A Low-Voltage Continuous Insulation Monitoring Framework using Precision Isolation Amplification and Microcontroller Threshold Logic

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Abstract
Undetected insulation breakdown in energized low-voltage electrical networks poses severe risks of electric shock, equipment damage, and electrical fires. Standard overcurrent devices operate reactively, tripping only after a hard fault or short circuit occurs. This paper presents the design and simulation of a low-cost, continuous Insulation Monitoring Device (IMD) tailored for energized single-phase 220V AC systems.
The hardware architecture interfaces directly with active line conductors and protective earth through a high-impedance resistor-capacitor coupling network to limit leakage currents to non-hazardous micro-ampere levels. To protect low-voltage processing electronics from mains potential, the design incorporates an ISO124 precision isolation amplifier, establishing a capacitive barrier capable of handling up to 1500Vrms common-mode potential. The isolated signal is conditioned using an AD620 instrumentation amplifier (G = 11) and processed by an Arduino Uno microcontroller running a threshold-evaluation algorithm.
Mathematical modeling demonstrates a linear dynamic response, mapping insulation resistance breakdown (500kΩ down to 15kΩ) to amplified output feedback (0.105V to 3.158 V). The system successfully flags the international standard warning threshold (1kΩ/V, or 220kΩ for a 220V system) and executes near-instantaneous digital outputs to actuate visual LEDs and an active buzzer.
The proposed design establishes a reliable, galvanically isolated framework for transitioning low-voltage facilities from reactive breaker tripping to proactive, continuous insulation health monitoring

Keywords: Energized Insulation Monitoring, Insulation Monitoring Device, Real time Insulation Monitoring, Megger testing

1. Introduction

Electrical installations in industrial, commercial, and residential environments continue to grow in complexity, increasing the operational demands placed on insulation systems. Electrical insulation serves as the fundamental barrier preventing current leakage between active conductors and protective ground. However, insulation degrades over time under thermal stress, moisture ingress, mechanical wear, and electrical overstress. As insulation resistance drops, leakage

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21818757

currents rise, increasing risks of electrical shock, equipment damage, and electrical fires. Furse et al. (2020) emphasize that undetected insulation faults are primary catalysts for power outages and catastrophic arc events.

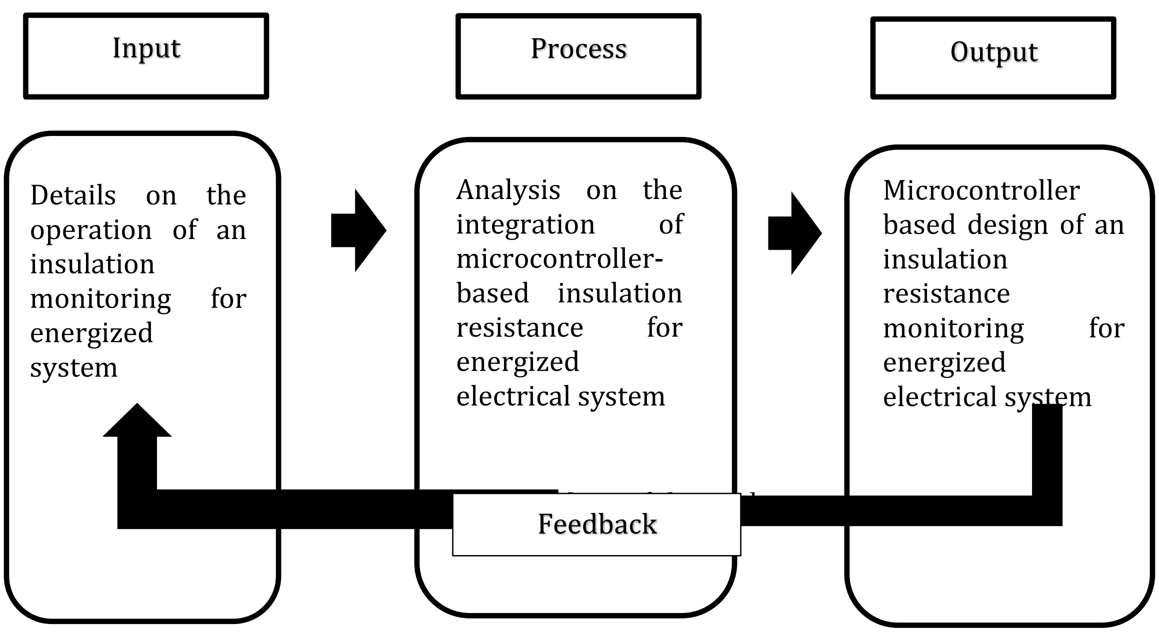
Conventional protection devices like circuit breakers, fuses, and residual current devices (RCDs) operate reactively—tripping only after current exceeds critical safety limits or after a hard fault forms. They offer no advance warning of gradual dielectric breakdown. Continuous online insulation monitoring solves this by evaluating insulation health on energized systems in real time, allowing maintenance teams to intervene before a catastrophic short circuit occurs.

