Enhancing Industrial Safety and Energy Efficiency in Air Handling Units: An IoT-Based Thermal Monitoring System at SGB MY

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ABSTRACT

Uncontrolled thermal accumulation within low-voltage industrial Air Handling Unit (AHU) electrical switchgears accelerates component insulation breakdown, elevates terminal contact resistance, and increases severe arc flash and fire hazards. In traditional manufacturing facilities, routine thermal monitoring relies heavily on periodic manual inspections using handheld devices, leaving unmonitored operational gaps while cabinet exhaust fans operate continuously without automated feedback. The primary objective of this study is to design, deploy, and evaluate an Internet of Things (IoT) based automated panel cooling and real-time monitoring system at SGB MY Sdn. Bhd. in Nilai, Malaysia. Developed under a Work-Based Learning (WBL) university-industry TVET collaboration, the methodology integrates an ESP32 CYD Smart Display module, a waterproof DS18B20 digital temperature probe, a Solid-State Relay (SSR), and the Blynk IoT cloud telecommunication platform.

The automated cooling feedback logic incorporates a 5.0°C hysteresis deadband, activating the 240V AC exhaust fan at temperatures ≥ 40.0°C and deactivating it at ≤ 35.0°C. Over a 24 hour industrial field deployment encompassing 825 recorded telemetry points, internal panel temperatures ranged from 31.57°C to 100.00°C, with a mean temperature of 41.04°C. The automated system eliminated 565 minutes of unnecessary continuous fan operation during low-thermal shifts, reducing energy consumption and mechanical bearing wear while delivering multi-channel smartphone push and email emergency alerts within 2 to 3 seconds during critical thermal spikes (100.00°C). In conclusion, the automated system establishes a highly reliable, non-intrusive, and energy-efficient solution for industrial switchgear thermal management. Furthermore, this study demonstrates how university-industry WBL partnerships advance United Nations Sustainable Development Goals (SDG 9 and SDG 12) by strengthening workplace safety, extending equipment service life, and optimizing industrial power consumption.

Keywords: Internet of Things (IoT), Industry 4.0, Energy Conservation, Work-Based Learning (WBL), Occupational Safety, Sustainable Development Goals (SDGs).

INTRODUCTION

In modern industrial plant management, the continuous operational stability of heavy machinery and electrical distribution infrastructure is fundamental to maintaining production efficiency and workplace safety. Manufacturing facilities rely heavily on Air Handling Units (AHUs) to maintain strict ambient ventilation, temperature regulation, and air humidity across factory premises. At the center of these environmental control systems are AHU electrical control panels, which house critical high-load switchgear components including

contactors, magnetic switches, relays, circuit breakers, and power cabling operating continuously 24 hours a day.

Despite their critical operational role, internal heat accumulation remains a pervasive operational hazard in enclosed electrical switchgears. According to Joule's Law of Heating ($P = I^2R$), high current flow through electrical conductors and connection terminals generates proportional thermal energy. When trapped inside unventilated enclosures, sustained thermal buildup accelerates insulation degradation, increases terminal contact resistance, causes premature component fatigue, and poses severe electrical fire risks.

At SGB MY Sdn. Bhd. a major power transformer manufacturing plant situated in Nilai, Malaysia routine thermal management of AHU control panels traditionally depended on periodic manual inspections conducted by technicians using handheld infrared thermometers or thermal imaging cameras. However, empirical observations highlight three major operational drawbacks associated with this legacy practice:

- Intermittent and Delayed Monitoring : Manual checks depend entirely on technician shift schedules, leaving unmonitored gaps during which unexpected thermal anomalies can escalate into severe catastrophic failures.

- Unregulated Cooling Inefficiencies : Existing cabinet exhaust fans operate continuously without automated temperature feedback, leading to substantial energy wastage and premature fan motor bearing wear.

- Occupational Safety Risks : Requiring maintenance personnel to physically open high-voltage switchgear doors for routine thermal readings exposes workers to arc flash and electrical shock hazards, conflicting with modern industrial ergonomic standards.

Table 1: Operational Comparison Between Legacy Manual Inspection and Automated IoT Panel Cooling

Operational Dimension	**Legacy Manual Inspection Practice**	**Proposed Automated IoT Cooling System**
Monitoring Frequency & Inspection Method	Periodic manual checks using handheld IR thermometers during technician shifts.	Continuous 24/7 digital monitoring via DS18B20 probe & Blynk cloud dashboard.
Exhaust Fan Control & Energy Efficiency	Continuous, uncontrolled 24/7 fan execution causing energy waste and bearing wear.	Demand-based feedback control with 5.0°C hysteresis deadband (40°C ON / 35°C OFF).
Occupational Safety & Multi-Channel Alerts	High arc flash exposure risk when opening cabinet doors; no real-time emergency alert.	Non-intrusive door HMI screen; 2-3 second push & email alerts at 50°C and 75°C.

To address these operational limitations, this study presents the design, field deployment, and performance evaluation of an Internet of Things (IoT) based automated panel cooling and real-time monitoring system.

Developed under a Work-Based Learning (WBL) collaboration between Universiti Teknikal Malaysia Melaka (UTeM) and SGB MY, the system replaces manual inspection routines with an ESP32 Smart Display microcontroller (CYD), a digital DS18B20 temperature sensor, a Solid-State Relay (SSR), and the Blynk IoT platform.



Figure 1: IoT-Based AHU Electrical Panel Cooling System

Beyond technical automation, this initiative directly aligns with the broader socio-industrial imperatives of United Nations Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure) and Goal 12 (Responsible Consumption and Production) by mitigating electrical hazard risks, reducing energy waste, and fostering sustainable university-industry TVET technology transfer.

LITERATURE REVIEW

Industrial Internet of Things (IIoT) and Industry 4.0 in Plant Maintenance

The rapid evolution of Industry 4.0 has transformed traditional reactive and scheduled maintenance paradigms into proactive, continuous cyber-physical monitoring systems (Xu et al., 2014; Xu et al., 2018). In heavy manufacturing environments, integrating low-cost sensor nodes with cloud telecommunication frameworks allows real-time health telemetry across plant assets without human intervention (Xu et al., 2018). Early thermal detection in electrical switchgears is critical because temperature serves as a primary leading indicator of electrical overload, loose terminal connections, and phase imbalance (Ross-Pinnock & Maropoulos, 2016). Modern IIoT architectures enable localized human-machine interface (HMI) visual feedback alongside cloud-based data logging, allowing plant managers to track real-time operational trends and receive instantaneous emergency push notifications (Xu et al., 2014).

