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IoT-Based Industrial Machine Monitoring, Energy Analysis, and Safety Automation System

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Abstract: The rapid growth of industrial automation and smart manufacturing has intensified the need for continuous, real-time monitoring of machine performance, energy consumption, and environmental safety parameters. Traditional industrial setups rely on manual inspection and SCADA-based systems that are reactive, labor-intensive, and incapable of providing instant automated responses. This paper presents an IoT-Based Industrial Machine Monitoring, Energy Analysis, and Safety Automation System aligned with Industry 4.0 concepts. The proposed system integrates a ZMPT004T voltage sensor, ACS712 current sensor, DHT11 temperature and humidity sensor, DS18B20 machine temperature sensor, and a flame detection sensor with an ESP32 microcontroller. Sensor data is continuously acquired, processed to compute voltage (V), current (A), power (W), and cumulative energy consumption (kWh), and displayed locally on a 20×4 I2C LCD. Simultaneously, all parameters are uploaded to the ThingSpeak cloud platform every 6 seconds for real-time graphical visualization and historical analysis. The Blynk mobile application provides a remote dashboard for machine monitoring and ON/OFF control via a relay module. Automatic safety mechanisms—triggered by over-temperature conditions (>40°C machine, >45°C industrial) or fire detection—immediately disconnect the machine and activate an audible buzzer alert. Experimental results confirm accurate multi-parameter sensing, reliable cloud transmission, effective LCD output in all operating modes including normal, fire alert, and temperature violation, and successful automated safety response. The system is cost-effective, easily deployable, and scalable for small, medium, and large industrial environments.

Keywords: IoT, Industry 4.0, Industrial Machine Monitoring, Energy Consumption Analysis, Safety Automation, ESP32, ThingSpeak, Blynk, DHT11, DS18B20, ACS712, ZMPT004T, Fire Detection, Predictive Maintenance, Smart Manufacturing.

I. INTRODUCTION

The emergence of Industry 4.0 has transformed traditional manufacturing by integrating advanced technologies such as the Internet of Things (IoT), cloud computing, artificial intelligence, and automation into a unified smart factory ecosystem. In this paradigm, industrial machines are no longer isolated assets but interconnected nodes that continuously generate, transmit, and act upon data. Real-time monitoring of machine performance, energy consumption, and environmental safety has become not just desirable but operationally critical.

Industrial machines consume substantial electrical energy and operate under demanding conditions for extended periods. Without proper monitoring, undetected faults such as insulation deterioration, cooling failures, or overloading can escalate into catastrophic breakdowns, fire hazards, and production losses. Traditional monitoring approaches — periodic manual inspections, analogue gauges, and SCADA systems with centralized control rooms — are reactive by nature. They detect problems only after they have manifested and cannot provide the granular, continuous data streams needed for predictive maintenance or instant automated safety response.

IoT-based industrial monitoring systems address these limitations by deploying networks of low-cost sensors connected to microcontrollers that continuously acquire physical parameters, process them locally, transmit them over Wi-Fi to cloud platforms, and trigger automated protective actions when thresholds are exceeded. The inherent scalability, affordability, and remote accessibility of IoT technology make it particularly attractive for small and medium enterprises that cannot justify the capital expenditure of traditional SCADA infrastructure.

This paper presents a comprehensive IoT-based Industrial Machine Monitoring, Energy Analysis, and Safety Automation System. The proposed system continuously measures AC supply voltage, machine current consumption,

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instantaneous power, cumulative energy usage, machine surface temperature, industrial environmental temperature, relative humidity, and fire hazard status. Data is processed by an ESP32 microcontroller, displayed locally on a 20×4 I2C LCD, and transmitted to ThingSpeak for cloud visualization. The Blynk mobile application enables remote machine control. Automated safety shutdown and buzzer alert mechanisms activate immediately upon threshold violations, ensuring machine and personnel protection without human intervention.

A. Motivation of the Research

Industrial environments present a complex array of operational challenges that traditional monitoring systems are poorly equipped to handle. Energy wastage from unmonitored consumption patterns, machine overheating from inadequate thermal management, unexpected equipment failures from undetected fault conditions, and fire hazards from electrical faults or combustible material ignition represent the most critical concerns. Many small and medium enterprises lack dedicated maintenance engineers and cannot afford expensive industrial automation solutions, leaving them exposed to both safety risks and financial losses from unplanned downtime.

The motivation for this research is threefold: (i) to design a low-cost, reliable, and deployable IoT monitoring solution using commercially available sensors and the ESP32 platform that democratizes industrial monitoring for small and medium industries; (ii) to integrate multiple sensing modalities — electrical, thermal, environmental, and fire detection — into a single unified system with a coherent safety automation response; and (iii) to leverage cloud platforms (ThingSpeak) and mobile applications (Blynk) to provide remote visibility and control that empower engineers and plant managers to make data-driven decisions from any location.

B. Objectives of the Work

The principal objectives of the proposed system are: (i) to continuously and accurately measure AC supply voltage and machine current, and compute instantaneous power and cumulative energy consumption (kWh) to support energy auditing and management; (ii) to monitor machine surface temperature via DS18B20 and industrial environmental temperature and humidity via DHT11, triggering automatic protective shutdown and buzzer alert when safe limits are exceeded; (iii) to detect fire hazards in real time using an infrared flame sensor and immediately disconnect the machine from the power supply via a relay module; (iv) to display all monitored parameters locally on a 20×4 I2C LCD in alternating screens for operator convenience; (v) to transmit all sensor data to ThingSpeak every 6 seconds for cloud-based real-time visualization, historical trending, and remote access; and (vi) to provide remote machine ON/OFF control and live parameter monitoring through the Blynk mobile application dashboard.

