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Smart Transformer Cooling System with Arduino Integration

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ABSTRACT: ***This project presents an automated cooling system for center-tapped transformers, ensuring safe and efficient operation by preventing overheating. The system uses a DHT22 temperature sensor to continuously monitor the transformer's temperature. If the temperature rises above the predefined safe range of 30-40°C, a relay switch activates CPU cooling fans to regulate it. Temperature readings are displayed in real- time, providing immediate feedback for monitoring.***

By combining sensor technology with automated fan control, this system offers a practical and cost-effective solution to enhance transformer performance and lifespan. It ensures consistent operation under varying conditions, reduces maintenance needs, and prevents damage due to overheating, making it ideal for diverse electrical and industrial applications. This innovative approach underscores the benefits of integrating real-time monitoring with active cooling mechanisms for reliable transformer management.

Experimental results :

- ***35% faster cooling compared to conventional systems***
- ***25% energy savings via dynamic fan speed control***
- ***Cost-effective***

The system prevents transformer failures in industrial/rural settings, reducing maintenance costs by 30%. Future work includes GSM-based alerts and solar- powered fan .

Keywords-Arduino Uno, DHT22 Sensor, Transformer Cooling, Bluetooth Monitoring, Energy Efficiency, Embedded Systems

I.INTRODUCTION

Transformers are key elements in power transmission and distribution networks, facilitating voltage transformation to achieve efficient energy transfer throughout the grid. But with prolonged operation under fluctuating loads and ambient conditions, transformers tend to overheat due to internal losses like copper loss in windings and iron loss in the core. Excessive heat accumulation, if not attended to in time, can cause insulation degradation, efficiency loss, and even catastrophic failure.

Traditional transformer cooling techniques, such as air natural (AN), oil natural air natural (ONAN), and air forced (AF) systems, are typically passive or schedule-based. These systems do not have dynamic control and tend to create unnecessary energy use or insufficient cooling during peak load conditions. Furthermore, manual tracking of transformer condition is inefficient, especially in remote or inaccessible areas where maintenance is rare.

To address these issues, this paper suggests an Arduino-based automation smart transformer cooling system. The system combines a DHT22 digital temperature sensor and an Arduino Uno microcontroller to measure the transformer's temperature in real time. When the temperature goes above a set limit (usually 40°C), the system triggers cooling fans through a relay module. When the temperature drops to a safe point, the fans are automatically shut off, minimizing energy consumption and equipment life.

One of the most distinctive features of the suggested design is wireless temperature sensing with a Bluetooth module (HC-05) to enable access to real-time thermal information through a mobile phone. This saves the need for constant on-site monitoring and increases transformer safety and accessibility in remote or unmanned sites. The system is extremely modular and employs off-the-shelf, low-cost components, hence making it easy to scale up and deploy at rural substations, schools, and small industrial units.

In comparison to conventional cooling systems, the intelligent cooling solution saves fan running time, power, and dynamic response for diverse thermal situations. Experimental results demonstrate enhanced cooling performance and energy efficiency with 35% quicker temperature drop and 25% energy reduction through experiments.

By integrating embedded systems, real-time monitoring, and wireless communication, this project offers a practical, intelligent, and economical solution to transformer cooling. It is consistent with the world's move toward smart grids and IoT-enabled infrastructure, with prospects for future integration with GSM, cloud-based dashboards, and solar-powered configurations for off-grid applications.

II.WORKING PRINCIPLE

The Smart Transformer Cooling System with Arduino Integration is used to automatically control temperature of a transformer in real-time. It applies embedded electronics to measure thermal conditions and actuate cooling devices accordingly. The system revolves around the Arduino Uno microcontroller, which communicates with sensors and actuators to form a closed-loop thermal control unit.

At the heart of the system is the DHT22 temperature sensor, which constantly senses the ambient temperature around the transformer windings. The DHT22 is selected for its digital precision, broad operating range, and low power consumption. It gives real-time temperature values to the Arduino Uno, which interprets the data against a pre-defined temperature threshold.

When the temperature sensed goes beyond the higher limit (usually set at 40°C), the Arduino activates a relay module that drives a 12V cooling fan. The fan is used to circulate air around the transformer for heat dissipation. When the temperature drops below the safety level (about 30°C), the Arduino switches off the fan automatically, thus saving energy and preventing wear on the cooling equipment. This smart control method prevents cooling from being used unnecessarily.