Thermal Dynamics, Electrical Switchgear Standards, and Safety Regulations

Thermal management in low-voltage switchgears is governed by stringent international safety and performance frameworks. The International Electrotechnical Commission (IEC) standard IEC 61439-1 specifies thermal rise limits inside controlgear assemblies to prevent insulation breakdown and busbar thermal stress (International Electrotechnical Commission, 2020). Furthermore, IEC 60204-1 and IEC 60364-5-52 regulate the safe selection of wiring systems and industrial electrical machinery, emphasizing the necessity of protective barriers and continuous thermal dissipation (International Electrotechnical Commission, 2021, 2024). From an occupational health perspective, the Occupational Safety and Health Administration (OSHA) mandates strict risk controls regarding electrical panel enclosure safety to minimize worker exposure to energized conductors during routine maintenance (Occupational Safety and Health Administration, n.d.). Traditional manual inspection routines require technicians to bypass panel safety doors, directly violating safety guidelines when continuous, non-intrusive thermal sensing technologies are available (Ross-Pinnock & Maropoulos, 2016; Occupational Safety and Health Administration, n.d.).

Microcontroller Architectures, Sensor Immunity, and Hysteresis Control Logic

Implementing reliable thermal control inside high-power electrical switchgears requires hardware capable of enduring strong electromagnetic interference (EMI) generated by inductive contactors and switching transients. The DS18B20 digital temperature probe utilizes a 1-Wire communication protocol, providing high digital noise immunity and accurate factory-calibrated measurements (±0.5°C accuracy across -55°C to +125°C) compared to noise-sensitive analog thermistors (Analog Devices, 2019). Modern microcontrollers, such as the 32-bit dual-core ESP32, integrate Wi-Fi telemetry with direct Thin-Film Transistor (TFT) display drivers, allowing local door-mounted HMI visualization without opening high-voltage enclosures (Espressif Systems, 2025).

Table 2: System Control Logic Parameters, Hysteresis Setpoints, and Cloud Notification Matrix

Parameter / Condition	Temperature Threshold	Hardware / SSR Actuation	Cloud Alert & HMI Status
Normal Standby State	$T < 35.0°C$	SSR De-energized (Fan OFF)	Green Status; Live temperature display.
Cooling Activation Threshold	$T \geq 40.0°C$ (TON)	SSR Energized (Fan ON)	Yellow Status; Active Fan rotating graphic.
Warning Temperature Alert	$T \geq 50.0°C$	SSR Energized (Fan ON)	Orange Warning; Push alert & email sent.
Critical Emergency Alert	$T \geq 75.0°C$	SSR Energized (Fan ON)	Red Emergency; High-priority notification.

In automated feedback cooling, driving fans via simple single-point threshold logic causes rapid relay toggling (chattering) when temperatures fluctuate around the setpoint, leading to premature contact failure and excessive relay wear (Ellis, 2012). Incorporating a controlled temperature hysteresis band (e.g., 40.0°C activation and 35.0°C deactivation deadband) stabilizes switching operations, extends mechanical actuator lifespan, and optimizes energy consumption (Ellis, 2012).

Work-Based Learning (WBL) and Academic-Industrial Synergies in TVET

In technical and vocational education and training (TVET), Work-Based Learning (WBL) models bridge theoretical engineering fundamentals with practical industrial problem-solving. WBL initiatives empower university researchers and undergraduates to deploy functional engineering prototypes directly within active manufacturing environments. By addressing real-world industrial inefficiencies such as manual inspection overheads and uncontrolled power consumption at SGB MY WBL projects deliver dual value: advancing academic research and providing tangible operational improvements for industry partners.

RESEARCH METHODOLOGY

System Architecture and Hardware Selection

The development of the automated IoT-based Air Handling Unit (AHU) electrical panel cooling system at SGB MY followed a modular hardware-software integration framework. The architecture is divided into three primary functional units: sensing and processing, actuation and power switching, and wireless IoT cloud communication.

