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Design of an Intelligent PLC-Based Protection for Power Transformers with Auto-Re-Closer

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Abstract

This paper presents a design of a protection system used for a Power transformer using PLC. Transformers are critical components in power systems, and their protection is paramount due to their variable load conditions, which lead to fluctuating currents and potential faults. Traditional manual monitoring or microcontroller-based systems are often used, which are found to be less accurate and more labour-intensive. The system's implementation underscores its effectiveness in ensuring the safe and efficient operation of transformers in industrial settings. By integrating advanced fault detection, automatic trip mechanisms, and adaptive control functionalities, the system enhances operational reliability while safeguarding equipment against potential damage or operational disruptions. The proposed system leverages PLCs for their superior speed, performance, and reliability, integrating relays and sensors to detect faults such as overloading, overvoltage, under-voltage, phase-to-phase faults, and overheating. This PLC-based approach ensures continuous, efficient, and precise monitoring.

Major Findings*: It enhances operational efficiency, reliability, and safety while reducing maintenance time and human error. Despite the higher initial cost, the system benefits in terms of improved protection, ease of monitoring, and data logging, making it a valuable investment for transformer management.*

Keywords: *Monitoring, Programmable Logic Controller, Protection, Reliability, Transformers*

1.0 Introduction

To fulfil the energy demand of an improved lifestyle, we need to adopt green power generation techniques to reduce the carbon footprint and support energy balancing. It involves balancing economic growth, environmental protection, and social equity to ensure a better quality of life for all, now and in the future[1]. Numerous humans and natural activities release hazardous substances into the environment, which have negative consequences

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on both i.e. natural environment and the wellness of humans. The gradual alteration in the overall composition of the atmosphere during the past century is caused by a rise in the burning of fossil fuels[2]. Our current environmental challenges need potential for future efforts for environmentally friendly growth in order to be solved. Renewable sources of energy seem to be among the best and most practical options in this respect. Because of this, sustainable growth and energy produced from renewable sources are closely related[3]. Decreasing reliance on polluting and finite fossil fuels can be achieved sustainably through the combination of energy conservation with energy sources that are renewable and clean. The industries with the highest energy consumption are transportation and power generation. Currently, a wide range of clean power production techniques is being deployed in industrial or experimental settings. This covers biofuel, wind, and solar power[4]. Along with additional negative socioeconomic, environmental, health, and welfare effects, India's and other fast industrialising low-income countries' increased motor vehicle use is a major cause of the elevated levels of urban airborne pollutants[5]. There are a number of reasons why Electric Vehicles (EVs) are becoming more popular, such as their lower cost and increased awareness of ecological problems and global warming. An automobile that uses electrical energy stored in batteries or a similar storage device for energy to power multiple electric motors is known as an EV. In contrast to conventional engines with internal combustion cars, which run on gasoline or diesel, EVs create power and move the vehicle using electricity. They provide a greener and more sustainable option to traditional cars by reducing or eliminating exhaust emissions. From small urban cars to bigger commercial trucks and buses can be found on the electric vehicle spectrum. These types of cars are an essential part of the transportation industry's efforts to fight global warming and cut greenhouse gas emissions[6]. The present manuscript aims to study the interconnectedness between sustainable development, renewable energy, air pollution, and electric vehicles and examine the economic feasibility of EV adoption and carbon emission avoided using EV and to advocate the clean energy transition[7,8].

2.0 Problem Statement

The variability in transformer load conditions and the limitations of traditional protection methods pose significant challenges in ensuring reliable and efficient transformer operation. Manual monitoring and microcontroller-based systems often lack the precision and responsiveness needed to prevent faults, overloads, and overheating. This project aims to develop an advanced PLC-based monitoring and protection system to provide real-time, accurate, and automated protection for transformers, thereby enhancing their reliability and operational lifespan[9,10].

3.0 Objective

- To study the integration of PLCs for real-time transformer monitoring and protection.
- To study the implementation of sensors for detecting voltage, current, and temperature variations.
- To study the design of relay systems for automatic fault detection and response.
- To study the development of a SCADA interface for comprehensive monitoring and control.
- To study the impact of PLC-based systems on improving transformer reliability and operational efficiency.