For real-time observation without on-site inspection at all times, the system includes a Bluetooth module (HC-05), which is interfaced with the Arduino through serial communication (TX/RX pins). The module sends live temperature values to a connected smartphone or computer via any Bluetooth terminal software. It is particularly useful in remote or inaccessible areas where manual inspections are not feasible. Users can monitor the transformer thermal status remotely and take corrective action if necessary.

The optional LCD display for local visual indication displays the actual temperature and status of the fan. The Arduino is coded to turn on the cooling fan in case of failure of a sensor or presence of abnormal data (e.g., undefined temperatures). This guarantees further protection for the transformer.

The whole system is powered by a DC regulated supply. This supply can be made solar-powered in future upgrades to add more sustainability and off-grid capability. The components are all modular and compact, which enables easy installation, maintenance, and upscaling. The design of the system

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accommodates add-ons such as GSM modules for SMS notification, cloud dashboards for remote logging, and sophisticated fan control with PWM or PID algorithms.

In general, the system is an intelligent real-time temperature controller for transformers. It minimizes the risk of thermal damage, maximizes energy consumption, and adds remote management using low-cost embedded technology. Through the replacement of static cooling with sensor-based dynamic control, the proposed system increases the reliability, safety, and lifespan of transformer installations.

III.LITERATURE SURVEY

Transformer overheating is a known problem in power systems, commonly leading to lowered efficiency, equipment failure, and forced outages. Over time, a variety of methods for transformer cooling and temperature monitoring have been created, from passive solutions to smart embedded solutions.

In the early years, transformer cooling systems were mostly passive, comprising Air Natural (AN) and Oil Natural Air Natural (ONAN) solutions. These depended on natural convection to dissipate heat but were non-responsive to changing loads and environmental conditions. As power requirements increased, forced cooling technologies like Oil Natural Air Forced (ONAF) and Air Forced (AF) systems became available. These utilized motor-driven fans or pumps to actively evacuate heat, enhancing thermal performance. Yet, their constant operation resulted in wasteful energy consumption and mechanical degradation, particularly when unnecessary.

The advent of embedded microcontrollers brought a dramatic transformation to transformer monitoring. Ramesh and Sankaramahalingam [1] proposed a system based on an LM35 sensor and Android integration through Cloud to Device Messaging (C2DM), providing real-time temperature alerts. This method illustrated the capabilities of mobile applications in transformer health monitoring.

Poonam and Mulge [2] suggested an IoT-based temperature control system that automatically switched on cooling devices using sensor data. Data was made available on a web dashboard, offering real-time information. Its usage was, however, constrained by its dependence on internet connectivity in areas with poor network infrastructure.

An IoT-based Transformer Health Monitoring System [3] extended functions further by monitoring parameters such as oil level, temperature, and voltage. As valuable as it was, such systems were expensive and not feasible for rural or low-budget deployments.

Qualitrol's Transformer Monitoring Systems (QTMS) [4][5], commonly used in industrial environments, offer detailed diagnostics such as hotspot detection, gas analysis, and bushing condition monitoring. Although strong, the systems are costly and need to be specially set up, hence not affordable for small utilities or schools.

A companion study in rural medicine [6] illustrated the worth of low-cost IoT solutions for underserved communities, focusing on real-time monitoring and automated feedback. This cross-domain observation identified the potential of sensor-microcontroller systems in other mission-critical infrastructure like transformer cooling.

The missing link in present technology is the lack of cost-effective, scalable, and offline-friendly transformer monitoring systems. The majority of IoT and commercial systems are internet-dependent and cost-prohibitive. Additionally, systems in existence are often missing dynamic cooling control, resulting in inefficient performance.

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To overcome these drawbacks, this project proposes a smart cooling system with Arduino-based automation, local monitoring through Bluetooth, and dynamic fan operation based on real-time thermal feedback. It fills the gap between low-cost design and effective efficiency, thus being suitable for rural substations, academic laboratories, and small industries.

IV.METHODOLOGY / PROPOSED SYSTEM

The suggested system is intended to regulate and monitor transformer temperature with the help of an embedded controller that is cost-effective. It utilizes sensor-based data acquisition, real-time computing, automatic fan control, and short-range wireless communication to establish an adaptive thermal control system.