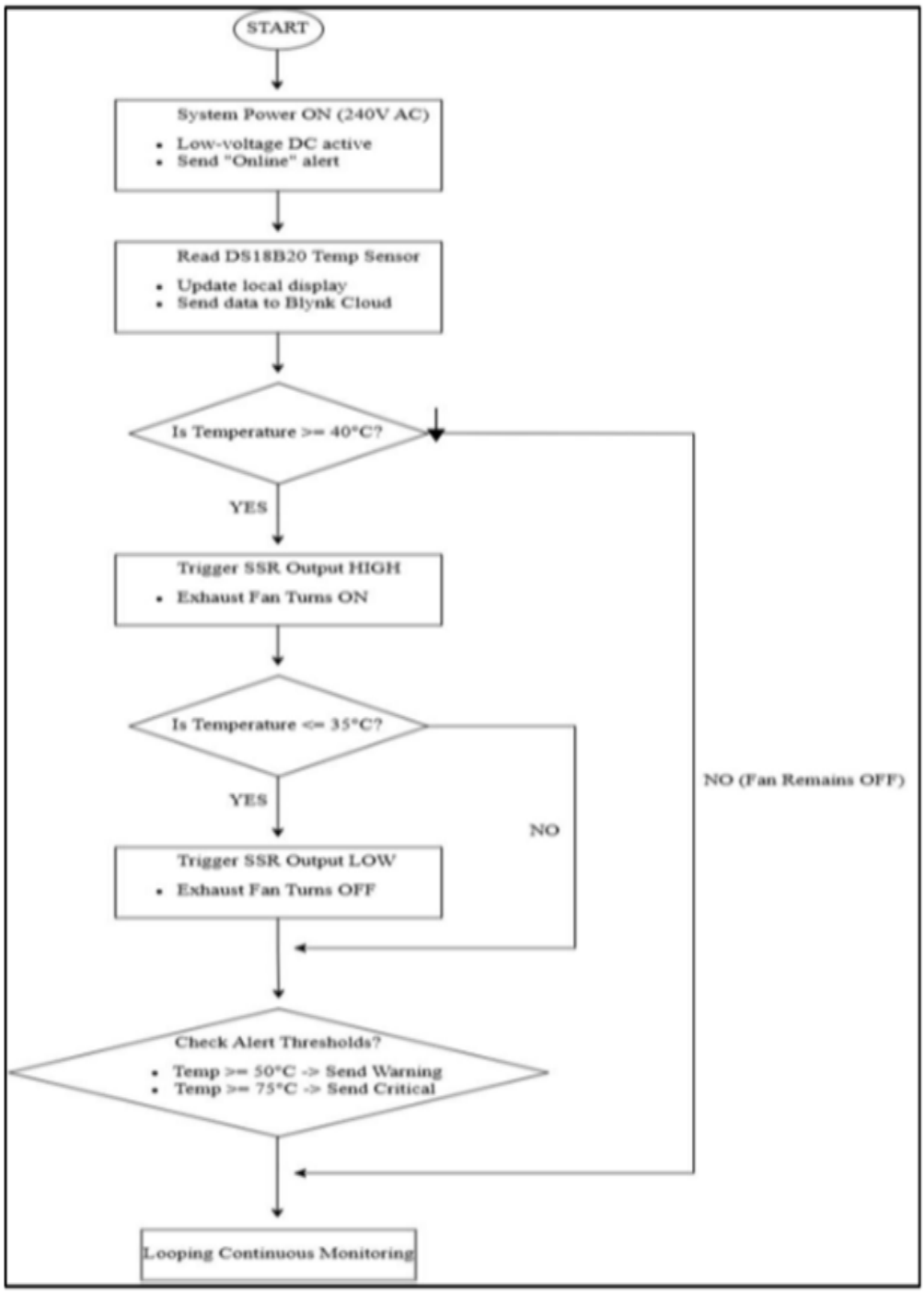


Figure 2: AHU Electrical Panel System Operation Process Flow

- Processing and Local Display Unit: An ESP32-2432S028R Smart Display (CYD) module featuring a 32-bit dual-core processor, built-in Wi-Fi, and an integrated 2.8-inch Thin-Film Transistor (TFT) LCD touchscreen serves as the primary edge controller and local Human-Machine Interface (HMI). Mounting this display externally on the panel door allows technicians to inspect real-time thermal conditions without opening high-voltage enclosures (Espressif Systems, 2025).
- Sensing Unit: Thermal sensing is performed using an industrial waterproof DS18B20 digital temperature probe operating via a 1-Wire bus protocol. Capable of measuring temperatures from -55°C to +125°C with an accuracy of ±0.5°C, the probe's digital signal output provides high immunity against electromagnetic interference (EMI) generated by nearby high-current inductive contactors (Analog Devices, 2019).
- Actuation and Power Switching: A Solid-State Relay (SSR-25DA) drives a high-power 240V AC 14-inch industrial exhaust fan. The SSR enables contactless optical switching using a 3–32V DC control

signal, eliminating mechanical contact arcing, acoustic noise, and physical wear during frequent switching operations (Ellis, 2012).

- Power Supply and Circuit Protection: Mains 240V AC power is supplied through a 20A Miniature Circuit Breaker (MCB) and a 2A protective inline fuse. A switching step-down power supply regulates AC voltage down to 12V DC and 5V DC to energize the low-voltage microcontrollers and sensor interfaces safely.

Figure 2 shows a comprehensive process flowchart illustrating system initialization, DS18B20 temperature acquisition, local TFT rendering, 40°C / 35°C hysteresis evaluation, SSR fan actuation, Blynk Wi-Fi telemetry transmission, and multi-tier email/push notification triggers.

Complete electrical schematic (figure 3) showing 240V AC mains input, 20A MCB, step-down DC power supplies, ESP32 CYD GPIO pin mappings to DS18B20 digital sensor, SSR-25DA control lines, indicator LEDs, and 14-inch exhaust fan AC wiring.