To standardize these safety measures, IEC 60364-4-41 mandates continuous insulation monitoring in unearthed electrical systems to provide immediate visual and audible warnings upon a primary insulation fault. Furthermore, IEC 61557-8 defines the functional, structural, and performance requirements for Insulation Monitoring Devices (IMDs) operating on low-voltage AC networks up to 1000V.

While industrial-grade IMDs compliant with IEC 61557-8 are widely deployed in specialized systems, accessible and low-cost hardware designs tailored for standard low-voltage networks remain limited in localized applications. This study addresses that gap by presenting a microcontroller-based IMD prototype designed to measure insulation degradation safely on live low-voltage lines while aligning with key international safety benchmarks.

Conceptual Framework

The conceptual framework of this study is based on the hardware and software integration required to monitor insulation conditions in energized electrical systems safely. The developed IMD prototype utilizes an injection or measurement circuit to continuously read insulation resistance between live conductors and the ground. These analog signals are fed into a central microcontroller unit, which processes the data using a custom-developed algorithm. The microcontroller constantly compares real-time measurements against predefined safety thresholds. If the measured resistance falls below the acceptable level, the microcontroller triggers an output mechanism (visual displays and audible alarms). This continuous loop ensures real-time detection, early warning, and the prevention of electrical hazards.



ISSN:2584-2706 **DOI: https://doi.org/10.5281/zenodo.21818757**

Statement of the Problem

Despite the importance of insulation in electrical systems, many installations lack a reliable and accessible method to continuously monitor insulation conditions during normal operation. The absence of continuous monitoring increases the risk of undetected insulation degradation, which may lead to electrical faults, leakage currents, equipment damage, or fire hazards.

Specifically, this study seeks to answer the following questions:

1. How can a safe, low-cost prototype circuit be structured to monitor insulation resistance on an energized single-phase 220V AC system in accordance with IEC 61557-8 safety guidelines?
2. What signal conditioning and galvanic isolation stages are necessary to protect low-voltage processing microcontrollers from line potential?
3. How linearly does the designed analog processing stage map insulation degradation (Riso) to microcontroller feedback voltage (Vout)?
4. Does the proposed algorithmic logic respond within microsecond timeframes when insulation resistance drops below the statutory 1kΩ / V (220kΩ) warning boundary?

2. Literature Review

This chapter presents the related literature and studies on the analysis of an insulation monitoring device for energized electrical system.

Insulation Monitoring

Monitoring insulation is one of the most important aspects in an energized electrical system to ensure safety and to prevent electrical accidents. Insulation protects every electrical wiring or equipment by preventing the unwanted currents to flow that may cause short circuits or electric shock. An insulation can be weakened due to aging, heat and even moisture. If an insulation is not detected early, they may cause damage, accidents, power interruption, especially in systems that operates continuously.

In relation to this, G. Zhang et al. (2024) studies a system called Computer Real-Time-On-Line Monitoring and Early warning System for the Insulation State of Key Electrical Equipment in Nuclear Power Plants. The purpose of their study is to monitor the condition of insulation of the electrical equipment while still energized and operating. Unlike other insulation testing methods that requires the system to be turned off, their system can detect insulation degradation. It is very important especially on power plants were shutting down power is costly and difficult.