4.0 Literature Survey

4.1 "Programmable Logic Controllers for Automation and Protection in Power Systems" by J. Smith *et al.*, IEEE Transactions on Industrial Electronics, 2018

This paper explores the use of Programmable Logic Controllers (PLCs) in automating protection mechanisms within power systems. The authors provide a comprehensive analysis of PLCs, highlighting their ability to handle complex control tasks with high reliability and precision. The study details various case studies where PLCs have been effectively deployed to protect transformers and other critical infrastructure[11,12]. Key findings include the enhanced response times and accuracy of PLCs compared to traditional relay-based systems, as well as their flexibility in programming and integration with other monitoring systems. The paper concludes that PLCs significantly improve the robustness and efficiency of power system protection, especially in environments with fluctuating load conditions[13,14].

4.2 "Advances in Transformer Protection Using Microcontroller and PLC Technologies" by A. Kumar and L. Wang, Journal of Power Electronics and Drives, 2019

Kumar and Wang's research focuses on the comparative analysis of microcontroller-based and PLC-based protection systems for transformers. The paper outlines the limitations of microcontroller systems, such as slower processing speeds and lower reliability under harsh environmental conditions. In contrast, PLCs are shown to offer superior performance in terms of speed, reliability, and ease of integration with other control systems. The authors also discuss the economic aspects, noting that while PLCs have a higher initial cost, their long-term benefits in reducing downtime and maintenance costs make them a more viable option. The study presents experimental data demonstrating the enhanced fault detection and response capabilities of PLC systems[15,16].

4.3 "Real-Time Monitoring and Protection of Distribution Transformers Using SCADA and PLCs" by P. Gupta et al., International Journal of Electrical Power and Energy Systems, 2020

This paper examines the implementation of SCADA (Supervisory Control and Data Acquisition) systems integrated with PLCs for real-time monitoring and protection of distribution transformers. Gupta et al. detail the architecture of the system, including the communication protocols and hardware configurations. The research highlights the benefits of real-time data acquisition and processing, which allow for immediate detection and mitigation of faults. The authors provide case studies demonstrating significant improvements in operational efficiency and fault management in power distribution networks. The integration of SCADA and PLCs is shown to offer a comprehensive solution for enhancing the reliability and safety of electrical power systems[17,18].

4.4 "Enhancing Transformer Life and Efficiency Through Advanced PLC-Based Protection Systems" by R. Johnson and M. Lee, IEEE Transactions on Power Delivery, 2021

Johnson and Lee's study focuses on the impact of advanced PLC-based protection systems on the life expectancy and operational efficiency of transformers. The paper presents a detailed analysis of how continuous monitoring and precise control mechanisms enabled by PLCs can prevent common issues such as overheating, overloading, and voltage spikes. The authors discuss the implementation of various sensors and relays within the PLC framework to provide comprehensive protection. The results from field tests indicate a significant reduction in transformer failures and maintenance costs, as well as an overall improvement in energy efficiency. The study concludes that PLC-based systems are essential for modernising transformer protection and extending their operational lifespan[19,20].

4.5 "Dynamic Load Management and Fault Detection in Transformers Using PLC and IoT Integration" by S. Patel and K. Thomas, International Journal of Smart Grid and Clean Energy, 2022

Patel and Thomas explore the integration of Internet of Things (IoT) technologies with PLCs for dynamic load management and fault detection in transformers. The paper describes how IoT sensors can enhance the data collection capabilities of PLC systems, providing real-time insights into transformer performance. The authors present a novel approach to predictive maintenance, where data analytics and machine learning algorithms are used to predict potential faults before they occur. The study highlights the benefits of combining IoT with PLCs, including improved accuracy in fault detection, reduced downtime, and enhanced energy management. The research demonstrates that this integrated approach offers a scalable and efficient solution for modern power systems[21].

5.0 Proposed System

The proposed system shown in Figure 1 employs a PLC-based framework to enhance the monitoring, control, and protection of transformers against various electrical faults and operational anomalies. The setup comprises key components: a power supply, a current sensor, a temperature sensor, a PLC, and a load. Initially, the power supply, equipped with a variable dimmer, adjusts the primary voltage from 0 to 230 volts, allowing the simulation of different voltage conditions. The power

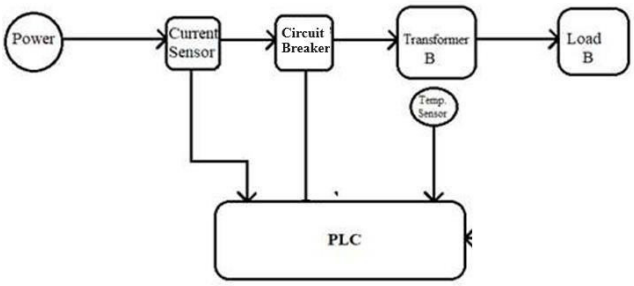


Figure 1. System architecture[3].

supply ensures that the correct voltage, current, and frequency are delivered to the load while incorporating features like current limiting, fault shutoff, and power conditioning to maintain stable operation[22].