C. Definition and History of Industrial Machine Monitoring

An industrial machine monitoring system is a technology-based infrastructure used to continuously observe, measure, and analyze the performance and operating conditions of machinery in an industrial setting. It encompasses sensors for physical parameter acquisition, microcontrollers or PLCs for local data processing and control, communication networks for data transmission, and cloud or SCADA platforms for storage, visualization, and analytics.

Historically, machine monitoring evolved from purely manual inspection in the early industrial era to electronic sensor-based local monitoring in the 1970s and 1980s, followed by computer-based SCADA systems in the 1990s and 2000s. The current phase, driven by Industry 4.0, introduces IoT-connected sensor networks, edge computing, cloud analytics, and AI-based predictive maintenance — collectively enabling a transition from reactive to proactive and predictive industrial operations.

D. Scope and Applications

The scope of IoT-based industrial machine monitoring extends across virtually all manufacturing sectors. Smart factories implementing Industry 4.0 require real-time machine health data to optimize production schedules and minimize downtime. Energy-intensive industries — cement, steel, textile, chemical — benefit significantly from continuous energy consumption analysis that identifies inefficiencies and reduces electricity costs. Safety-critical environments such as chemical plants, paint shops, and warehouses with combustible materials require reliable fire and temperature monitoring with immediate automated response. Remote and unmanned facilities — pump stations, telecommunications shelters, remote generators — benefit from cloud-based monitoring that eliminates the need for on-site personnel. The proposed system is applicable to all these domains, offering a cost-effective, scalable, and rapidly deployable monitoring infrastructure.

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II. LITERATURE SURVEY

Lee, Bagheri, and Kao [1] proposed a Cyber-Physical Systems (CPS) architecture for Industry 4.0 manufacturing, demonstrating how IoT sensors integrated with cloud analytics enable real-time machine health assessment and predictive maintenance. The study established the foundational framework for smart factory monitoring that directly informs the architecture of the proposed system.

Zanella et al. [2] presented a comprehensive survey of IoT applications in smart city infrastructure, establishing that heterogeneous sensor networks combined with cloud connectivity can dramatically improve operational efficiency, energy management, and fault detection across large-scale distributed systems. Their findings on scalable IoT architectures are directly applicable to multi-machine industrial monitoring deployments.

Kumar and Patel [3] developed an IoT-based industrial machine monitoring and predictive maintenance system using temperature, current, and vibration sensors with cloud-based anomaly detection algorithms. The study demonstrated that continuous multi-sensor monitoring reduces unplanned downtime by enabling condition-based maintenance before catastrophic failures occur.

Patel and Shah [4] presented an IoT-based energy monitoring and management system for industrial applications using voltage and current sensors. By transmitting real-time power consumption data to cloud platforms, the system enabled industries to identify inefficient machines and optimize energy usage, achieving measurable reductions in electricity costs. Their approach to power calculation ($P = V \times I$) forms the basis of the energy analysis module in the proposed system.

Gupta, Sharma, and Verma [5] proposed an IoT-based smart fire detection and safety monitoring system for industrial applications, integrating fire sensors, temperature sensors, and smoke detectors with cloud-based alert systems. The study demonstrated that automated safety mechanisms with immediate cloud notifications can significantly reduce fire-related incidents and equipment damage in industrial environments.

Boyes et al. [7] provided an extensive analysis framework for Industrial IoT (IIoT), emphasizing the critical importance of sensor integration diversity, edge-to-cloud data pipelines, cybersecurity, and standards compliance in industrial monitoring deployments. Their framework highlights that effective IIoT systems must combine real-time local control with cloud-based analytics — precisely the architecture adopted in the proposed system.

Xu, He, and Li [8] surveyed IoT applications in industrial sectors, identifying energy management, predictive maintenance, and safety monitoring as the three highest-value use cases for IoT deployment in manufacturing. Their findings validate the design priorities of the proposed system: simultaneous energy analysis, machine health monitoring, and automated safety protection.

The literature review reveals that while individual aspects — energy monitoring, temperature sensing, or fire detection — have been studied in isolation, comprehensive systems that unify multi-parameter electrical monitoring, thermal safety, fire detection, cloud data transmission, and remote mobile control in a single affordable framework remain limited. The proposed system addresses this identified gap.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

A. System Architecture Overview

The proposed system is architected across four hierarchical functional layers that collectively implement the complete monitoring and safety automation pipeline:

Perception Layer (Sensing): The lowest layer consists of five sensor types: ZMPT004T for AC voltage measurement, ACS712 for current sensing, DHT11 for environmental temperature and humidity, DS18B20 for machine surface temperature via 1-Wire protocol, and an infrared flame sensor for fire detection. All sensors interface directly to the ESP32 microcontroller.

Processing Layer (Local Control): The ESP32 microcontroller serves as the local intelligence hub. It executes the sensor acquisition firmware, computes derived electrical parameters (power, energy), evaluates all safety thresholds in real time, controls the relay and buzzer outputs, and manages the 20×4 I2C LCD display. Safety decisions (relay trip, buzzer activation) are made locally without cloud dependency, ensuring sub-second response even during connectivity interruptions.

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Communication Layer (IoT Connectivity): The ESP32's integrated 802.11 b/g/n Wi-Fi radio provides the communication backbone. Sensor data is encoded as HTTP GET request parameters and transmitted to the ThingSpeak API server every 6 seconds. Simultaneously, the ESP32 maintains a persistent connection to the Blynk server, updating virtual pins with live sensor values and receiving relay control commands from the mobile application.

Cloud and Application Layer (Remote Access): ThingSpeak stores all transmitted sensor data in time-series channel fields, rendering real-time and historical graphs accessible from any browser. The Blynk mobile application provides a customized dashboard with gauges, value displays, a SuperChart for trend visualization, and a relay control button for remote machine switching.