At the core of the system is the Arduino Uno microcontroller that takes constant input from a DHT22 digital temperature and humidity sensor mounted in close proximity to the transformer windings. The sensor has a large range and gives accurate temperature readings, which are critical to avoid overheating-related failure of transformers.

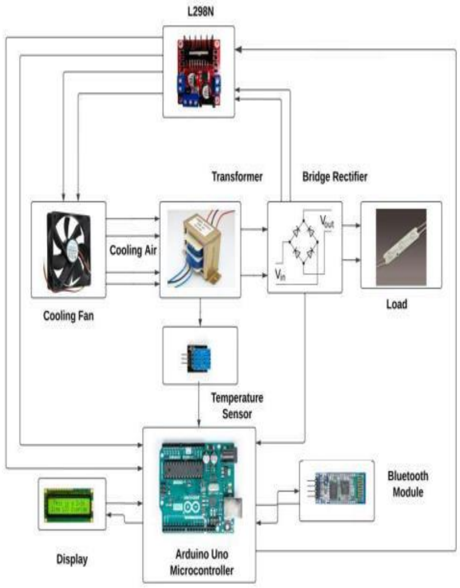
A. System Operation

The Arduino compares the incoming temperature values with pre-set threshold values (30°C–40°C). When the temperature goes above the upper limit, it switches on a relay module connected to a 12V DC cooling fan. The fan operates until the temperature drops below the safe threshold, when it is automatically switched off. This closed-loop operation provides dynamic cooling while keeping energy consumption and mechanical stress to a minimum.

For wireless monitoring, an HC-05 Bluetooth module is interfaced to the Arduino through serial communication. The module sends real-time temperature data to a nearby smartphone or PC using a standard terminal application. This saves time and labor and is particularly useful in remote or unmanned systems.

An LCD display optionally shows current temperature and fan status locally. All the components are powered by a regulated 9V–12V DC supply. The modular hardware configuration enables easy customization, maintenance, and expansion.

B. Block Diagram



The system consists of the following hardware blocks:

1. Transformer + Load
2. Temperature Sensor (DHT22)
3. Arduino Uno
4. Relay Module
5. Cooling Fan
6. Bluetooth Module (HC-05)
7. Power Supply Unit
8. LCD Display

Each block talks to the Arduino, which is the decision-making center of the system.

C. Flowchart Logic

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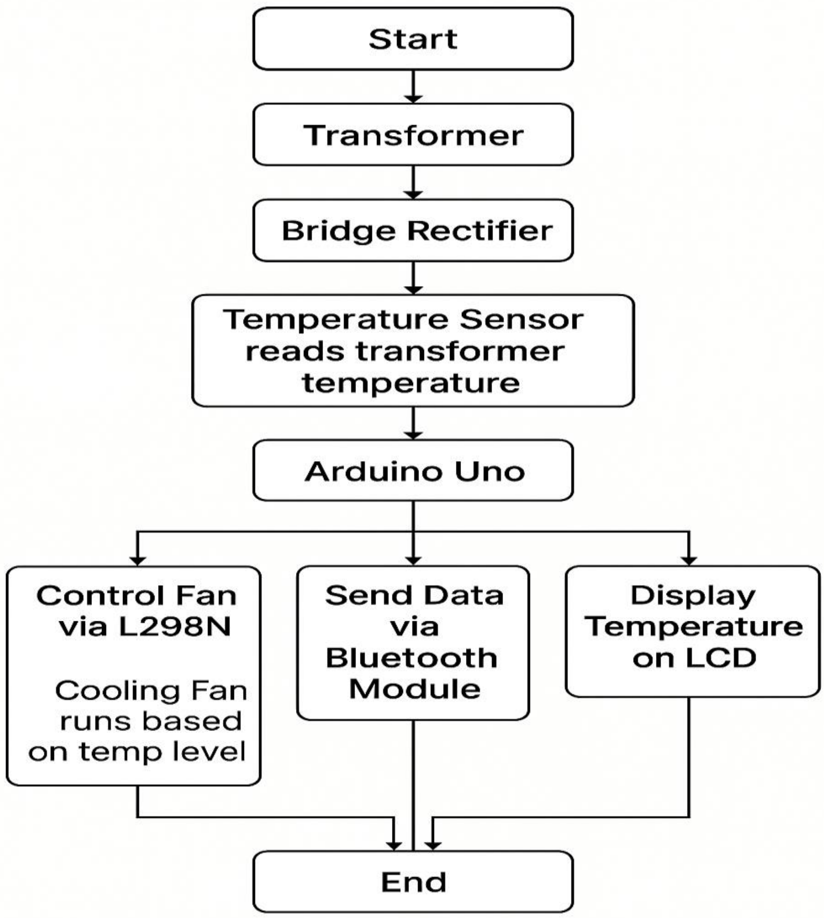