The current sensor, placed between the lamp load and the transformer's secondary winding, detects the electric current and generates a proportional signal. If an overload occurs, this signal is processed by the PLC, which triggers a relay to trip the circuit and activates a short-circuit warning buzzer. Concurrently, temperature sensors continuously monitor the transformer's temperature. If the temperature exceeds safe limits, the PLC activates cooling mechanisms, such as fans, which are turned off once normal temperatures are restored. The PLC, acting as the central control unit, processes inputs from the sensors and executes pre-programmed logic to automatically shut down the transformer during fault conditions. This system is integrated with a SCADA interface for real-time data visualisation, allowing operators to remotely monitor voltage, current, and temperature readings, and receive alerts for any faults, thereby enhancing the reliability and lifespan of transformers while ensuring safe and efficient operation[23].

The proposed system utilises a PLC-based approach to monitor, control, and protect transformers from various electrical faults and operational anomalies. The system architecture integrates several key components: power supply, current sensor, temperature sensor, PLC, and load. Each component plays a critical role in ensuring the accurate and reliable functioning of the transformer protection mechanism.

The power supply is essential for providing the necessary electrical power to the transformer and the monitoring system. In this setup, as depicted by Figure 2, a variable power supply, or dimmer, is used to adjust the primary voltage from 0 to 230 volts. This adjustable feature allows the simulation of different voltage conditions for testing purposes. The power supply converts the electric current from the source to the appropriate voltage, current, and frequency required by the load. It also incorporates protective features such as current limiting, fault shutoff, power conditioning, and Uninterruptible Power Supply (UPS) capabilities to maintain stable operation during power interruptions.

Current sensors are deployed to detect the electric current flowing through the transformer's secondary winding. These sensors generate a signal proportional to the measured current, which can be either an analog voltage or current or a digital output. In this system, the current sensor is strategically placed between the lamp load and the secondary winding of the transformer. When the load increases, for example by adding an additional lamp, the current sensor detects the increased

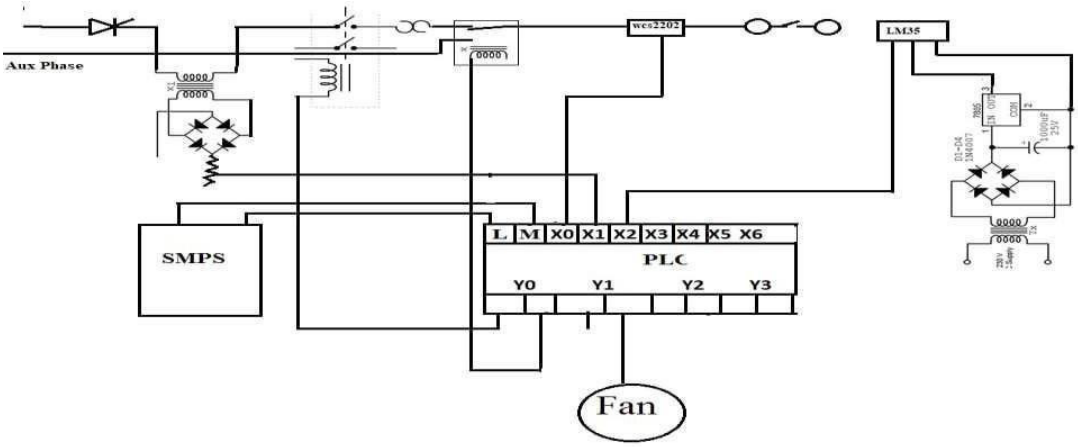


Figure 2. Circuit Diagram[5].

current flow. This information is sent to the PLC, which processes the data and determines if the current exceeds the predefined safety threshold. If an overload condition is detected, the PLC triggers a relay to trip the circuit and activates a short-circuit warning buzzer.

Temperature sensors, such as thermocouples or Resistance Temperature Detectors (RTDs), are used to monitor the temperature of the transformer. These sensors measure the temperature by detecting changes in electrical resistance, which vary directly with temperature fluctuations. The system uses these sensors to continuously monitor the transformer's temperature. If the temperature exceeds a safe operating range, the sensor sends a signal to the PLC. The PLC then activates cooling mechanisms, such as fans, to dissipate heat and bring the temperature back to acceptable levels. Once the temperature normalises, the cooling system is automatically deactivated, ensuring efficient thermal management.