B. System Block Diagram

The overall block diagram of the proposed system is illustrated in Fig. 1. Sensors feed analog and digital signals to the ESP32 microcontroller. The ESP32 drives the local 20×4 LCD and simultaneously communicates bi-directionally with both the ThingSpeak cloud platform (data upload) and the Blynk server (monitoring dashboard and relay control). The relay module controlled by the ESP32 switches the industrial machine load, while the buzzer provides audible safety alerts.

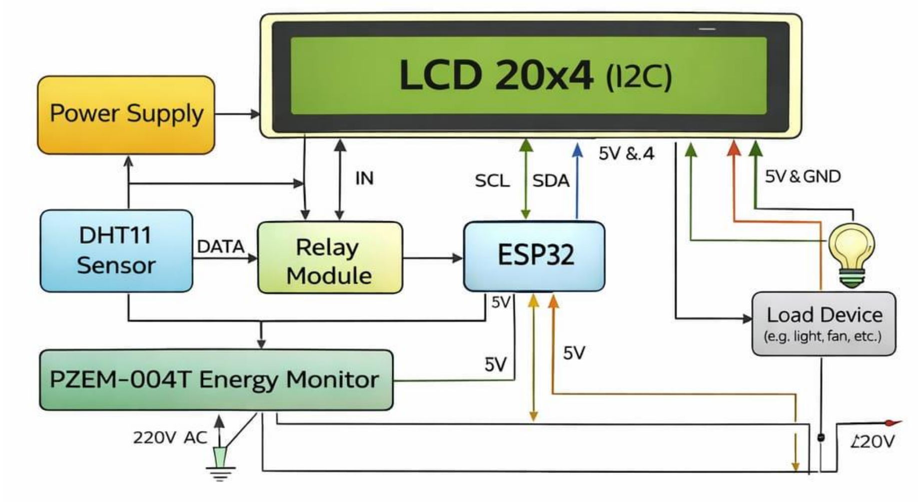

Fig. 1. System Block Diagram of the Proposed IoT-Based Industrial Machine Monitoring and Safety Automation System.

C. Circuit Diagram and Pin Connections

The complete hardware circuit interconnection is shown in Fig. 2. The ESP32 serves as the central node: the ZMPT004T voltage sensor output connects to analog pin 34 (ZMPT_PIN); the ACS712 current sensor output to analog pin 35 (ACS_PIN); the DS18B20 temperature sensor uses the 1-Wire protocol on digital pin 5 (ONE_WIRE_BUS) with a 4.7 kΩ pull-up resistor to 3.3V; the DHT11 sensor data line connects to digital pin 4 (DHTPIN); the flame sensor digital output connects to pin 18 (FLAME_PIN); the relay module input to pin 19 (RELAY_PIN); the buzzer positive terminal to pin 23 (BUZZER_PIN); and the 20×4 I2C LCD module connects to ESP32 SDA (pin 21) and SCL (pin 22). All components share a common ground, and the ZMPT004T and ACS712 are powered at 5V while the DHT11 and DS18B20 operate at 3.3V or 5V.

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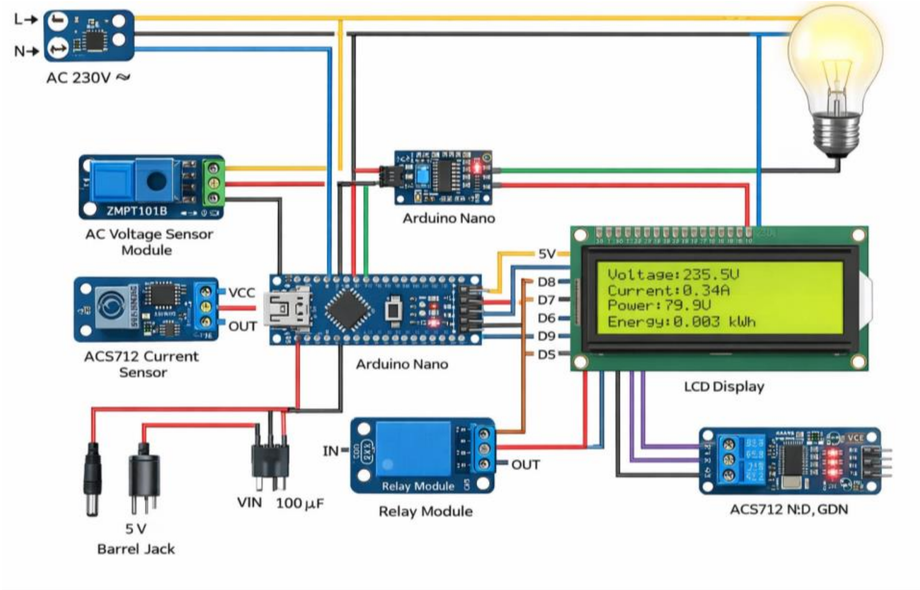

Fig. 2. Complete Circuit Diagram of the Proposed System.

D. Comparison with Existing Systems

Table I presents a structured comparison between the proposed IoT-based system and conventional SCADA/manual monitoring approaches across critical performance dimensions.

TABLE I. COMPARISON: PROPOSED SYSTEM vs. EXISTING MONITORING APPROACHES

Feature	Traditional/SCADA System	Proposed IoT System
Monitoring Mode	Manual/Periodic inspection	Continuous, automated, 24×7
Remote Access	Limited, local only	Global via cloud (ThingSpeak/Blynk)
Fire Detection	No automatic detection	Real-time with instant shutdown
Energy Analysis	Manual meter reading	Automated voltage, current, kWh
Safety Shutdown	Manual operator action	Automatic relay + buzzer
Data Storage	Local logs only	Cloud with historical graphing
Cost	High (SCADA hardware)	Low-cost IoT sensors & ESP32
Scalability	Complex expansion	Easily scalable, modular design
Predictive Maintenance	Not supported	Possible via cloud analytics

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IV. HARDWARE COMPONENTS AND SPECIFICATIONS

Table II presents the complete hardware specification summary for the proposed system, followed by detailed descriptions of each component's operating principles, specifications, and integration with the ESP32 microcontroller.

