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Research Article

Development of a Basic Power Distribution Unit (PDU) Test Jig

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ABSTRACT

Power Distribution Units (PDUs) are critical components in electrical and industrial systems, ensuring efficient power management, distribution, and protection. However, verifying their operational integrity necessitates a robust and standardized testing framework. This paper presents the design and implementation of a Basic PDU Test Jig, developed to assess key performance parameters, including continuity validation, load capacity testing, and electrical reliability analysis. The proposed testing architecture integrates advanced methodologies to systematically evaluate electrical connectivity, fault tolerance, and compliance with regulatory safety standards. The study further explores the impact of different configurations on the performance of PDUs, ensuring adaptability across varied industrial applications. By providing a structured approach to PDU validation, this work contributes to the development of a scalable and cost-efficient testing paradigm, enhancing the reliability and safety of power distribution systems.

Keywords: Power Distribution Units (PDUs), power management, power distribution, electrical protection, testing framework, PDU Test Jig, continuity validation, load capacity testing

INTRODUCTION

Power Distribution Units (PDUs) are integral components of electrical systems, playing a crucial role in distributing electrical power to various loads in both commercial and industrial environments. These devices ensure that power is efficiently delivered to critical systems, such as servers in data centers, heavy machinery in industrial plants, and electronic equipment in research facilities. PDUs can be designed in a variety of configurations to handle different voltages, load capacities, and specialized functions. As the complexity and reliability requirements of electrical systems increase, the need for accurate and efficient testing of PDUs becomes paramount.

The primary function of a PDU is to distribute power from a single source to multiple outlets while providing protection and monitoring capabilities. PDUs are designed to meet various standards, ensuring they handle overcurrent protection, voltage regulation, and surge suppression. However, the reliability of PDUs is often taken for granted until faults such as overloading, wiring errors, or electrical malfunctions occur. This raises the need for comprehensive testing methods to ensure that PDUs are functioning optimally under all operational conditions, guaranteeing uninterrupted power supply to connected loads.

Existing testing methodologies for PDUs are often fragmented, with each test focusing on specific aspects such as continuity testing, load testing, or performance under stress. While these methods are useful, they lack an integrated framework that can test the entire functionality of a PDU, especially under diverse operational conditions. For example, continuity testing ensures that there are no breaks in the power distribution, but it may not evaluate the PDU's ability to withstand overloads or faults that could compromise system reliability. On the other hand, load testing assesses the capacity of a PDU to handle electrical loads but might not fully simulate the dynamic environment of industrial applications where varying load conditions are the norm. The survey focuses on examining various components and methodologies involved in PDU testing, including hardware design, the testing process, and the effectiveness of the testing framework. We will discuss the key features of the test jig, including its adaptability to different PDU configurations, its compatibility with industry safety standards, and its ability to simulate real-world electrical stress scenarios. By reviewing related work in PDU testing and comparing it with the proposed test jig design, this paper aims to provide a comprehensive analysis of the current landscape of PDU testing solutions and suggest directions for future advancements. [1],[2],[9][14]

OBJECTIVES

The primary objective of this research project is to design and implement a comprehensive, automated test system tailored for Power Distribution Units (PDUs). This system aims to streamline the quality assurance process by integrating various electrical and functional tests into a single jig setup. The jig ensures that each PDU meets industry standards and safety requirements before deployment. It is engineered to conduct detailed evaluations of continuity, load capacity, line integrity, and connection correctness, with minimal manual involvement. Additionally, the system is scalable, supporting testing for multiple units and panel-based configurations. Specifically, the objectives include developing an automated testing process that reduces human error, verifying the continuity of all power lines including R, Y, B, Neutral, and Earth, and validating the PDU's load handling capacity under a 4A system voltage. The jig is also designed to check wiring integrity by detecting open, missing, or incorrectly wired connections, and to identify reversal faults such as phase-neutral, phase-earth, and earth-neutral reversals. A relay-controlled switching mechanism simulates various test scenarios, dynamically managed by a microcontroller (ATmega328P-AU) that oversees test execution, result interpretation, and output display. The project ensures scalability for panel-based testing of multiple relays or PDUs and incorporates safety features like fuses and isolation mechanisms to provide safe and reliable testing conditions.

