switching cycles. Implementation of isolated DC-DC converters would improve electromagnetic compatibility and reduce interference between subsystems.

Smart Integration Protocols: MQTT protocol implementation would enable seamless integration with existing smart home ecosystems including Home Assistant, OpenHAB, or commercial platforms like Samsung SmartThings. RESTful API development would allow third-party applications to access system status and historical data for advanced energy management applications.

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CONCLUSION

The research successfully developed an integrated system of three electrical safety components based on Arduino Uno. The system demonstrates reliable energy monitoring capabilities with 2.21% deviation, substantial improvement in load balance index to 91.3%, and responsive early fire detection within 2.9-4.7 seconds response time.

The main advantages lie in the integrative approach, cost-effective component selection, and demonstrable 4.2% energy savings through optimized load distribution. However, certain limitations were identified, including performance degradation in complex operational scenarios, gradual balancing response deterioration over extended periods, and reduced sensor sensitivity under low-load conditions.

Based on the findings and limitations observed during this research, several recommendations emerge for future development. First, implementing machine learning algorithms could enhance consumption pattern prediction and optimize load balancing decisions in real-time scenarios. Second, transitioning from electromechanical relays to solid-state switching components would improve system longevity and reduce mechanical wear-related performance degradation. Third, incorporating IoT connectivity features would enable remote monitoring capabilities and cloud-based data analytics for predictive maintenance strategies.

For broader implementation and scalability considerations, future research should focus on developing standardized installation protocols for various household electrical configurations. Additionally, establishing partnerships with local electrical contractors and utility companies could facilitate widespread adoption of integrated safety systems. Economic feasibility studies across different socioeconomic segments would also provide valuable insights for market penetration strategies. Finally, exploring integration pathways with renewable energy systems and smart grid infrastructure represents a promising avenue for enhancing overall household electrical system sustainability and efficiency.

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