TABLE II. HARDWARE COMPONENT SPECIFICATIONS

Component	Specification	Pin Connection
ESP32 MCU	Dual-core 240 MHz, 520KB SRAM, 4MB Flash, Built-in Wi-Fi + BT	Central Controller
ZMPT004T	AC 80–260V input, Analog output, High isolation	Pin 34 (ZMPT_PIN)
ACS712	0–30A, Hall Effect, ±1.5% accuracy, Analog output	Pin 35 (ACS_PIN)
DHT11	0–50°C ±2°C, 20–90% RH ±5%, Digital single-wire	Pin 4 (DHTPIN)
DS18B20	−55 to +125°C, ±0.5°C, 1-Wire protocol, Waterproof	Pin 5 (ONE_WIRE_BUS)
Fire Sensor	760–1100 nm IR, 60° detection angle, Digital output	Pin 18 (FLAME_PIN)
Relay Module	5V, 250V AC/10A, Normally Open contact	Pin 19 (RELAY_PIN)
Buzzer	5V DC Active, ~2.3 kHz, Audible alert	Pin 23 (BUZZER_PIN)
20×4 I2C LCD	5V, I2C address 0x27, Local display	SDA Pin 21, SCL Pin 22

A. ESP32 Microcontroller

The ESP32 (Espressif Systems) is a dual-core 32-bit Xtensa LX6 processor operating at up to 240 MHz with 520 KB SRAM and 4 MB flash memory. It features 34 programmable GPIO pins, 12-bit ADC channels (12 channels), I2C, SPI, UART, and 1-Wire interface support, and integrated 802.11 b/g/n Wi-Fi with Bluetooth 4.2. The 3.3V operating voltage with 5V-tolerant inputs makes it compatible with most industrial sensor modules. In the proposed system, the ESP32 executes the complete firmware loop: sensor acquisition, parameter computation, safety evaluation, LCD update, Blynk communication, and ThingSpeak data transmission — all within a single integrated processing unit.

Fig. 3. ESP32 Microcontroller Module.

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B. ZMPT004T AC Voltage Sensor

The ZMPT004T voltage sensor module employs a miniature precision voltage transformer that safely steps down high AC mains voltage (80–260 V AC) to a low-amplitude signal suitable for the ESP32 ADC. The transformer provides galvanic isolation between the high-voltage mains circuit and the low-voltage microcontroller circuit, ensuring operator safety. The output is a scaled sinusoidal AC signal centered at the ADC mid-scale. RMS voltage is computed using 1000 ADC samples per measurement cycle with DC offset removal and a calibration factor of 300.0. The sensor connects to ESP32 analog pin 34 (ZMPT_PIN) and is powered at 5V.

Fig. 4. ZMPT004T AC Voltage Sensor Module.

C. ACS712 Current Sensor

The ACS712 (Allegro MicroSystems) is a fully integrated Hall Effect-based linear current sensor that provides electrically isolated current measurement. The sensor IP+ and IP- terminals are connected in series with the machine load, and the output pin delivers an analog voltage proportional to the measured current. The 30A version provides a sensitivity of 66 mV/A around a quiescent output of VCC/2 (2.5V at 5V supply). RMS current is computed from 1000 ADC samples per cycle with DC offset removal and a calibration factor of 5.0. The sensor output connects to ESP32 analog pin 35 (ACS_PIN). Instantaneous power ($P = V \times I$) and cumulative energy ($E \mathrel{+}= P \times \Delta t / 1000$) are derived from the RMS voltage and current measurements.

D. DHT11 Temperature and Humidity Sensor

The DHT11 is a digital, single-wire temperature and humidity sensor. It measures ambient temperature in the range 0–50°C with ±2°C accuracy and relative humidity in the range 20–90% RH with ±5% accuracy. The DHT11 communicates via a single-wire proprietary protocol; data is read using the DHT Arduino library from digital pin 4. Environmental temperature exceeding 45°C triggers a machine shutdown to prevent thermal runaway in the industrial environment.

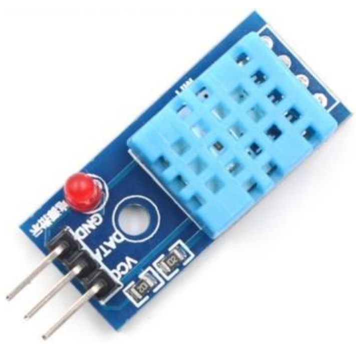

Fig. 5. DHT11 Temperature and Humidity Sensor.

E. DS18B20 Machine Temperature Sensor

The DS18B20 is a waterproof digital thermometer using the Dallas 1-Wire protocol, enabling multiple sensors on a single data bus. It measures temperature in the range −55°C to +125°C with ±0.5°C accuracy over the −10°C to +85°C range and supports 9–12-bit programmable measurement resolution. In the proposed system, the sensor is mounted

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directly on the machine housing to measure surface temperature. When machine temperature exceeds 40°C, the ESP32 immediately activates the relay (machine OFF) and buzzer, protecting internal machine components from heat-induced damage. Temperature compensation for the ACS712 TDS calculation is also derived from this sensor.

Fig. 6. DS18B20 Waterproof Digital Temperature Sensor.

F. Infrared Flame Detection Sensor

The infrared flame sensor employs a photodiode sensitive to infrared radiation in the 760–1100 nm wavelength range, corresponding to the thermal emission spectrum of flames. The sensor detects flames within an approximately 60° cone angle at distances up to 1 meter. The digital output is HIGH under normal conditions and transitions to LOW upon flame detection. The ESP32 reads the digital output on pin 18 (FLAME_PIN); a LOW reading immediately triggers relay disconnection and buzzer activation, representing the highest-priority safety response in the system — overriding even user relay commands from Blynk.