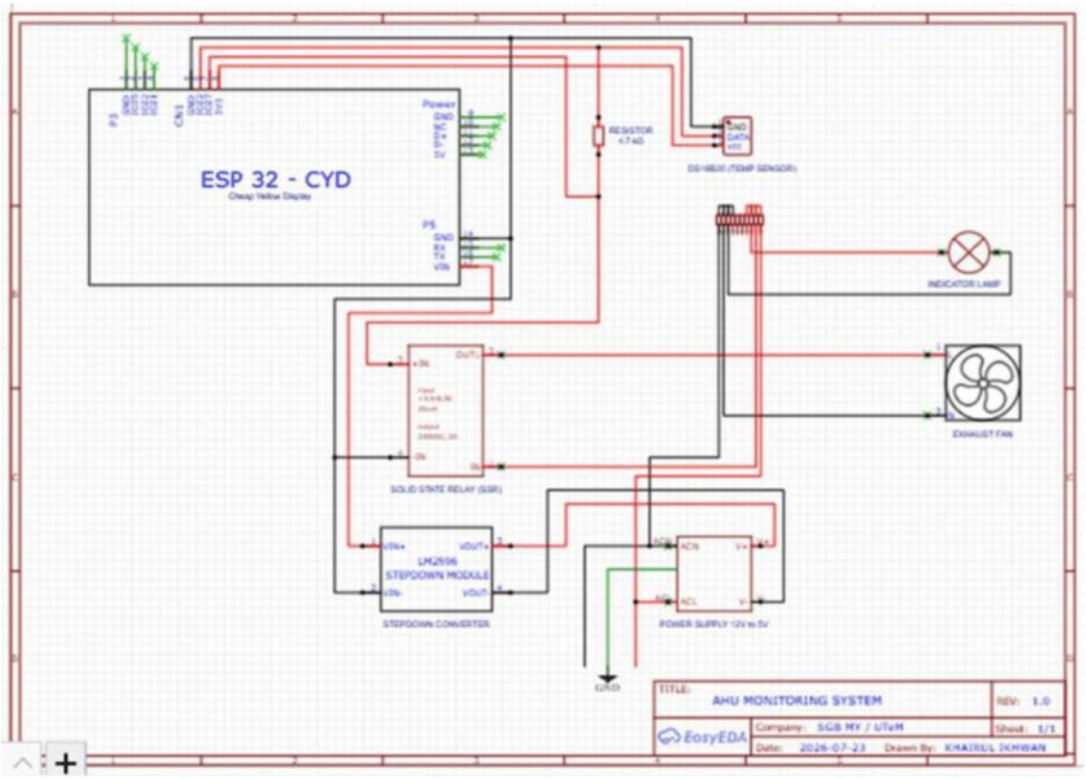


Figure 3: Circuit Diagram and Wiring Schematic

Table 3: Hardware, Software, and Test Equipment Specifications

Category	**Component / Tool**	**Technical Specifications / Role**
Processing	ESP32 CYD (2432S028R)	32-bit Dual-Core 240MHz, 2.8" TFT LCD (240x320), Wi-Fi & BLE
Sensing	DS18B20 Waterproof Probe	1-Wire Digital Bus, -55°C to +125°C Range, ±0.5°C Accuracy
Actuation	SSR-25DA Solid State Relay	Input: 3-32V DC, Output: 24-380V AC (25A), Optically Isolated
Cooling Fan	14-Inch Exhaust Fan	240V AC, 50Hz, Industrial Cabinet Ventilation Fan
Protection	20A MCB & Fuse	20A Single-Pole MCB, 2A Inline Glass Fuse for DC Controller

Power	AC-DC Converter Module	Input 240V AC, Output Dual 12V DC & 5V DC Regulated Bus
Software	Arduino IDE & Blynk IoT	Embedded C++ Firmware Compiler & Blynk Cloud Telemetry Platform
Testing	UNI-T Multimeter & FLIR	UNI-T Digital Multimeter Voltage Check & Thermal Camera Calibration

Control Logic, Setpoint Thresholds, and Hysteresis Deadband

To overcome the energy inefficiency and bearing wear caused by continuous fan operation, an event-driven feedback control algorithm was programmed in C++ using the Arduino IDE environment.

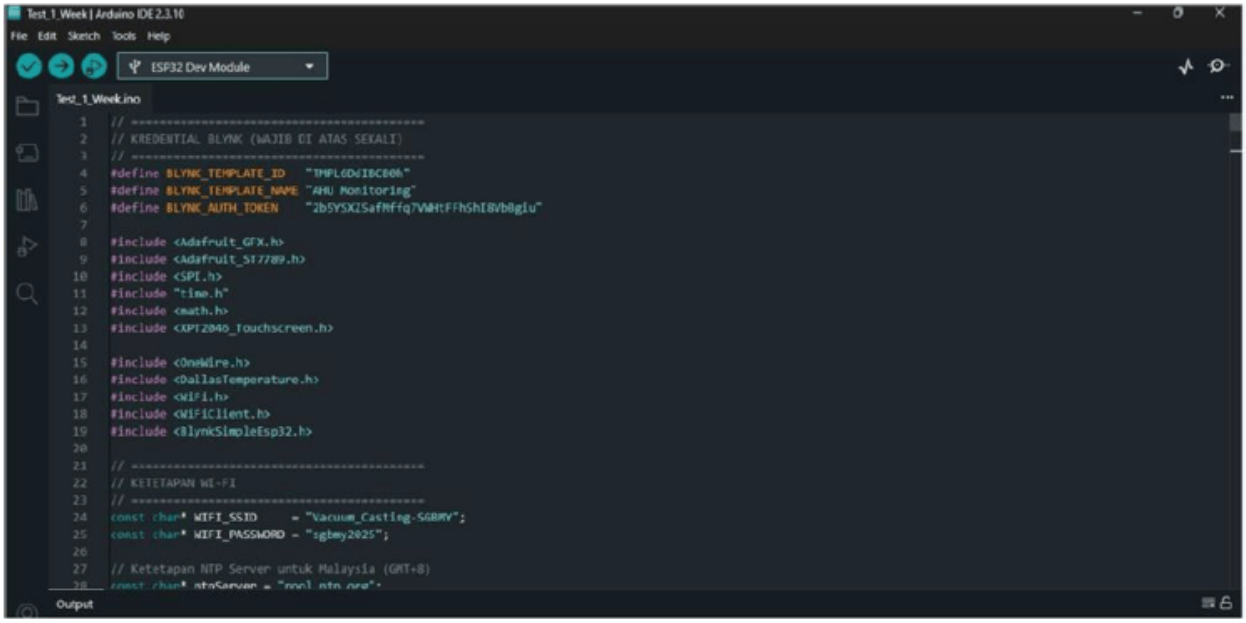


Figure 4: Programming setup and library initialization using Arduino IDE

Screenshot of the Arduino IDE setup showing C++ firmware code structure, OneWire and DallasTemperature library inclusions, Blynk Wi-Fi token authentication, and hysteresis decision loop code shown in figure 4.

The system employs a 5.0°C temperature hysteresis deadband to govern exhaust fan actuation:

• Fan Activation Setpoint (T ON): When internal panel temperature reaches or exceeds 40.0°C, the ESP32 drives GPIO signal HIGH, energizing the SSR and activating forced exhaust ventilation.

• Fan Deactivation Setpoint (T OFF): The exhaust fan continues operating until forced heat dissipation cools the panel down to 35.0°C or below, at which point GPIO signal drops LOW, de-energizing the SSR.

Incorporating this 5.0°C deadband prevents rapid relay chattering near single-point threshold limits, stabilizing the mechanical control loop, extending relay lifespan, and minimizing unnecessary power draw (Ellis, 2012).

Table 4: System Control Logic Parameters and Output Conditions

Temperature Range (°C)	SSR State	Cooling Fan Status	Blynk Cloud Alert Status
T < 35.0°C	OFF (LOW)	Fan Deactivated	Normal Telemetry Logging

35.0°C ≤ T < 40.0°C	Maintains State	Hysteresis Deadband State	Normal Telemetry Logging
40.0°C ≤ T < 50.0°C	ON (HIGH)	Fan Active (Forced Cooling)	Active Fan Status Dashboard Icon
50.0°C ≤ T < 75.0°C	ON (HIGH)	Fan Active (Forced Cooling)	WARNING: Push & Email Notification
T ≥ 75.0°C	ON (HIGH)	Fan Active (Emergency Cooling)	CRITICAL: Urgent Push & Email Alert

IoT Telemetry and Multi-Channel Notification Architecture

Remote data logging and emergency alerts are managed through the Blynk IoT cloud platform over Wi-Fi, routed via a dedicated industrial TP-Link wireless router. Figure 5 shows the configuration screen of the Blynk Web Console illustrating Datastream setup (V0 Temperature, V1 Fan Status, V2 System State), widget placements (Gauges, Charts, LCD Monitors), and threshold event rules.