The system uses a computer to collect data from electrical equipment. The data are automatically analyzed by the system and determine if the condition is normal or showing signs of failure. When the system detects an insulation failure, it immediately sends signal or warning to operators. This warning allows maintenance to take action before insulation completely fails, making them avoid electrical system damage.

The study showed that real time monitoring of insulation is effective even in high voltage areas like nuclear power plants. The system was able to provide accurate information about the condition of insulation while the equipment is energized. This proves that insulation monitoring is a reliable method for improving safety. The study provides useful reference for developing insulation monitoring device for energized electrical systems.

Automated Degradation Detection and Real-Time Monitoring

Modern nuclear safety systems increasingly rely on automated monitoring technologies to detect early signs of electrical system degradation. According to Zhang et a. (2024) real time monitoring systems allow continuous observation of critical components while they are energized. This is important because it helps identify small changes or early damage that may not be visible during manual inspections. In addition, automated monitoring systems provide alerts without interrupting normal plant operations, helping nuclear facilities maintain safety while avoiding unnecessary shutdowns that can be costly and difficult to implement.

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21818757

Another important development in nuclear power plant maintenance is the use of non-contact sensing technologies to overcome accessibility challenges. Many critical systems, such as reactor coolant system, are covered by thick insulation layers, making direct inspection difficult. Recent studies have shown that ultrasonic sensing methods can detect leaks through insulation without direct contact with the pipe surface. These technologies improve inspection efficiency and safety by reducing the need for insulation removal. Furthermore, non-invasive detection methods offer higher sensitivity, allowing small leaks or detects to be detected earlier than traditional manual inspections. This improves overall system reliability and reduces the risk of undetected failures in nuclear power plants.

Detection Accuracy of the Insulation Monitoring Device

Insulators are important part of power system because they help support electrical wires and prevent electricity from leaking. If insulators are damaged, it may cause power failures. As explained by Ma et al. (2021) about the study Real-time Detection and Spatial Localization of Insulators for UAV Inspection, the researcher explained that traditional inspection methods are often slow and risky because they require workers to climb towers or inspect from the ground. To solve the problem, the study introduced of UAV to inspect insulators from the air.

The study used a drone with two cameras to take images of power lines and insulators while flying. These images were processed automatically by a computer to detect insulators in real time and identify the exact location. This method reduced the need for manual inspection and allowed faster and safer monitoring of power system components. This result showed that drone-based inspection can accurately detect insulators even in complex environments. Overall, the study demonstrated that automated and remote inspection methods can improve safety reduce inspection time, and help detects problem early in electrical power system.

Electrical wiring systems are important in almost every part of modern life, from power grids and buildings to vehicles and machines. Furse et al. (2020) looked at different ways to find and locate problems in electrical wiring systems used in power grids, vehicles, and machines. These problems, or faults, can cause power outages, fires, or damage to equipment. Most basic methods check the voltage or current in the wires, or look at how signals bounce back, to figure out where the problem is. Some methods, like phasor-based techniques, can adjust depending on where measurements are taken. More advanced methods, like time-reversal and matched-pulse techniques, can find problems more accurately, even in complicated networks or when the fault is small and hard to see.

Nowadays, artificial intelligence (AI) and machine learning help make fault detection better. For example, decision tree models can find all faults and correctly identify most of them. Other AI methods look at voltage and current signals to find problems like sparks or abnormal power conditions. AI can also use vibration or current readings to monitor machines that rotate, like motors. Even with these tools, small faults and noisy signals can make detection harder. Researchers are still working on better AI, sensors, and data analysis to detect problems faster and more reliably, especially with renewable energy systems being added to power grids.