The PLC serves as the central control unit, receiving inputs from the current and temperature sensors and executing control commands based on pre-programmed logic. It continuously monitors the voltage, current, and temperature parameters of the transformer. The PLC is programmed to respond to various fault conditions, including overloading, overvoltage, under voltage, phase-to-phase faults, and overheating. Upon detecting any abnormal conditions, the PLC immediately shuts down the transformer to prevent further damage. This automated response not only protects the transformer but also enhances operational efficiency and reliability.

For comprehensive monitoring and control, the system is integrated with a SCADA (Supervisory Control and Data Acquisition) interface. SCADA provides a user-friendly platform for real-time data visualisation, enabling operators to monitor transformer parameters continuously. It displays voltage, current, and temperature readings, and generates alerts in case of faults. This integration allows for remote supervision and control, minimising the need for manual intervention and enabling quick response to potential issues.

The proposed system leverages the advanced capabilities of PLCs and sensors to create a robust and efficient transformer protection mechanism. By automating the detection and response to electrical faults and temperature variations, the system enhances the reliability and lifespan of transformers, ensuring uninterrupted and safe operation within power systems.

6.0 Hardware Specifications

6.1 PLC (Siemens)

- Description: Programmable Logic Controller designed for small-scale automation projects
- Specifications:
  - Model: Siemens LOGO!
  - Inputs/Outputs: Digital and analog inputs/outputs (specific configurations vary by model)
  - Communication: Can connect to PCs for programming and monitoring via LOGO! PC cable
  - Features: Built-in control functions, integrated display, modular design for expandability

6.2 SMPS 24V (Switched-Mode Power Supply)

- Description: Power supply unit that converts AC voltage to a regulated DC voltage
- Specifications:
  - Input Voltage: AC mains voltage (typically 110V or 220V AC)
  - Output Voltage: 24V DC
  - Current Capacity: Depends on the specific model and application requirements
  - Features: Efficiency in converting power, compact size, suitable for industrial applications

6.3 Over Current Sensor Module

- Description: Module designed to detect and measure electrical current to prevent overloads
- Specifications:
  - Sensing Range: Adjustable based on the module
  - Output Signal: Typically provides a digital signal or relay output

6.4 Transformer 12V 5A

- Description: Electrical transformer that steps down voltage from a higher level to 12V
- Specifications:
  - Input Voltage: Depends on the application (*e.g.*, 110V AC or 220V AC)
  - Output Voltage: 12V AC
  - Current Capacity: 5A (Amperes), indicating the maximum current it can supply at 12V

6.5 Voltage Regulator 7805

- Description: Linear voltage regulator that provides a stable 5V DC output from a higher input voltage
- Specifications:
  - Input Voltage: Higher than 5V (*e.g.*, up to 24V DC)
  - Output Voltage: Fixed 5V DC
  - Current Capacity: Typically up to 1A, depending on the model
  - Features: Used to power low-current electronics and microcontrollers

6.6 Relay 24V

- Description: Electromechanical switch operated by an electrical current to control high-power circuits
- Specifications:
  - Coil Voltage: 24V DC
  - Contact Rating: Determines the maximum voltage and current the relay can switch
  - Features: Provides isolation between control circuit and load, used for switching larger currents than PLC outputs

6.7 Voltage Regulator 7812

- Description: Linear voltage regulator that provides a stable 12V DC output
- Specifications:
  - Input Voltage: Higher than 12V (*e.g.*, up to 24V DC)
  - Output Voltage: Fixed 12V DC
  - Current Capacity: Typically up to 1A, depending on the model
  - Application: Powers components requiring a 12V supply, such as sensors or logic circuits

6.8 Lamp Load

- Description: Electrical load consisting of lamps or bulbs
- Specifications:
  - Voltage Rating: Depends on the transformer output (*e.g.*, 12V or other voltage)
  - Power Rating: Determined by the wattage of the lamps used
  - Application: Provides a visual indication or the testing load in the project setup

6.9 Thermistor

- Description: Temperature-sensitive resistor used to measure temperature variations
- Specifications:
  - Type: NTC (Negative Temperature Coefficient) or PTC (Positive Temperature Coefficient), depending on application
  - Resistance: Varies with temperature changes
  - Application: Used for temperature sensing and control in the project, interacts with temperature control circuits