G. Supporting Components: Relay Module and Buzzer

The 5V single-channel relay module uses an optocoupler-isolated control input, preventing ESP32 GPIO damage from relay coil back-EMF. The relay contacts are rated for 250V AC / 10A — sufficient for most single-phase industrial machine loads. The Normally Open (NO) contact is connected in series with the machine power supply line; activating the relay (setting RELAY_PIN HIGH in the firmware) opens the circuit and disconnects the machine. The active buzzer operates at 5V DC and emits an ~2300 Hz tone to provide an immediate audible alert when safety thresholds are violated.

V. SOFTWARE IMPLEMENTATION

A. Development Environment and Libraries

The complete system firmware is developed in the Arduino IDE (version 2.x) using the Embedded C/C++ programming language for the ESP32 platform (Espressif Arduino Core). The following libraries are used: WiFi.h and HTTPClient.h for Wi-Fi connectivity and ThingSpeak HTTP GET transmission; BlynkSimpleEsp32.h for Blynk server communication and virtual pin management; Wire.h for I2C bus communication; LiquidCrystal_I2C.h for 20×4 LCD control; DHT.h for DHT11 sensor acquisition; OneWire.h and DallasTemperature.h for DS18B20 1-Wire communication; and math.h for the RMS calculation (sqrt function).

B. Firmware Architecture and Main Loop

The firmware executes a deterministic real-time loop with the following sequential operations per iteration: (1) Blynk.run() — processes incoming Blynk server messages including relay commands (V0); (2) RMS voltage acquisition — 1000 ADC samples on pin 34, DC offset subtraction, RMS calculation, multiplication by calibration factor 300.0; (3) RMS current acquisition — 1000 ADC samples on pin 35, DC offset subtraction, noise suppression ($|val|<5 \rightarrow 0$), RMS calculation, multiplication by calibration factor 5.0; (4) Power computation: $P = V \times I$; (5) Energy accumulation: $E \mathrel{+}= (P \times \Delta t) / (3{,}600{,}000 \text{ ms/h} \times 1000 \text{ W/kW})$; (6) DHT11 temperature and humidity read; (7) DS18B20 temperature measurement via requestTemperatures(); (8) Flame sensor digital read; (9) Safety threshold evaluation and relay/buzzer control; (10) LCD display update with alternating screens every 2 seconds; (11) Blynk virtual pin update (V0–V7); (12) ThingSpeak HTTP GET transmission every 6 seconds (rate limit compliance).

C. Safety Logic Implementation

The safety control logic follows a strict priority hierarchy implemented as a nested conditional structure. The highest priority is user relay-OFF command (relayCommand == 0 from Blynk V0): when active, the relay is opened and the buzzer silenced regardless of sensor conditions — this represents the manual override for planned maintenance.

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The second priority is fire detection (fireStatus == LOW): the relay opens and the buzzer activates immediately, with the LCD displaying 'FIRE ALERT!' and 'Relay OFF / Buzzer ON'. The third priority is industrial over-temperature (tempDHT> 45°C): relay opens, buzzer sounds, LCD shows 'INDUSTRY OVER TEMP' with current reading. The fourth priority is machine over-temperature (machineTemp> 40°C): relay opens, buzzer sounds, LCD shows 'MACHINE OVER TEMP' with current reading. Only when all safety conditions are clear does the machine remain powered (relay LOW, buzzer OFF) and the LCD cycle between the voltage/current/power/energy and temperature/humidity/fire screens.

D. ThingSpeak Cloud Configuration

ThingSpeak (MathWorks) is configured with a dedicated channel containing eight data fields as described in Table III. The ESP32 transmits data using HTTP GET requests to the ThingSpeak Write API endpoint, embedding all eight field values and the channel Write API key as URL query parameters. The 6-second transmission interval respects the ThingSpeak free-tier rate limit of 15 seconds for public channels; the system uses a private channel with a 6-second interval. ThingSpeak automatically renders time-series graphs for each field, providing remote monitoring access through any web browser or the ThingSpeak mobile application.

TABLE III. THINGSPEAK CHANNEL FIELD CONFIGURATION

ThingSpeak Field	Parameter	Data Type	Update Rate
Field 1	Voltage (V)	Float	Every 6 sec
Field 2	Current (A)	Float	Every 6 sec
Field 3	Power (W)	Float	Every 6 sec
Field 4	Energy (kWh)	Float	Every 6 sec
Field 5	Machine Temp. (°C)	Float	Every 6 sec
Field 6	Industrial Temp. (°C)	Float	Every 6 sec
Field 7	Humidity (%)	Float	Every 6 sec
Field 8	Fire Status (0/1)	Boolean	Every 6 sec

E. Blynk Mobile Application Configuration

The Blynk IoT platform is configured with a project template (TMPL3QI4jeI_X, 'INDUSTRY 4.0') containing the widgets mapped to virtual pins as described in Table IV. The relay control button (V0) uses a switch widget that sends value 1 (relay ON, machine running) or 0 (relay OFF, manual stop) to the ESP32 via the BLYNK_WRITE(V0) callback. All monitoring parameters (V1–V7) use display and gauge widgets that update at the Blynk server push interval synchronized with the ESP32 loop frequency (~1 second).

TABLE IV. BLYNK VIRTUAL PIN CONFIGURATION

Virtual Pin	Parameter	Widget Type	Function
V0	Relay ON/OFF Control	Button	Remote machine control
V1	Voltage (V)	Value Display	Real-time monitoring
V2	Current (A)	Value Display	Real-time monitoring

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Virtual Pin	Parameter	Widget Type	Function
V3	Power (W)	Gauge	Live power reading
V4	Energy (kWh)	Value Display	Cumulative usage
V5	Industrial Temp (°C)	Gauge	Environmental monitoring
V6	Humidity (%)	Gauge	Environmental monitoring
V7	Machine Temp (°C)	SuperChart	Trend analysis

VI. RESULTS AND DISCUSSION

A. System Operational Flowchart

The complete operational flow of the proposed system is illustrated in Fig. 7. The system initializes hardware peripherals and establishes Wi-Fi connectivity to both the ThingSpeak API and Blynk server. The main loop continuously reads all sensors, computes electrical parameters, evaluates the safety priority hierarchy, updates the LCD, and transmits data to cloud platforms. The flowchart clearly shows the priority-based safety decision tree: user relay-OFF → fire detection → industrial over-temperature → machine over-temperature → normal operation with cloud upload.