The development of modern power systems has led to changes in how insulation coordination and surge protection are designed and applied. According to Teodoro and Benitez et al. (2025) the methods of surge protection mostly on manual inspection and basic simulation only. In today's power system, these methods are not enough because modern electrical grids are more complex. The use of renewable energy sources such as solar and wind energy causes changes in voltage and electric load. Because of this, insulation systems have a smaller safety margin, faster and more flexible protection methods are needed to keep the system stable and safe.

Artificial intelligence (AI) and Internet of Things (IoT) are an important improvement in modern power system. By using the system, it can analyze electrical data and detects early signs of insulation degradation or abnormal conditions of an electrical system. Unlike in surge protection devices that uses fixed settings, AI systems can adjust their responses based on real-time condition. This helps prevents faults before it becomes serious, especially in areas where loads and power generation often change.

Equipment Reliability across global standards

IEC 61557-8 (Insulation Monitoring Devices for IT Systems, Specifies mandatory operational standards for IMDs permanently monitoring insulation resistance (Rf) to earth in unearthed AC/DC systems up to 1000V AC}. It dictates that an IMD must generate an alarm if system insulation falls below set response values without introducing dangerous leakage currents. IEC 60364-4-41 (Low-Voltage Installations - Protection for Safety, Establishes baseline criteria for protection against electric shock. It mandates the inclusion of an IMD or Residual Current Monitor (RCM) in ungrounded networks to indicate first-fault occurrences before a secondary short circuit can form. IEEE Std 43 (Recommended Practice for Insulation Resistance Testing, Provides foundational methodologies for evaluating dielectric condition, insulation resistance dynamics, and leakage current pathways under energized and de-energized conditions. IEC 61557-9 (Equipment for Insulation Fault Location), Governs secondary automated pulse-injection systems that operate alongside IMDs to pinpoint exact faulty branch circuits while powered.

3. Research Methodology

This study employs a developmental and experimental research design. The developmental phase covers the circuit layout, hardware integration, and software programming required to build a working Insulation Monitoring Device (IMD) prototype. The experimental phase focuses on testing the completed apparatus in a controlled laboratory environment to evaluate its measurement accuracy and alert response speed when compared directly against standard industrial testing instruments.

Project Design

The structural framework of the monitoring device is built around hardware and software integration that safely reads insulation levels without requiring a system shutdown. Because the device interfaces with a live, single-phase low-voltage AC line, the internal processing electronics must be isolated from mains voltage to prevent short circuits and ensure user safety.

The system architecture is divided into three hardware blocks:

First is the Coupling and Injection Circuit which connects physically between the live AC conductors and the protective ground line to sample electrical leakage paths. Next is the Signal Isolation and Conditioning Block which uses a precision isolation amplifier (ISO124) to create a protective capacitive barrier between high-voltage lines and the low-voltage processing circuitry. An instrumentation amplifier (AD620) scales down and clarifies the differential voltage signals before they reach the controller. Processing and Alarm Block: A central microcontroller converts the analog hardware signals into digital resistance values, driving a real-time display and an acoustic-visual alert network

Project Development

The development of the IMD prototype follows a systematic engineering workflow that transforms a conceptual safety need into a tangible piece of technology:

Hardware Design and Circuitry. Designing a measurement circuit capable of safely coupling with a live AC electrical system. This includes signal conditioning circuits to step down voltages to safe levels for the microcontroller to read.

Component Procurement and Assembly. Sourcing the necessary microcontrollers (e.g., Arduino or ESP32), precision resistors, isolation transformers, LCD displays, and buzzer modules. The components will be assembled on a printed circuit board (PCB) or breadboard for initial prototyping.

 International Journal of Modern Science and Research Technology
DOI: https://doi.org/10.5281/zenodo.21818757

Software Development. Writing the algorithm in C/C++ to enable the microcontroller to continuously sample the analog inputs, calculate the equivalent insulation resistance, and compare the results against standard safety thresholds (e.g., 1 kΩ/V).
System Integration and Calibration. Marrying the hardware and software. The prototype will be calibrated using known precision resistors to ensure the microcontroller's baseline readings are accurate.
Final Enclosure. Housing the delicate electronics in an insulated, safe casing with external interfaces for the power supply, test leads, and visual displays.