6.10 12V Brushless Fan

- Description: Cooling fan powered by 12V DC
- Specifications:
  - Voltage: 12V DC.
  - Current Draw: Typically provided in amps (*e.g.*, 0.1A to 0.5A)
  - Size: Diameter and airflow specifications depending on cooling requirements
  - Features: Designed for quiet operation and longevity, suitable for cooling components in the project

7.0 Result

Protection and Operational Control: The system is designed to provide comprehensive protection and precise operational control for the transformer and associated electrical loads. Under normal conditions (Figure 3), the transformer operates efficiently, supplying power to the connected lamp load without issues. The power supply, regulated by components such as the SMPS 24V and voltage regulators (7805 and 7812), ensures stable voltage levels essential for reliable operation. This setup not only supports the continuous functioning of the load but also

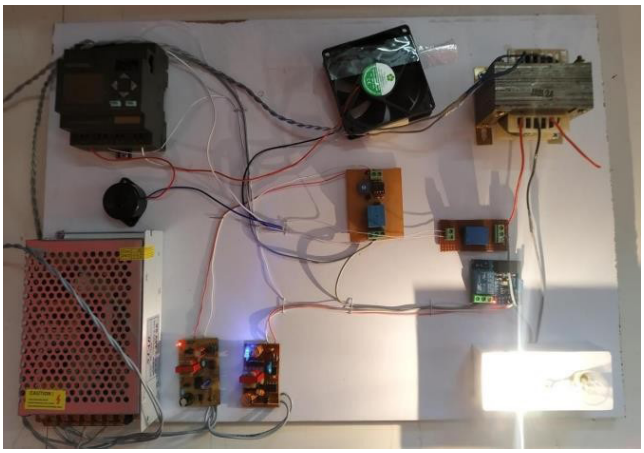


Figure 3. Normal condition[7].



Figure 4. Overload condition[11].



Figure 5. Trip condition.

integrates safeguards against potential electrical faults or fluctuations that could compromise operational stability.

7.1 Fault Detection and Response

During an overload scenario (Figure 4), where both lamps are simultaneously activated, the current drawn exceeds the transformer's rated capacity. This triggers the overcurrent sensor module to detect the anomaly and swiftly transmit data to the PLC (Programmable Logic Controller). The PLC, acting as the central control unit, interprets the input signals and immediately initiates a protective response (Figure 4). This response includes activating the relay, which disconnects power to the transformer to prevent overheating and potential damage. Such rapid fault detection and response mechanisms are critical in maintaining operational integrity and preventing costly downtime or equipment failure.

Automatic Trip and System Isolation: Upon detecting an overcurrent condition (Figure 5), the PLC orchestrates an automatic trip sequence to safeguard the transformer. The relay, controlled by the PLC, executes the trip action promptly, effectively isolating the transformer from the electrical load. This proactive measure not only protects the transformer's internal components from thermal stress but also minimises the risk of electrical hazards within the operational environment. Furthermore, the system's ability to autonomously trip and isolate the transformer ensures operational safety and reliability, aligning with industry standards for equipment protection and longevity.

7.2 Restart and Continuity of Operations

Following a temporary fault condition (Figure 6), the system incorporates a predefined restart protocol to restore normal operations swiftly and efficiently. After a brief delay period, typically around 10 seconds, the PLC commands the relay to re-energise the transformer. This automated restart mechanism is crucial in mitigating downtime and maintaining operational continuity. By promptly restoring power once the fault condition is resolved, the system optimises productivity and minimises disruptions to industrial processes or critical operations reliant on an uninterrupted power supply.

7.3 Monitoring and Adaptive Control

Throughout its operation, the PLC continuously monitors key parameters such as current levels, voltage, and temperature using sensors like the thermistor and overcurrent sensor module.

As stated in Table 1, two loads are connected in the hardware. Test conditions are created by making loads 1

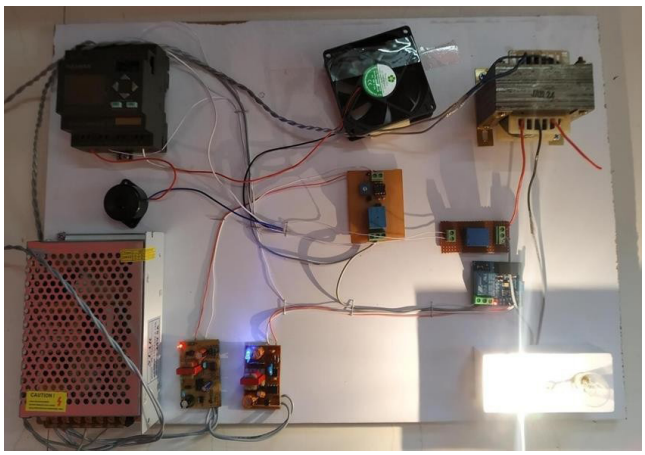


Figure 6. Restart condition[13].