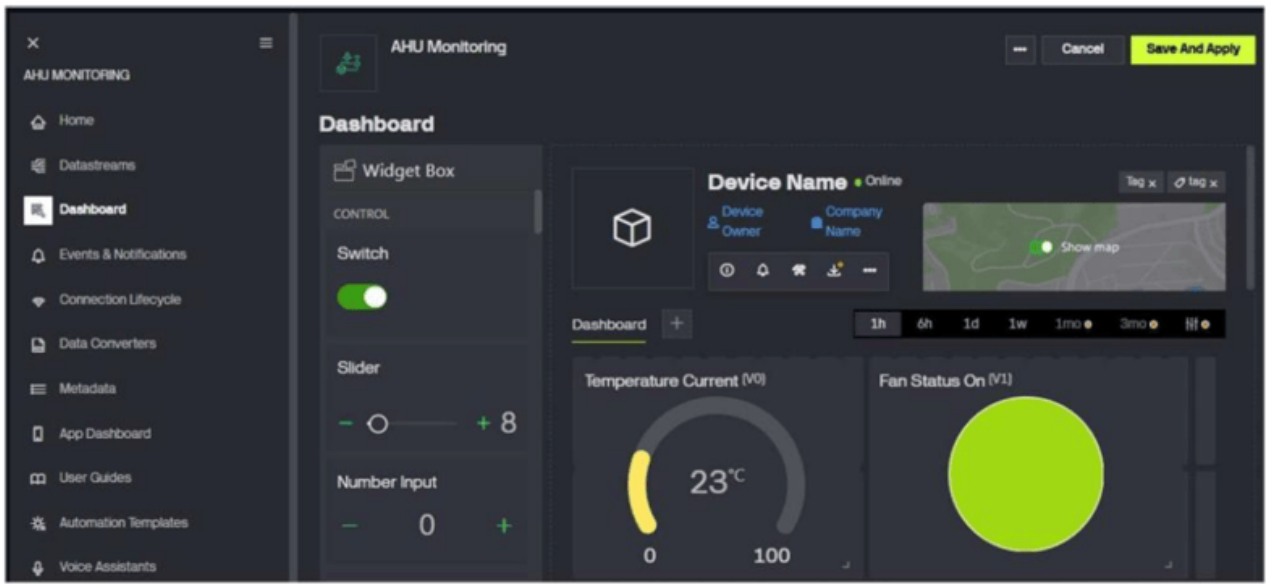


Figure 5: Blynk IoT dashboard interface design and widget configuration process

The system implements a four-stage emergency notification matrix:

- System Online Alert: Transmitted upon system boot or AC mains power restoration.
- System Offline Alert: Executed via Blynk server-side Last Will and Testament (LWT) heartbeat tracking within 30–60 seconds of Wi-Fi disconnection or panel power trip.
- Warning Alert (50.0°C): Triggers instant smartphone push alerts and automated emails when panel heat exceeds baseline operational bounds.
- Critical Emergency Alert (≥75.0°C): Sends continuous high-priority smartphone push notifications and email warnings to plant engineers to prevent catastrophic equipment failure.

Experimental Setup and On-Site Field Installation at SGB MY

To evaluate the system under real industrial conditions, the complete hardware setup was mounted directly on the Air Handling Unit (AHU) electrical panel at SGB MY in Nilai. Step-by-step prototyping hardware workflow: (Figure 6) Custom PCB breadboard soldering; (Figure 7) Component layout inside protective ABS enclosure; (Figure 8) Dual AC-DC power supply voltage calibration using UNI-T digital multimeter; (Figure 9) Initial prototype bench test setup with heat source validation.