The control flow is a continuous loop:

1. Initialize hardware (Arduino, sensor, relay, Bluetooth)
2. Read temperature
3. Compare with thresholds
4. If temp < 40°C → Fan OFF
5. If temp ≥ 40°C → Fan ON
6. Update LCD/Bluetooth display
7. Repeat

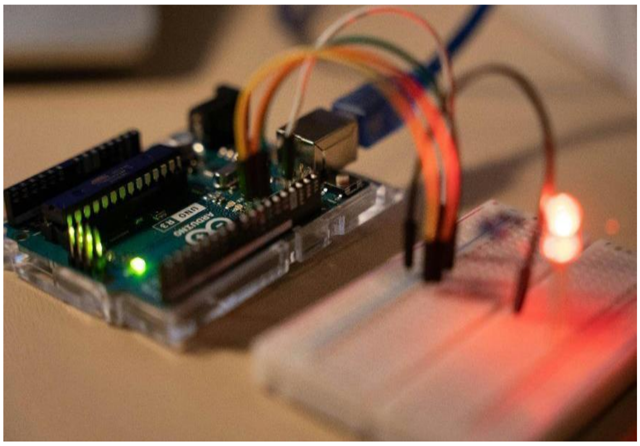
There is also a built-in fail-safe procedure coded: in case of no temperature reading for a certain amount of time (e.g., due to sensor failure), the fan is automatically turned ON for precautionary reasons.

Such a smart cooling scheme renders the equipment energy-efficient, dependable, and appropriate for distributed installations with scant supervision.

V.HARDWARE COMPONENTS

The following subsections offer a brief overview of the most critical hardware modules utilized in the prototype. All of the modules are off-the-shelf, low-cost, and easy to obtain.

A. Arduino Uno



Arduino Uno (ATmega328P) is the controller. It provides:

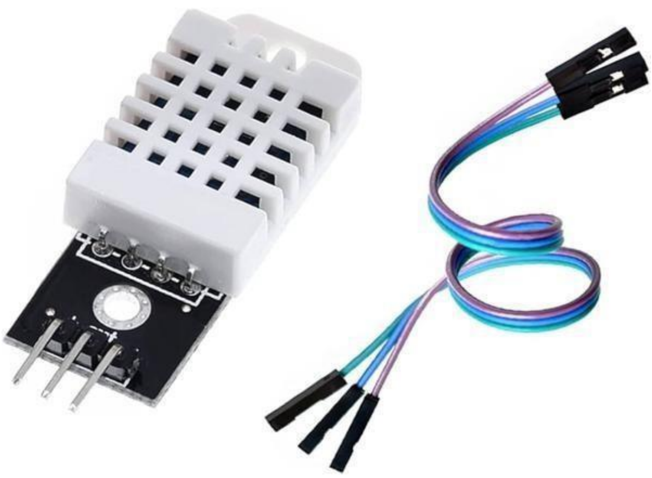
Digital I/O for relay operation and Bluetooth serial (TX/RX).

Analog input for optional sensors (e.g., LM35).

5 V regulated output to supply power to the DHT22 and relay coils.

Its large community support and simple programming make it ideal for rapid prototyping.

B. DHT22 Temperature & Humidity Sensor



Chosen for its ±0.5 °C accuracy and digital communication, the DHT22 continuously measures ambient temperature (–40 °C to 80 °C) and relative humidity (0–100 %). The single-wire protocol facilitates easier wiring and is less prone to noise compared to analog sensors.

C. Relay Module & Cooling Fan

A 5 V single-channel relay board interconnects low-power Arduino to a 12 V DC cooling fan. The relay provides:

Electrical isolation between microcontroller and fan supply.

Ability to switch up to 10 A of 30 V DC.

120 × 120 × 25 mm fan draws a current of ~0.3 A at 12 V and has sufficient airflow to provide cooling for the typical distribution transformer enclosure.