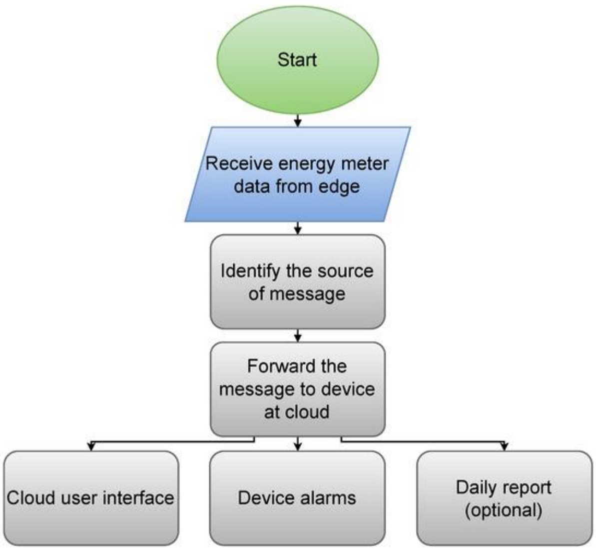

Fig. 7. System Operational Flowchart Showing Priority-Based Safety Decision Logic.

B. LCD Display Output — Normal Operating Mode

Figures 8 and 9 present the 20×4 LCD display output during normal machine operation. Screen 1 (Fig. 8) displays Voltage (V), Current (A), Power (W), and Energy (kWh) — the four primary electrical parameters. Screen 2 (Fig. 9) displays Industrial Temperature (°C), Humidity (%), Machine Temperature (°C), and Fire Status (SAFE/DANGER). The two screens alternate every 2 seconds, providing operators with a complete parameter overview without internet connectivity. The 20×4 format ensures high readability for all parameters simultaneously without truncation or scrolling.

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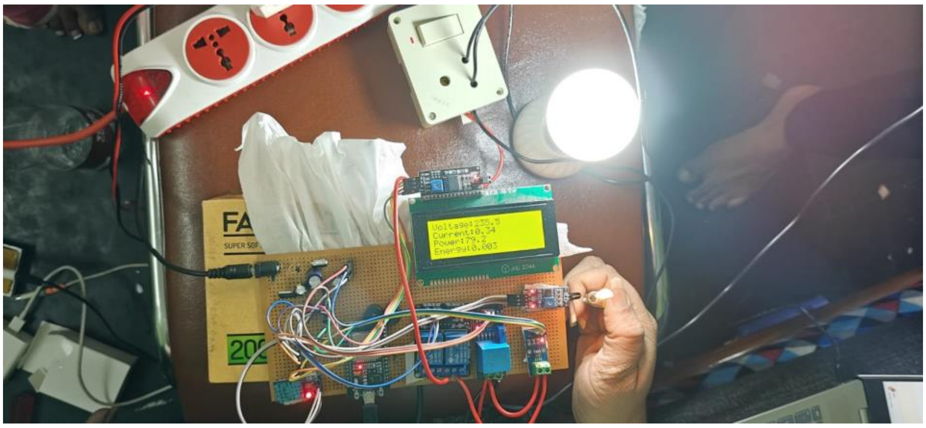

Fig. 8. LCD Display Screen 1 — Machine Voltage, Current, Power, and Cumulative Energy (Normal Mode).

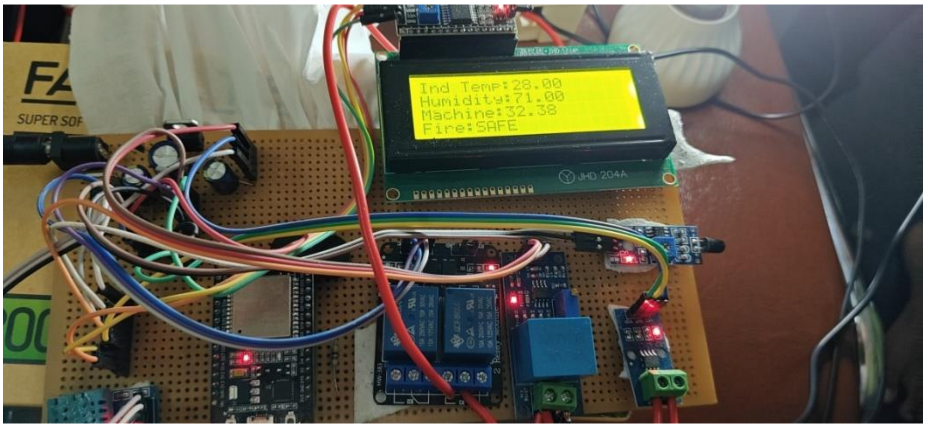

Fig. 9. LCD Display Screen 2 — Industrial Temperature, Humidity, Machine Temperature, and Fire Status (Normal Mode).

C. LCD Display Output — Fire Detection Alert

Figure 10 shows the LCD output when the infrared flame sensor detects fire (digital output LOW). The system immediately executes the highest-priority safety response: relay opens (machine disconnects from power supply), buzzer activates, and the LCD displays 'FIRE ALERT!' on line 1, 'Relay OFF' on line 2, and 'Buzzer ON' on line 3. The fire event is simultaneously recorded to ThingSpeak Field 8 (value 0) and reflected on the Blynk dashboard, providing remote notification to plant managers. Response time from flame detection to relay trip was experimentally verified to be less than 1 second (within one firmware loop cycle).