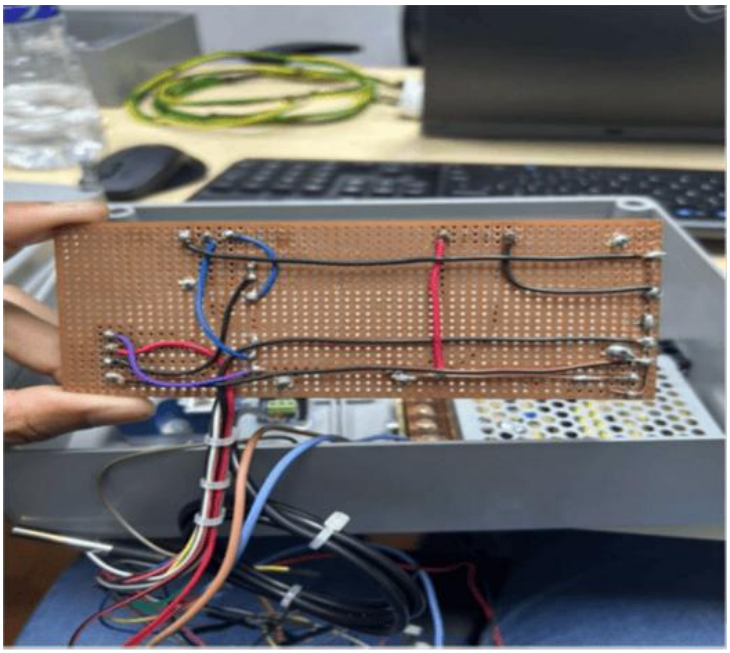


Figure 6**:** Soldering process and wiring connections on the breadboard / PCB



Figure 7: Component placement and internal wiring inside the main enclosure box

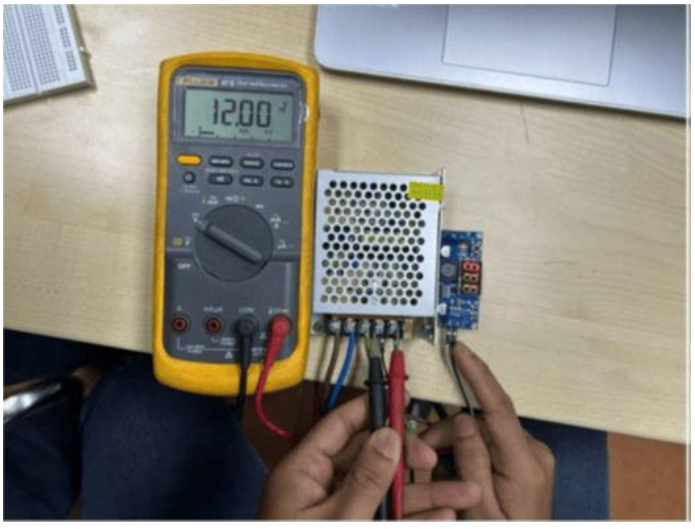


Figure 8**:** Voltage output measurement of the power supply using a digital multimeter

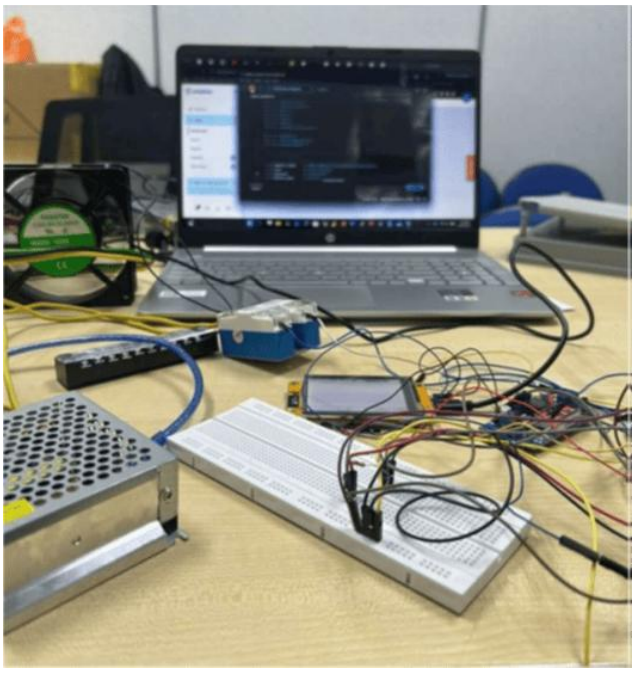


Figure 9: Initial prototype testing on a breadboard prior to final assembly

Field deployment involved dividing components between two physical enclosures linked via surface-mounted PVC conduit piping:

- Main AHU Switchgear Cabinet: Houses high-power 240V AC contactors, circuit breakers, the internal DS18B20 sensor probe, and the 14-inch door-mounted exhaust fan.
- Smart Display External Housing: Wall-mounted adjacent to the panel, containing the ESP32 CYD module, indicator lamps, and DC power supply converters.

A Field deployment at SGB MY Nilai plant: (Figure 10) External PVC conduit routing and junction box installation; (Figure 11) Electrical wiring integration inside main AHU panel connected to 240V AC contactors and DS18B20 probe.



Figure 10: Surface conduit and junction box installation at the AHU site



Figure 11: Electrical wiring integration inside the AHU main control panel

Industrial Safety and Risk Mitigation

Operating low-voltage electronic microcontrollers within heavy industrial switchgear cabinets introduces electrical shock and interference risks (International Electrotechnical Commission, 2021). Safety procedures were strictly enforced during installation.

Table 5: Risk Assessment and Mitigation Control Measures

Identified Industrial Risk	Risk Severity	Mitigation Control Strategy Implemented
Electrical Shock / Arc Flash	High	Lockout/Tagout (LOTO) during wiring; physical separation of AC/DC lines.
Short Circuit / Overcurrent	High	Dedicated 20A MCB and 2A glass inline fuse protection on DC controller bus.
Electromagnetic Interference (EMI)	Medium	Digital DS18B20 1-Wire shielded cabling routed away from contactors.
Dust & Moisture Ingress	Medium	IP65 waterproof DS18B20 probe and sealed external ABS controller enclosure.
Relay Thermal Overheating	Medium	Optically isolated SSR-25DA mounted on aluminum heatsink block.

RESULTS AND DISCUSSION

Local Human-Machine Interface (HMI) Performance

Field testing confirmed the execution of local monitoring on the panel door via the ESP32-2432S028R 2.8-inch TFT LCD touchscreen. On-site testing setup at SGB MY Nilai plant (Figure 12) and On-site firmware

tuning and sensor calibration (Figure 13) was fully installed automated panel cooling setup on active AHU panel.



Figure 12**:** On-site system programming, troubleshooting, and field testing near the AHU panel



Figure 13: Physical installation setup of the AHU panel, Smart Display Enclosure Box, 240V AC Exhaust Fan, and AC Conduit Piping

The local GUI provides real-time operational feedback:

- Primary Telemetry Interface: Displays live panel temperature (41.6°C), programmed setpoints (T ON = 40.0°C, T OFF = 35.0°C), and active AUTO fan rotating graphics.
- Real-Time Graphical Trend Display: Renders a dot-matrix temperature graph tracking short-term thermal shifts.
- Diagnostic Runtime Screen: Maintains an accumulated exhaust fan run-time log (e.g., logging 00H:06M:25S during baseline validation).



Figure 14: Local TFT LCD screen displaying live panel temperature (41.6°C), fan operational mode (AUTO), and control setpoints



Figure 15: Real-time dot-matrix temperature trend graph on the local 2.8-inch TFT LCD screen



Figure 16: Local screen logging accumulated exhaust fan runtime (00H: 06M: 25S) and system operation status

Touchscreen GUI interfaces as shown above are : (Figure 14) Main dashboard showing 41.6°C live temperature and active fan icon; (Figure 15) Real-time dot-matrix thermal trend graph and (Figure 16) System diagnostic screen logging fan active runtime.

Benchmark Controlled Heat Trial and Relay Response

A controlled thermal simulation was conducted to validate the automatic switching logic and heat dissipation performance as shown in table 6. Thermal cooling curve graph plotting panel temperature against time during controlled heat trial, highlighting instant SSR activation at 100°C and steady cooling down to 33.06°C over 5 minutes and 19 seconds shown in figure 17.