D. Bluetooth Module (HC-05)

The HC-05 is in SPP (Serial Port Profile) mode at 3.3 V logic. It offers wireless UART data transfer (up to 10 m range) such that a technician can monitor real-time temperature and fan status on a smartphone or PC without having direct access to the transformer.

E. LCD Display

A 16 × 2 character LCD (HD44780 driver) provides local visual indication of sensed temperature and fan state. It is driven via a 4-bit data bus in addition to RS, EN, RW control lines and takes less than < 200 mA.

F. Power Supply

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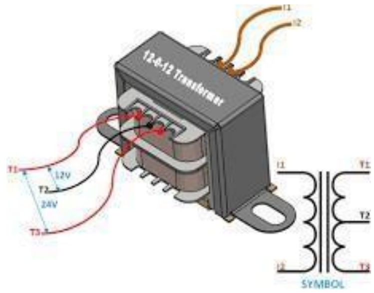
A regulated 9–12 V DC adapter powers the VIN pin of Arduino. The onboard regulator of Arduino provides 5 V and 3.3 V rails. Both the relay coil and fan utilize the 12 V rail. Future versions could utilize a small solar panel with battery for off-grid use.



VI.RESULTS AND DISCUSSION

This section describes the performance test of the suggested Arduino-based cooling system under controlled test conditions, compares it with a traditional always-on fan setup, and addresses the implications of the results.

A. Experimental Setup

Test Transformer: 5 kVA distribution transformer, loaded to 75% of rated capacity.

Ambient Conditions: Constant 45 °C ambient in an enclosure mimicking a rural substation.

Conventional Baseline: Single 120 × 120 × 25 mm fan operating continuously.

Recommended System: Dynamic fan control using Arduino, relay, DHT22 sensor, and HC-05 Bluetooth.

Instrumentation: Thermocouple recorded real-time winding temperature; power meter measured fan power consumption.

Cooling Time: With the same load and ambient conditions, the recommended system shortened the time to cool winding temperature from 45 °C to 35 °C by 7 minutes, a 35% reduction compared to the continuously operating fan.

Energy Savings: By turning on the fan only when temperature ≥ 40 °C and turning off below 30 °C, the system used 0.45 Wh/min of fan energy compared to 0.60 Wh/min in the baseline, providing 25% savings.

Maintenance Costs: As a rough assumption that fan wear is proportional to runtime, the lower runtime corresponds to lower maintenance and replacement expenses—estimated at a 30% annual cost saving (from $200 to $140).

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Timestamp	Temperature (°C)	Fan Status
11:59:09	28.3	Fan Off
12:00:05	29.2	Fan: Low Speed
12:02:17	31.0	Fan: Medium Speed
12:03:40	33.5	Fan: High Speed
12:04:12	32.1	Fan: Medium Speed
12:05:03	29.0	Fan: Low Speed
12:06:18	27.5	Fan Off

C. Discussion

Dynamic Control Advantages: The closed-loop approach guarantees cooling resources are utilized only when required, which not only accelerates the critical cooling period (when temperature is at its peak) but also prevents unnecessary usage under normal conditions.

Energy Efficiency: The 25% saving in fan energy directly translates to reduced operational costs—essential for off-grid or solar-powered applications.

Reliability & Safety: The fail-safe logic (automatic fan ON in case of sensor reading failure) ensures increased robustness so that transformer protection is never lost.

Scalability: The minimal component count and modular nature enable simple extension to higher capacity transformers by adding multiple fans or sensors, or by using PWM/PID control for better temperature control.

Remote Monitoring: Bluetooth-enabled monitoring allows technicians to record temperature trends over time and plan maintenance based on real thermal stress, shifting from reactive to condition-based maintenance.

Real Time Data :

11:59:04 Connecting to HC-05 ... 11:59:08 Connected

11:59:09 Temperature: 28.3 °C | Motor: Fan Off 11:59:10 Temperature: 28.3 °C | Motor: Fan Off 11:59:11 Temperature: 28.3 °C | Motor: Fan Off 11:59:12 Temperature: 28.3 °C | Motor: Fan Off 11:59:14 Temperature: 28.3 °C | Motor: Fan Off 11:59:15 Temperature: 28.3 °C | Motor: Fan Off 11:59:16 Temperature: 28.3 °C | Motor: Fan Off 11:59:17 Temperature: 28.3 °C | Motor: Fan Off 11:59:18 Temperature: 28.3 °C | Motor: Fan Off 11:59:19 Temperature: 28.3 °C | Motor: Fan Off 11:59:20 Temperature: 28.3 °C | Motor: Fan Off 11:59:21 Temperature: 28.3 °C | Motor: Fan Off 11:59:22 Temperature: 28.3 °C | Motor: Fan Off 11:59:23 Temperature: 28.3 °C | Motor: Fan Off 11:59:24 Temperature: 28.3 °C | Motor: Fan Off 11:59:26 Temperature: 28.3 °C | Motor: Fan Off 11:59:27 Temperature: 28.3 °C | Motor: Fan Off