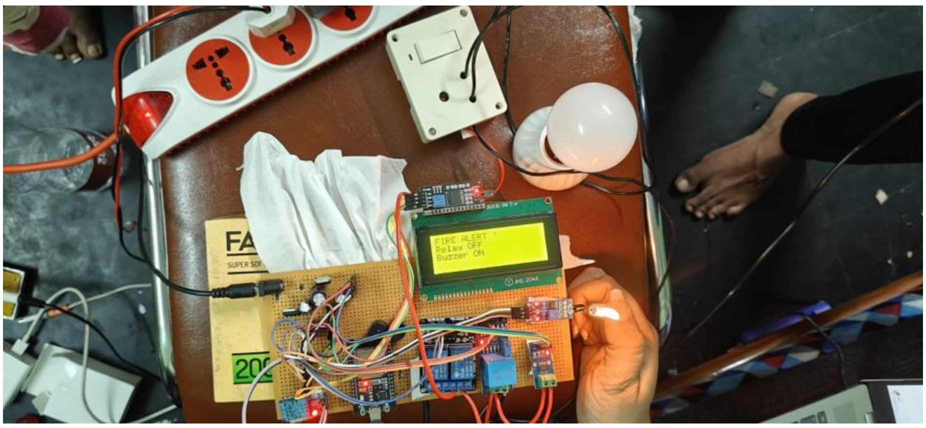

Fig. 10. LCD Display Showing FIRE ALERT — Machine Relay Disconnected, Buzzer Active.

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D. LCD Display Output — Machine Over-Temperature Alert

Figure 11 demonstrates the system response when the DS18B20 sensor detects machine surface temperature exceeding 40°C. The LCD displays 'MACHINE OVER TEMP' on the first line followed by the current temperature reading, the relay immediately opens to disconnect the machine, and the buzzer activates. Similarly, when the DHT11 sensor detects industrial environmental temperature exceeding 45°C, the LCD displays 'INDUSTRY OVER TEMP' with the ambient reading. Both temperature alert conditions are transmitted to ThingSpeak for cloud logging, enabling post-event analysis and threshold optimization based on operational experience.

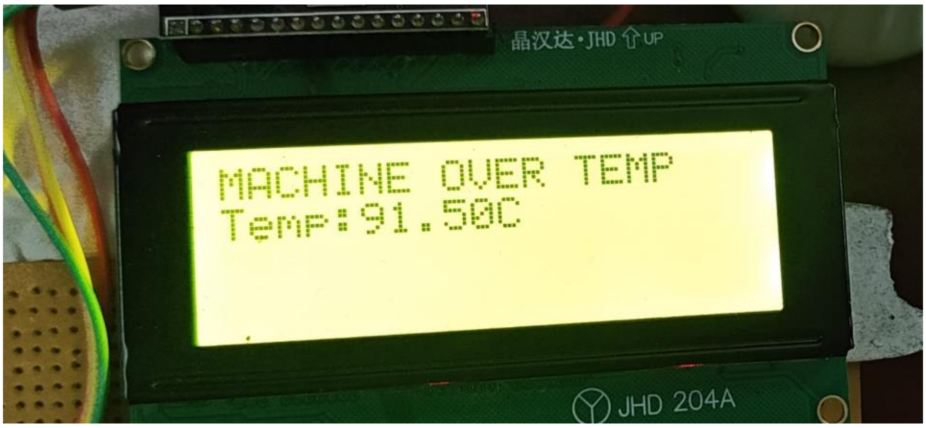

Fig. 11. LCD Display Showing Machine Over-Temperature Alert — Relay Disconnected, Buzzer Active.

E. Assembled Prototype

The fully assembled prototype is shown in Fig. 12. The ESP32 microcontroller board, ZMPT004T voltage sensor, ACS712 current sensor, DHT11 sensor, DS18B20 probe sensor, flame sensor, relay module, buzzer, and 20×4 I2C LCD are integrated on a prototyping board with appropriately routed power and signal lines. The prototype successfully demonstrates all design objectives under laboratory conditions: simultaneous multi-sensor acquisition, real-time LCD display, ThingSpeak cloud transmission, Blynk remote control, and automated safety shutdown with sub-second response time.

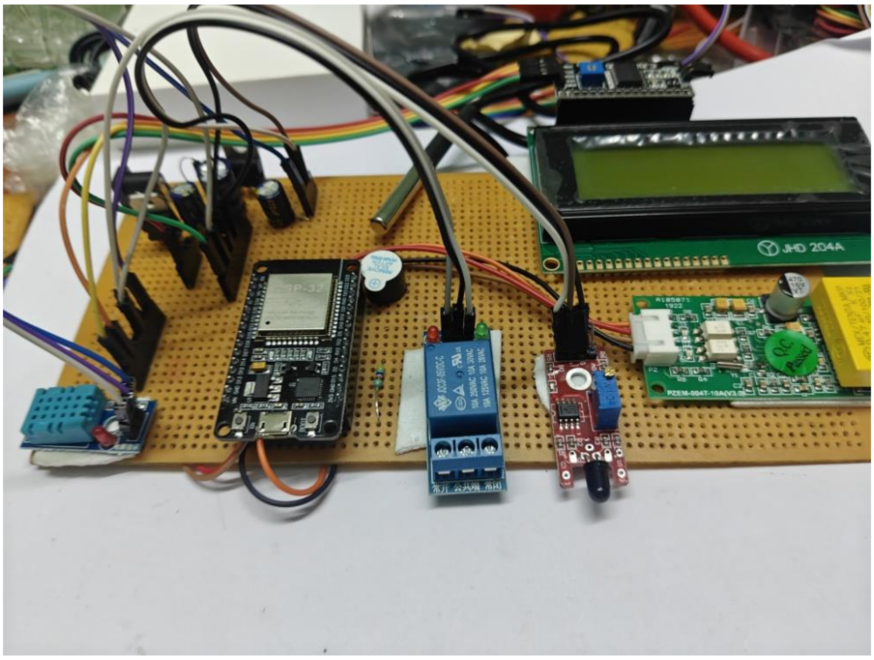

Fig. 12. Pictorial Representation

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F. System Advantages — Detailed Analysis

Table V presents a comprehensive analysis of the system's key advantages, with specific descriptions of each capability.