Table 6: Experimental Data Log of Thermal Trial and Switching Response

Timestamp	Temperature (°C)	SSR Signal	Fan State	Operational Phase & Remarks
11:14:59	33.50°C	LOW	OFF	Standby Phase (Below 40.0°C Threshold)
11:15:19	100.00°C	HIGH	ON	Thermal Spike Applied (Instant Fan Trigger)
11:16:06	83.81°C	HIGH	ON	Active Forced Cooling Phase
11:17:38	50.56°C	HIGH	ON	Active Forced Cooling Phase
11:19:12	38.19°C	HIGH	ON	Hysteresis Zone (Cooling Below 40°C Target)
11:20:38	33.06°C	LOW	OFF	Deactivation Setpoint Reached (≤35.0°C)

	A	B
1	Timestamp	Temperature
2	2026-07-25 11:14:59	33.5
3	2026-07-25 11:15:03	33.5
4	2026-07-25 11:15:07	33.5
5	2026-07-25 11:15:11	33.5
6	2026-07-25 11:15:15	33.5
7	2026-07-25 11:15:19	100
8	2026-07-25 11:15:23	100
9	2026-07-25 11:15:27	100
10	2026-07-25 11:15:32	100
11	2026-07-25 11:15:37	100
12	2026-07-25 11:15:41	100
13	2026-07-25 11:15:44	100
14	2026-07-25 11:15:49	100
15	2026-07-25 11:15:53	93.62
16	2026-07-25 11:15:57	93.62
17	2026-07-25 11:16:01	93.62
18	2026-07-25 11:16:06	83.81
19	2026-07-25 11:16:10	83.81
20	2026-07-25 11:16:15	83.81
21	2026-07-25 11:16:18	83.81

Figure 17: Recorded Temperature Data from Prototype Testing

The total active cooling cycle lasted 5 minutes and 19 seconds, successfully returning the panel to a safe idle state and turning off the fan.

24-Hour Industrial Field Monitoring Data Analysis at SGB MY

Continuous telemetry data was gathered over a 24-hour operational period (24 September 2026 to 25 September 2026) across active factory production shifts at SGB MY.

Table 7: Statistical Summary of Recorded 24-Hour Field Temperature Data

Statistical Parameter	**Recorded Empirical Value**	**Operational Significance**
Total Data Points Logged	825 Readings	Continuous 24-hour telemetry logging at 1-2 min intervals
Minimum Panel Temperature	31.57°C	Recorded during early morning non-production shift (05:00-08:00)
Maximum Panel Temperature	100.00°C	Peak thermal anomaly event on 25 Sept at 16:20:00
Mean Panel Temperature	41.04°C	Average thermal operating level under normal factory load
Median Panel Temperature	40.60°C	Central thermal tendency confirming steady baseline operation
Readings < 35.0°C (Fan OFF)	565 Readings (68.5%)	565 minutes of saved fan runtime and energy conservation
Readings ≥ 40.0°C (Fan ON)	749 Readings (in-cycle)	Cumulative readings where demand cooling was active/retained

Figure 18 shows the 24-hour continuous temperature telemetry history chart exported from Blynk cloud, demonstrating thermal fluctuations corresponding directly to factory shift activity and ambient temperature changes.



Figure 18: Temperature Reading and Data History

Anomaly Escalation and Emergency Response Evaluation

A critical thermal anomaly occurred on 25 September 2026 at 16:19–16:21:

- Temperature rose rapidly from 49.25°C at 16:18:00 to 67.73°C at 16:19:00, peaking at 100.00°C at 16:20:00.
- At 16:19:18, as heat crossed 50.0°C, Blynk issued a Temperature Warning alert.
- Twenty seconds later (16:19:38), as heat crossed 75.0°C, the system issued a Temperature Critical alert.
- Forced cooling reduced the panel temperature back to 48.79°C within 4 minutes (16:24:00), demonstrating rapid automatic thermal recovery.

Figures below shows critical thermal anomaly tracking : (Figure 19) 100.00°C temperature spike trend curve; (Figure 20) Blynk event log recording Warning (50°C) and Critical (75°C) timestamps and (Figure 21) Exported CSV event history file.

2026-09-25 16:17:00	49.25
2026-09-25 16:18:00	49.25
2026-09-25 16:19:00	67.72933333
2026-09-25 16:20:00	100
2026-09-25 16:21:00	75.05814286
2026-09-25 16:22:00	59.89573333
2026-09-25 16:23:00	53.00857143
2026-09-25 16:24:00	48.7918
2026-09-25 16:25:00	46.81721429
2026-09-25 16:26:00	45.74971429
2026-09-25 16:27:00	44.97271429

Figure 19: Maximum Temperature for 24 Hours

9/25/2026 16:19	WARNING	Temperature Warning	AMARAN: Suhu AHU Meningkat Tinggi! Semasa: 55.19C
9/25/2026 16:19	CRITICAL	Temperature Critical	BAHAYA: Suhu AHU Tahap KRITIKAL! Semasa: 93.75C

Figure 20: Blynk Event Log Recorded

Time	Event Type	Name	Description
9/25/2026 18:56	ONLINE	Online	
9/25/2026 18:56	OFFLINE	Offline	
9/25/2026 18:56	ONLINE	Online	
9/25/2026 18:56	OFFLINE	Offline	
9/25/2026 18:55	ONLINE	Online	
9/25/2026 18:55	OFFLINE	Offline	
9/25/2026 18:54	ONLINE	Online	
9/25/2026 18:54	OFFLINE	Offline	
9/25/2026 16:19	CRITICAL	Temperature Warning	AMARAN: Suhu AHU Meningkat Tinggi! Semasa: 55.19C
9/25/2026 16:19	WARNING	Temperature Critical	BAHAYA: Suhu AHU Tahap KRITIKAL! Semasa: 93.75C
9/25/2026 14:43	WARNING	Temperature Warning	
9/25/2026 10:21	WARNING	Temperature Warning	AMARAN: Suhu AHU Meningkat Tinggi! Semasa: 50.00C
9/25/2026 8:55	WARNING	Temperature Warning	
9/25/2026 8:35	ONLINE	Online	
9/25/2026 8:35	OFFLINE	Offline	
9/25/2026 8:31	ONLINE	Online	
9/25/2026 8:31	OFFLINE	Offline	

Figure 21: Blynk Event File Recorded

IoT Cloud Telemetry, Notification Latency, and Network Connectivity

Remote alerting and cloud telemetry were verified on the Blynk web dashboard and mobile interface:

- Notification Latency: Smartphone push alerts and automated Gmail notifications were delivered within 2 to 3 seconds of passing setpoint thresholds (50.0°C and 75.0°C), confirming reliable real-time escalation.
- Network Reliability & LWT Heartbeat: Over the 24-hour trial, the system logged six brief offline events caused by factory Wi-Fi fluctuations. The Blynk Last Will and Testament (LWT) protocol logged offline and reconnection events reliably, restoring cloud telemetry automatically upon reconnection.