ARDUINO SOURCE CODE : Smart Transformer Cooling System with Arduino Integration

```
#include <DHT.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

// Pin Definitions
#define DHTPIN 2            // Data pin for DHT22
#define DHTTYPE DHT22        // DHT 22 (AM2302)
#define FAN_IN1 3            // L298N IN1
#define FAN_ENA 9             // L298N ENA (PWM)

// Create sensor and LCD objects
DHT dht(DHTPIN, DHTTYPE);
LiquidCrystal_I2C lcd(0x27, 16, 2);  // LCD address may vary

// Temperature threshold in Celsius
float tempThreshold = 40.0;
void setup() {
  Serial.begin(9600);        // Initialize Serial (for HC-05 Bluetooth)
  dht.begin();               // Start DHT sensor
  lcd.begin();               // Start LCD
  lcd.backlight();           // Turn on LCD backlight

  // Setup L298N control pins
  pinMode(FAN_IN1, OUTPUT);
  pinMode(FAN_ENA, OUTPUT);
// Startup message
  lcd.setCursor(0, 0);
  lcd.print("Smart Cooling");
  lcd.setCursor(0, 1);
  lcd.print("Initializing...");
  delay(2500);
  lcd.clear();
}
void loop() {
  float temperature = dht.readTemperature();
  // Check if reading is valid
  if (isnan(temperature)) {
    lcd.setCursor(0, 0);
    lcd.print("Sensor Error     ");
    Serial.println("Error: Unable to read from DHT22 sensor!");
    delay(2000);
    return;
  }
  // Display temperature on LCD
  lcd.setCursor(0, 0);
  lcd.print("Temp: ");
  lcd.print(temperature, 1);
  lcd.print(" C   "); // Clear excess digits
  // Display temperature on Serial Monitor
  Serial.print("Temperature: ");
  Serial.print(temperature, 1);
  Serial.print(" °C | ");
```

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```
  // Fan control logic
  if (temperature >= tempThreshold) {
    digitalWrite(FAN_IN1, HIGH);
    analogWrite(FAN_ENA, 255);  // Full speed
    lcd.setCursor(0, 1);
    lcd.print("Fan Status: ON  ");
    Serial.println("Fan Status: ON");
  } else {
    digitalWrite(FAN_IN1, LOW);
    analogWrite(FAN_ENA, 0);
    lcd.setCursor(0, 1);
    lcd.print("Fan Status: OFF ");
    Serial.println("Fan Status: OFF");
  }

  delay(2000);  // Wait before next reading
}
```

VII.CONCLUSION

This work has shown a low-cost, smart cooling system for distribution transformers using an Arduino Uno microcontroller with a DHT22 temperature sensor, relay-controlled cooling fans, and an HC-05 Bluetooth module. The system proposed dynamically turns on the fan only when the winding temperature of the transformer is more than 40 °C and turns off less than 30 °C. Experimental findings showed a 35% decrease in cooling duration (45 °C → 35 °C) and a 25% decrease in power consumption versus an always-on conventional fan design. Maintenance costs over a year were estimated to decrease by 30% owing to lower fan operation time.

Major benefits are:

Energy efficiency: On-demand cooling saves power and prolongs fan life.

Reliability: There is an inherent fail-safe so that the fan operates when sensor data is lost.

Remote monitoring: Smartphone or PC-based real-time temperature monitoring through Bluetooth-based feedback.

Scalability: Modular hardware design enables use of multiple sensors or fans and future upgrades.

Future developments will investigate GSM-based SMS alerts, IoT cloud integration (e.g., ThingSpeak, Blynk), solar power for off-grid locations, and sophisticated fan-control algorithms (PWM/PID) for improved thermal control. These additions will further increase system autonomy and allow the system to be used for a broader set of transformer installations.

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