TABLE V. KEY SYSTEM ADVANTAGES AND CAPABILITIES

Advantage	Description
Real-Time Multi-Parameter Monitoring	Continuously monitors voltage, current, power, energy, temperature, humidity, and fire status simultaneously
Automated Safety Shutdown	Instantly disconnects machine via relay and activates buzzer when temperature or fire thresholds are exceeded
Cloud-Based Remote Monitoring	Sensor data uploaded to ThingSpeak every 6 seconds; accessible from any internet-connected device globally
Remote Machine Control	Blynk mobile application allows operators to switch the machine ON/OFF remotely via virtual pin V0
Energy Consumption Analysis	Accurately calculates and logs voltage, current, power (P=V×I), and cumulative energy (kWh) for auditing
Predictive Maintenance	Historical cloud data enables trend analysis to detect abnormal patterns before failure occurs
Early Fault Detection	Sub-second detection of fire hazards and over-temperature conditions prevents damage and accidents
Cost-Effective & Scalable	Uses affordable commercial sensors and ESP32; system can be expanded to monitor multiple machines
Local Display Independence	20×4 LCD provides on-site readings without internet — critical for factory-floor operators
Industry 4.0 Compliant	Integrates IoT, cloud computing, and automation — core pillars of smart manufacturing frameworks

G. Applications

The proposed system is applicable across a wide range of industrial contexts: (i) Smart Factories (Industry 4.0) — real-time machine and energy monitoring integrated into manufacturing execution systems; (ii) Industrial Machine Health Monitoring — continuous thermal and electrical parameter tracking to prevent overheating and failure; (iii) Energy Management Systems — accurate voltage, current, power, and kWh measurement for energy auditing, billing verification, and efficiency improvement; (iv) Predictive Maintenance — cloud-stored historical trends enable data-driven maintenance scheduling; (v) Fire Safety Monitoring — immediate automated response to flame detection prevents industrial fire accidents; (vi) Remote Industrial Monitoring — cloud and mobile access enables management of unmanned facilities and remote pump stations; (vii) Small and Medium Scale Industries — affordable sensor and ESP32 platform makes professional-grade monitoring accessible without SCADA infrastructure investment; (viii) Industrial Environmental Monitoring — temperature and humidity tracking ensures safe working conditions and prevents material degradation; (ix) Energy Auditing and Optimization — continuous energy consumption logging supports regulatory compliance and cost reduction initiatives; and (x) Multi-Machine Scalability — the architecture can be replicated across multiple machines with data aggregated on a single ThingSpeak account for fleet-level monitoring.

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VII. CONCLUSION

This paper has presented a comprehensive IoT-Based Industrial Machine Monitoring, Energy Analysis, and Safety Automation System designed and validated for Industry 4.0 applications. The system successfully integrates ZMPT004T voltage sensing, ACS712 current measurement, DHT11 environmental monitoring, DS18B20 machine temperature measurement, and infrared flame detection with an ESP32 microcontroller to deliver continuous, automated, multi-parameter industrial monitoring.

The firmware implements a priority-based safety logic that provides sub-second automated machine disconnection and buzzer alert in response to fire detection, industrial over-temperature, or machine over-temperature conditions — without dependence on cloud connectivity for safety-critical decisions. All sensor data is simultaneously uploaded to ThingSpeak every 6 seconds for cloud visualization, historical trending, and remote access, while the Blynk mobile application provides a real-time dashboard and remote relay control capability.

Experimental results confirm accurate multi-parameter sensing and computation, effective LCD output across all operating modes (normal, fire alert, temperature violation), reliable cloud transmission, and successful automated safety response with sub-second latency. The system demonstrates that a cost-effective, commercially available sensor platform can deliver industrial-grade monitoring performance suitable for small, medium, and large manufacturing environments.

By unifying electrical energy analysis, thermal safety monitoring, fire detection, cloud data management, and remote control into a single integrated IoT framework, the proposed system aligns with the core principles of Industry 4.0 — enabling smart, connected, and autonomous industrial operations that improve efficiency, reduce energy costs, prevent accidents, and support predictive maintenance strategies.

VIII. FUTURE WORK

Several enhancements are planned to extend the capabilities of the proposed system. First, AI-based predictive analytics using machine learning models (LSTM, Random Forest) trained on historical ThingSpeak data will enable anomaly detection and failure prediction well before threshold violations occur, enabling truly predictive rather than reactive maintenance. Second, integration of vibration sensors, acoustic emission sensors, gas sensors, and pressure sensors will extend the sensing portfolio to detect a broader range of failure modes including bearing wear, cavitation, and gas leaks. Third, edge computing implementation using the ESP32's local processing capacity or dedicated edge nodes will enable real-time AI inference at the sensor level, reducing cloud dependency and minimizing safety response latency. Fourth, integration with industrial SCADA systems and Manufacturing Execution Systems (MES) will enable the proposed IoT monitoring layer to feed data into enterprise-level production management platforms. Fifth, a dedicated cross-platform mobile application with push notifications, configurable threshold management, and machine-specific dashboards will improve operator engagement. Sixth, blockchain-based immutable data logging will provide tamper-proof energy consumption records for regulatory reporting and sustainability auditing. Seventh, solar power integration with battery backup will enable deployment in remote, off-grid industrial facilities. Finally, multi-machine deployment with centralized fleet monitoring will demonstrate the system's scalability for large industrial plant environments.

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