METHODS

The PDU test jig project follows a structured methodology, combining both hardware and firmware development to ensure accurate and automated testing. The process began with a detailed requirement analysis and planning phase where functional and safety needs were defined, and key components such as relays, microcontrollers, connectors, and load elements were selected. This was followed by schematic development and PCB design, incorporating the ATmega328P-AU, ULN2003A drivers, and necessary protection elements, while maintaining proper layout practices like separating power and control sections and ensuring correct trace sizing. Firmware was then developed to enable relay control, input reading, and result display, leveraging I2C communication with expanders like PCF8575DW to manage multiple I/Os efficiently. Relay switching logic was carefully implemented to simulate continuity checks, line reversals, and load applications with appropriate isolation and timing. The hardware was assembled and wired into the test panel, integrating terminals, relays, and loads per the design. Rigorous testing and debugging followed, beginning with dry runs using dummy PDUs and addressing any issues related to signal integrity or relay operation. Once verified, the final testing phase involved running complete test cycles on actual PDUs, recording results, and validating performance against predefined criteria. The entire development was supported by comprehensive documentation including schematics, test protocols, error logs, and a user manual. This methodical approach ensured the resulting jig was robust, reliable, and effective for automated PDU testing. Various methodologies for testing PDUs have been proposed over the years. Traditional testing often involves a combination of continuity tests, insulation resistance checks, and load tests, each targeting specific aspects of a PDU's functionality. Continuity testing ensures that electrical connections between inputs, outputs, and neutral grounds are intact. This is critical for preventing system failures due to broken or misconnected wires. Insulation resistance testing evaluates the PDU's insulation performance, ensuring that it can withstand electrical stresses without leakage or breakdown.

Load testing, on the other hand, aims to verify that the PDU can handle the expected electrical load without overheating or malfunctioning. While these traditional tests are essential, they tend to focus on isolated characteristics of the PDU, without evaluating its ability to perform under realistic conditions. For instance, load testing typically applies a static load, which may not represent the fluctuating and dynamic power demands found in real-world applications, such as those seen in industrial settings.

However, automation still faces challenges in terms of versatility. While automated test systems can test

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functionalities, they often struggle to simulate real-world conditions, such as transient electrical disturbances or faulty connections, without specialized hardware. Additionally, automated systems tend to be expensive and can require significant space and resources to operate effectively.

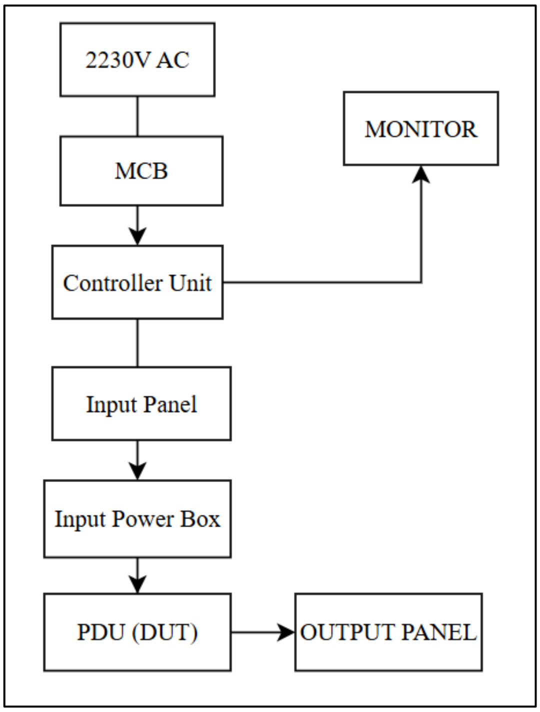

Figure 1:

Block Diagram of the Basic PDU Test Jig [1]

Figure 1: Block Diagram of the Basic PDU Test Jig illustrates the fundamental structure of the test setup used to evaluate the performance PDU. The system begins with a 230V AC power input, which passes through a Miniature Circuit Breaker (MCB) for protection against overcurrent and short circuits. A Controller Unit (Raspberry Pi) manages the testing process, controlling power distribution and logging data, while a Monitor displays real-time test results, including voltage, current, and fault conditions. The Input Panel acts as an interface for connecting power to the test setup, feeding into the Input Power Box, which contains multiple sockets for connecting the PDU (Device Under Test - DUT). The PDU is then evaluated based on its output, which is measured and analyzed through the Output Panel. This test jig ensures continuity testing, load testing, and fault detection to verify the PDU's reliability before deployment. [7]

The core components of the Basic PDU Test Jig are as follows:

Controller (Microcontroller or Embedded System): At the heart of the PDU Test Jig lies a microcontroller or embedded which acts as the central processing unit (CPU) of the test platform. This controller is responsible for orchestrating the Power Supply: A stable and reliable power supply is essential for the test jig, as it powers both the controller and the PDU under test.