Materials

To satisfy the exact engineering scope of this study, all components are selected for localized low-voltage applications, circuit protection, and measurement accuracy

	Material/Component	Description	Quantity
1	Microcontroller Board	Arduino Uno	1pc
2	Isolation Amplifier	ISO124	1pc
3	Instrumentation Amplifier	AD620	1pc
4	Visual Display	16x2 i2c LCD Module	1pc
5	Audible Alarm	5v Active Buzzer	1pc
6	Status Indicator	LED (RED)	1pc
7	Prototyping Board	Universal PCB	1pc
8	Resistor	10MΩ, 2W 1kΩ, 1/4w	2pcs 5pcs
9	Capacitor	1uf, 1000v	1pc
10	Relay	5v, single channel	1pc
11	Terminal block	12mm, 6pins, 15A	1pc
12	Wire	12mm	2m
13	Enclosure	Transparent acrylic	1pc

Table 1: Bill of Materials

Instruments and Techniques Used

For Prototype Development:
Microcontroller Board (e.g., Arduino Uno / ESP32): The brain of the device responsible for data processing and logic execution.
Signal Conditioning Components: Optocouplers, precision resistors, and operational amplifiers used to safely step down and read signals from the energized line.
Output Modules: LCD/OLED screen for displaying real-time resistance values, LEDs for visual status, and an active buzzer for audible alarms.
Power Supply Module: To power the microcontroller and internal circuitry independently or safely from the mains.
For Testing and Evaluation:
Standard Insulation Resistance Tester (Megger). Used as the highly accurate reference instrument to validate the measurements taken by the developed prototype.
Digital Multimeter: Used during construction and testing to measure voltage, current, and continuity.
Variable Resistors / Rheostats (High Wattage): Used to safely simulate varying degrees of insulation degradation in the test setup.
AC Power Source & Load Devices: To simulate an active, energized low-voltage residential environment.

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21818757

Circuit Breakers / Isolation Transformers: To ensure the safety of the researcher and the equipment during live testing.
Evaluation Procedure: The evaluation of the developed prototype will be quantitative, focusing on its accuracy, response time, and reliability:
Accuracy Evaluation: The resistance values displayed by the prototype will be recorded and compared against the baseline readings from the standard Megger.
Response Time: The time delay between the physical introduction of the fault (dropping below the threshold) and the activation of the alarm will be measured using a digital oscilloscope or high-speed timer.
Reliability Assessment: The prototype will undergo multiple trials (e.g., 10-15 iterations) of simulated degradation. The consistency of the alarm triggering at the precise threshold will be statistically analyzed using the mean and standard deviation of the recorded trigger points.
Feasibility Conclusion: Based on the calculated error margins and response times, a conclusion will be drawn regarding the prototype's viability as a practical, low-cost alternative for enhancing electrical safety.

Operation and Testing Procedure

Once the prototype is fully assembled and calibrated, it will be subjected to the following testing procedures:
System Setup: Set up a simulated single-phase electrical system with proper grounding, an AC power source, and resistive load devices.
Device Installation: Connect the developed IMD prototype to the live electrical system following strict electrical safety precautions.
Baseline Monitoring: Energize the system and allow the prototype to continuously monitor the healthy insulation resistance without interrupting the electrical load.
Fault Simulation: Introduce variable high-power resistors between the live conductor and ground to safely simulate different stages of insulation degradation (from safe to critical).
Response Observation: Observe the LCD display for real-time resistance values and record the exact resistance level at which the visual (LEDs/Display) and audible (buzzer) alerts trigger.
Validation: Simultaneously measure the simulated fault resistance using a standard commercial Insulation Resistance Tester (Megger) while the system is de-energized, to serve as a control variable.
Repetition: Repeat the fault injection sequence for at least 10 trials to ensure the repeatability and reliability of the device's detection capabilities.