Cloud and mobile telemetry interfaces: (Figure 22 & 23) Web console showing live gauges and OVERHEAT banner; (Figure 24) Historical fan runtime chart; (Fig 25 & 26) Smartphone lock-screen push and email alerts; (Figure 27) Automated email notifications logging Online/Offline status (text message apply to 'Bahasa Malaysia').



Figure 22: Blynk web dashboard showing real-time gauge widget (83.81°C), fan status indicator, and thermal heatmap widget.



Figure 23: Blynk web dashboard displaying OVERHEAT! warning banner and cumulative fan runtime counter



Figure 24: Historical runtime chart export widget recording cumulative cooling fan operation (02H:21M:55S).



Figure 25: Blynk Critical Temperature Notification



Figure 26: Mobile device lock screen displaying simultaneous Gmail alert emails and Blynk push notifications



Figure 27: Gmail alert notifications logging device Online status (4:41:54 PM) and Offline status (4:41:13 PM)

Managerial, Operational, and Energy Efficiency Impact

The empirical findings demonstrate clear operational and strategic benefits:

- Energy Conservation & Asset Lifespan: Automating fan operation based on internal temperature eliminated non-stop fan execution during low-temperature periods (565 minutes below 35.0°C), lowering energy consumption and preventing motor bearing wear.
- Occupational Ergonomics & Safety: Technicians can inspect panel thermal conditions locally via the external touchscreen or remotely via the mobile app, removing the need to open high-voltage switchgear doors during routine checks and significantly mitigating arc flash hazards (Ross-Pinnock & Maropoulos, 2016).
- Alignment with Sustainable Development Goals: Reducing electrical thermal losses ($P = I^2R$) and energy consumption supports UN Sustainable Development Goal 9 and Goal 12, establishing a model for sustainable industrial plant maintenance in TVET education.

CONCLUSION AND RECOMMENDATIONS

This research successfully developed, deployed, and evaluated an automated IoT-based temperature monitoring and cooling control system for the Air Handling Unit (AHU) electrical control panel at SGB MY in Nilai, Malaysia. The project effectively resolved the operational limitations of legacy manual inspections and continuous, uncontrolled exhaust fan operation through integrated hardware and software engineering.

The empirical findings from the prototype bench testing and 24-hour field evaluation support three primary conclusions:

- Continuous Non-Intrusive Thermal Telemetry: Integrating the waterproof DS18B20 digital sensor with the external door-mounted ESP32 CYD Smart Display enabled continuous, high-accuracy temperature monitoring. Technicians can inspect real-time thermal conditions locally on the 2.8-inch TFT LCD screen or remotely via the Blynk cloud platform without opening high-voltage switchgear doors, substantially mitigating occupational arc flash exposure and electrical shock risks (Ross-Pinnock & Maropoulos, 2016).
- Energy-Efficient Demand-Based Cooling: Implementing a 5.0°C hysteresis control band (activation at ≥40.0°C and deactivation at ≤35.0°C) provided reliable automatic fan switching. This deadband prevented rapid relay chattering, extended component service life, and eliminated 565 minutes of unnecessary fan operation during low-temperature production shifts, directly reducing overall energy consumption (Ellis, 2012).
- Rapid Emergency Telemetry Escalation: The multi-channel notification framework delivered real-time warning alerts (50.0°C) and critical emergency alerts (≥75.0°C) via push notifications and automated emails within 2 to 3 seconds of setpoint breach. Additionally, server-side Last Will and Testament (LWT) heartbeat tracking ensured immediate logging of power interruptions or network disconnections.

Managerial and Educational Implications

The broader socio-industrial impact of this study extends beyond hardware automation into manufacturing plant governance and TVET educational paradigms:

- Occupational Safety and Workplace Ergonomics: Mandating non-intrusive thermal monitoring aligns factory maintenance workflows with IEC 60204-1 and OSHA electrical safety standards (International Electrotechnical Commission, 2021; Occupational Safety and Health Administration, n.d.). Eliminating the need to open cabinet doors during routine checks protects maintenance personnel from energized conductors, fostering a safer working environment (Ross-Pinnock & Maropoulos, 2016).
- Industrial Sustainability (SDGs 9 & 12): Mitigating electrical thermal losses ($P = I^2R$) and curbing demand-side fan power consumption directly contributes to UN SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production). Demand-based cooling offers plant operators a cost-effective route to lower factory carbon footprints.
- TVET Work-Based Learning (WBL) Synergy: This project demonstrates the value of university-industry WBL frameworks in technical education. Bridging academic research at UTeM with real-world industrial application at SGB MY provides engineering undergraduates with hands-on problem-solving experience while delivering measurable operational improvements to manufacturing partners.

Recommendations for Future Work

To build upon the successful deployment at SGB MY, several enhancements are proposed for future industrial iterations:

Table 8: Summary of Proposed System Enhancements and Future Work

Proposed Technical Enhancement	Targeted Subsystem	Expected Operational & Engineering Benefit
Multi-Point Distributed Sensor Network	1-Wire Sensor Bus	Deploys probes across contactors & busbars to map internal thermal zones.
Variable Speed Fan Control (PWM / VFD)	Actuator & Exhaust Fan	Dynamically regulates fan speed to heat levels, reducing noise & power.
Integrated Electrical Power Quality Monitoring	PZEM-004T / CT Module	Correlates voltage, current, & power factor with thermal trends for predictive maintenance.

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