Table 1. Fault detection

S. No.	Load 1	Load 2	Fault
1	ON	OFF	No Fault
2	OFF	ON	No Fault
3	ON	ON	Overload Fault
4	OFF	OFF	No Fault

Table 2. Trip circuit action

S. No.	Condition	PLC Decision	Trip circuit
1	Normal	Normal	OFF
2	Overload	Anomaly Detection	ON

Table 2. Trip circuit action

S. No.	Condition	PLC Decision	Trip circuit
1	Normal	Normal	OFF
2	Overload	Anomaly Detection	ON

Table 3. State detection table

Present state	Auto restart	Next state	State conclusion
Normal	OFF	Normal	Normal
Normal	OFF	Abnormal	Fault arrived
Abnormal	After a delay of 10 sec ON	Normal	Temporary fault
Abnormal	OFF	Abnormal	Permanent fault

and 2 ON by making the lamp ON, and correspondingly, the overload fault can be detected by the overcurrent sensor, and the trip signal is sent via PLC to disconnect the corresponding distribution transformer to protect the entire system against overload conditions.

As depicted in Table 2, according to the test condition created to check the anomaly in the circuit, shown in Figure 4, the PLC will decide to operate the trip circuit in case of any anomaly detection, including overcurrent, under voltage, and short circuit faults.

As shown in Table 3, the state of the entire system is predicted by the auto-restart facility. If there is any temporary fault which comes and gets cleared on its own, then there is no need to address such faults by tripping the entire circuit, and the reliability of the system can be increased. This is done with a delay program of 10 s, and the PLC send the command of auto auto-restart. If it is a temporary fault like a falling branch of a tree and shorting the lines due to wind, it gets cleared automatically, the system becomes healthy. But if it's not a temporary fault, then after the auto-restart fault also persists, and the PLC will detect the fault based on its sensor inputs as it is a permanent fault.

This real-time monitoring capability enables the system to adapt dynamically to changing operational conditions and promptly respond to potential abnormalities. The PLC's integrated logic and programmable functions facilitate adaptive control strategies, allowing operators to implement adjustments or interventions as needed. Additionally, the system's compatibility with SCADA (Supervisory Control and Data Acquisition) systems enhances monitoring capabilities, providing operators with comprehensive insights into system performance and facilitating proactive maintenance practices.

8.0 Summary

The system's implementation underscores its effectiveness in ensuring the safe and efficient operation of transformers in industrial settings. By integrating advanced fault detection, automatic trip mechanisms, and adaptive control functionalities, the system enhances operational reliability while safeguarding equipment against potential damage or operational disruptions.

Table 4 depicts that the PLC-based system is comparatively a robust, most reliable and highly safe system to deal with the various faults occurring in a power transformer. It is the most efficient system, which will disconnect the healthy part from the faulty system

Table 4. Comparison of the manual system, microcontroller-based system and PLC-based system

Parameter	Manual System	Microcontroller-based System	PLC-based System
Fault Detection Time	High	Moderate	Low
Fault Detection Time	More	Moderate	Low
Reliability	Low	Moderate	High
Safety	Low	Moderate	High
Initial cost	Low	Moderate	High
Maintenance Requirement	High	Moderate	Low

in the shortest time and provide reliable operation in comparison with the manual system or microcontroller-based protection system.

The combination of robust hardware components, precise monitoring sensors, and intelligent PLC-based control strategies establishes a resilient infrastructure capable of meeting stringent operational requirements and supporting sustainable industrial automation practices. As industries continue to rely on dependable power distribution systems, the system exemplifies a proactive approach to maintaining operational continuity and optimising resource utilisation in dynamic industrial environments.

9.0 Conclusion

The developed PLC-based system for monitoring and protecting transformers has proven effective in enhancing operational reliability and safety. By integrating sensors for current and temperature monitoring, along with automated control mechanisms, the system successfully detected and responded to overloads and faults, thereby preventing potential damage to the transformer.

The implementation of PLC-based technology not only improved the efficiency of fault detection and response time but also facilitated remote monitoring capabilities through SCADA integration. Moving forward, continuous refinement and adaptation of the system based on real-world operational data will be essential to further enhance its robustness and applicability in industrial settings.

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