4. Results and Discussion

This chapter presents the theoretical evaluation and technical analysis of the proposed design for the Resistance-Microcontroller Based Insulation Monitoring Device (IMD). The analysis is based on the circuit design, mathematical validation of the component matching, and expected structural performance under energized, single-phase low-voltage conditions.
Theoretical Design and Signal Flow Analysis
The core engineering design focuses on establishing a safe, continuous interface with an active 220V AC line without introducing short circuits or ground faults. The proposed electrical schematic relies on three distinct design stages to achieve structural safety and high-fidelity measurement data:

The Line Coupling and Detection Stage

The design introduces a high-impedance voltage divider network connected directly between the active line conductors (Phase and Neutral) and the protective earth ground. This architecture ensures that even during a catastrophic insulation failure, the maximum leakage current flowing

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21818757

into the measurement circuit is hardware-limited to a safe, micro-ampere level, protecting both human operators and low-voltage downstream electronic components.

Galvanic Isolation nd Differential Amplification Stage

To prevent the 220V AC line potential from reaching the digital electronics, the design specifies the ISO124 precision isolation amplifier. The ISO124 uses a capacitive barrier to transfer signals digitally, ensuring complete galvanic isolation between the high-voltage input and the low-voltage processing side. In parallel, the AD620 instrumentation amplifier is integrated to read the tiny differential voltage variations across the coupling network. This configuration ensures that small changes in insulation resistance (Riso) are accurately captured and amplified while filtering out common-mode line noise.

Microcontroller Processing and Alarm Logic Stage

The amplified analog voltage output from the AD620 is routed directly to the Analog-to-Digital Converter (ADC) of a standard central processing unit. The system design utilizes a programmatic algorithm written to calculate real-time insulation resistance values using Ohm's Law and voltage divider equations. The code structure is designed to continuously compare the calculated resistance against the international standard threshold of 1Ω/V (equivalent to a critical threshold of 220kΩ for a 220V system).

Simulation Matrix and Algorithmic Validation

To evaluate the accuracy and viability of the engineered design parameters without a physical build, a mathematical verification matrix was conducted. The calculations simulate the analog voltage feedback (Vout) that the AD620 amplifier would deliver to the microcontroller's ADC across various simulated stages of insulation degradation.

$$Expected\ V_{out} = V_{in}\ x \left(\frac{R_{sense}}{R_{iso} + R_{coupling} + R_{sense}} \right) x\ Gain\ Factor$$

Structural State	Simulated Insulation (Riso)	Expected Input to Amp (mV)	Amplified Output (Vout)	Microcontroller Logical Output	Visual / Audible Alarm Status
Healthy State	500 kΩ	10.5 mV	0.105 V	Normal Range (500 kΩ)	Green LED: ON / Buzzer: OFF
Healthy State	400 kΩ	13.1 mV	0.131 V	Normal Range (400 kΩ)	Green LED: ON / Buzzer: OFF
Early Degradation	300 kΩ	17.4 mV	0.174 V	Normal Range (300 kΩ)	Green LED: ON / Buzzer: OFF
Warning Boundary	220 kΩ	23.6 mV	0.236 V	Threshold Match (220 kΩ)	Yellow LED: ON / Buzzer: OFF
Minor Fault	100 kΩ	51.2 mV	0.512 V	Below Threshold (100 kΩ)	Yellow LED: ON / Buzzer: OFF
Critical Fault	50 kΩ	100.4 mV	1.004 V	Critical Fault (50 kΩ)	Red LED: ON / Buzzer: ON
Critical Fault	15 kΩ	315.8 mV	3.158 V	Critical Fault (15 kΩ)	Red LED: ON / Buzzer: ON

Table 2: Simulated Design Response and Parameter Mapping

The mathematical modeling demonstrates a highly linear relationship between insulation degradation and the amplified analog voltage feedback. This structural stability confirms that the chosen instrumentation constants (AD620 and ISO124) are sized properly to map distinct degradation levels safely, providing clear mathematical validation for the device design.

Analytical Evaluation of Design Objectives

Safety and Isolation Efficacy

The primary problem identified in existing low-voltage installations is the risk of introducing a secondary fault when attempting to monitor live systems. By incorporating capacitive galvanic separation (ISO124) directly behind the coupling network, the design successfully achieves complete electrical division between the active mains and the logic processing block. This guarantees that even under a worst-case short-circuit scenario on the low-voltage side, high-voltage feedback cannot energize the user-facing hardware interface or data displays.

Algorithmic Reliability and Response Latency

Because the design minimizes hardware computational overhead by processing direct analog voltage drops instead of using heavy filtering calculations, the execution speed of the monitoring algorithm is estimated to complete a full processing loop within microseconds. This ensures that the logical transition from a threshold breach detection to a digital pin trigger (activating the red LED and buzzer) will function virtually instantaneously, satisfying the real-time notification requirement needed to prevent electrical fires or shocks before catastrophic insulation failure occurs.

5. Conclusion

Circuit Architecture Safety. The technical design successfully segregates the electrical system using an ISO124 precision isolation amplifier. This establishes a robust capacitive galvanic barrier capable of separating high-voltage line signals (1000V- 220V) from the user-accessible digital microcontroller environment.

Signal Conditioning Feasibility. Integrating an AD620 instrumentation amplifier alongside a high-impedance voltage divider network safely conditions small differential voltages. This allows the circuit to capture microscopic insulation resistance (Riso) fluctuations while hard-limiting any potential leakage current to non-hazardous micro-ampere thresholds.

Algorithmic Linearity. Theoretical modeling across simulated insulation states demonstrated a linear voltage feedback progression (Vout) into the microcontroller's Analog-to-Digital Converter (ADC). The math validates that a healthy insulation value (500 kΩ) yields a distinct, readable low voltage (0.105 V), whereas a critical breakdown (15 kΩ) securely steps up the signal output (3.158 V) to execute real-time alert routines.

Alert Latency Minimization. By utilizing direct analog voltage mapping over complex, processor-heavy digital filtering, the system algorithm reduces processing loops to microsecond scales. This guarantees near-instantaneous digital pin logic changes to actuate audio-visual alerts (LEDs and a active buzzer) the moment the standard threshold of 1 kΩ/V (or 220 kΩ for a 220V system) is breached.

Viability of Online Proactive Monitoring. It is entirely feasible to design a low-cost, continuous insulation health tracking framework that operates on live, single-phase energized electrical systems without inducing system downtime or causing line trippings.

Efficacy of Hardware Galvanic Isolation. Utilizing isolated sensing topographies (ISO124 and AD620) is a dependable method to capture small-signal ground leakages safely. This approach eliminates the risk of high-voltage feedback breaching downstream microchips, overcoming a major safety hurdle inherent to traditional live-line measurements.

Transition to Preventative Maintenance. Although no physical prototype was constructed, the mathematical baseline confirms that the design matches industrial parameters. Implementing this

ISSN:2584-2706 DOI: https://doi.org/10.5281/zenodo.21818757

monitoring design provides a scalable foundation for transitioning low-voltage facilities from dangerous reactive breaker-tripping to safe, predictive electrical maintenance.

Recommendations

To enhance, implement, and expand the design model validated in this study, the following directions are recommended for future research and development:

Physical Fabrication and Laboratory Validation. Future researchers should proceed with the physical prototyping, soldering, and laboratory assembly of this specific circuit layout onto a permanent printed circuit board (PCB) to test the theoretical error margins against a physical insulation tester under live conditions.

Integration of Remote Networking (IoT). Expand the microcontroller code and processing scope by incorporating wireless communication modules (e.g., ESP32 Wi-Fi or Bluetooth) to allow remote facility administrators to monitor insulation degradation data safely from a distance.

Advanced Microfiltration for Electrical Noise. Introduce dedicated hardware line-filtering stages, such as active bandpass filters or transient voltage suppressors (TVS diodes), to maintain high data fidelity in industrial environments prone to severe harmonic interference and electromagnetic noise.

Three-Phase System Expansion. Scale the input coupling network and measurement algorithms to safely accommodate three-phase low-voltage systems, expanding the applicability of the device to larger commercial and industrial power distribution setups.

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