In the case of the Basic PDU Test Jig, the power supply must be capable of providing multiple output voltages corresponding to different PDU configurations, such as 230V, 110V, or 208V systems. The power supply must also offer the ability to simulate various power disturbances, such as voltage surges or drops, to assess the PDU’s response to abnormal conditions. I/O Expander: An I/O expander is used to extend the I/O capabilities of the microcontroller, The expander helps in managing high-voltage components, enabling the controller to safely monitor and control various parts of the test jig without the need for additional microcontrollers. Through the I/O expander, the controller can trigger relays that manage the input and output connections of the PDU, switching between different testing modes and configurations as needed. Relays and Switching Mechanism: The relay system forms the backbone of the test jig, allowing the platform to simulate different electrical conditions for the PDU under test. The relays act as

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switches, connecting and disconnecting various components of the PDU (e.g., input, output, and ground lines) based on the test requirements. This modular relay setup ensures that different test conditions can be simulated, such as 70checking for continuity between electrical paths, verifying load handling capabilities, and introducing fault conditions (e.g., short circuits or grounding issues). The use of solid-state relays or mechanical relays offers flexibility in handling the load requirements.

allowing it to interface with multiple relays and sensors without overloading the system.

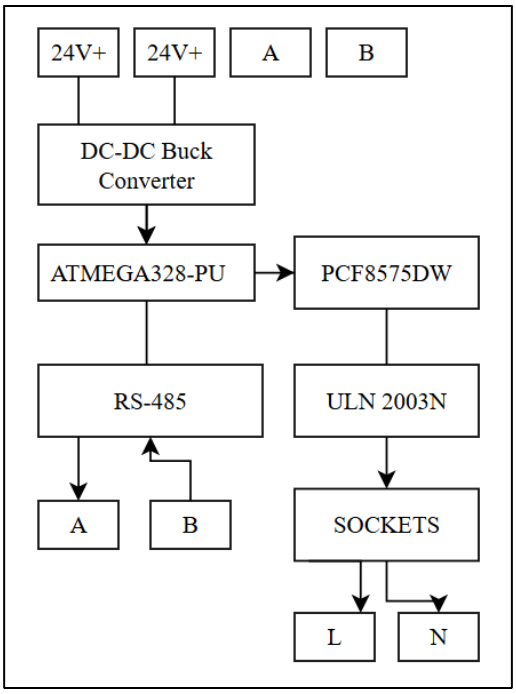

Figure 2:

System Architecture of the PDU Test Jig [1]

Load Simulator: A critical feature of the test jig is the load simulator, which is used to test the PDU's load-bearing capacity. This simulator mimics the typical load behavior of electrical systems, allowing the test jig to apply static or dynamic loads to the PDU under various conditions. The load simulator can be controlled to increase or decrease the power demand on the PDU, allowing for real-time monitoring of how the unit responds to varying electrical loads. By simulating fluctuating or high-load conditions, the test jig can evaluate the PDU's efficiency, safety, and operational stability.

Fault Injection System: The fault injection system introduces electrical faults, such as short circuits, ground faults, or overcurrent situations, to test the PDU's fault tolerance and safety features. The system is controlled by the microcontroller, which enables it to simulate various real-world fault scenarios that could affect the PDU's operation. This is crucial for testing the robustness of the PDU's protection mechanisms, such as overcurrent protection, thermal shutdown, or surge suppression.

Measurement and Monitoring Instruments: The test jig is equipped with various sensors and measurement instruments that monitor key parameters such as voltage, current, temperature, and resistance during testing. These instruments collect data that is used by the microcontroller to assess the PDU's performance. The data can also be logged for future analysis or to generate test reports. For example, current sensors may be used to measure the current drawn by the PDU under load, and voltage sensors monitor any fluctuations or imbalances in the output voltage.

User Interface: The user interface (UI) plays a pivotal role in the operation of the PDU Test Jig, allowing users to set parameters, initiate tests, and view the results in real time. The UI is a physical display (e.g., an LCD) connected to the controller.[8][9]

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The interface is intuitive, providing options for the user to select various testing modes, configure testing conditions (such as load levels or fault types), and analyze the test results. [3],[4],[5],[6].

Detailed Description of the Test Flow:

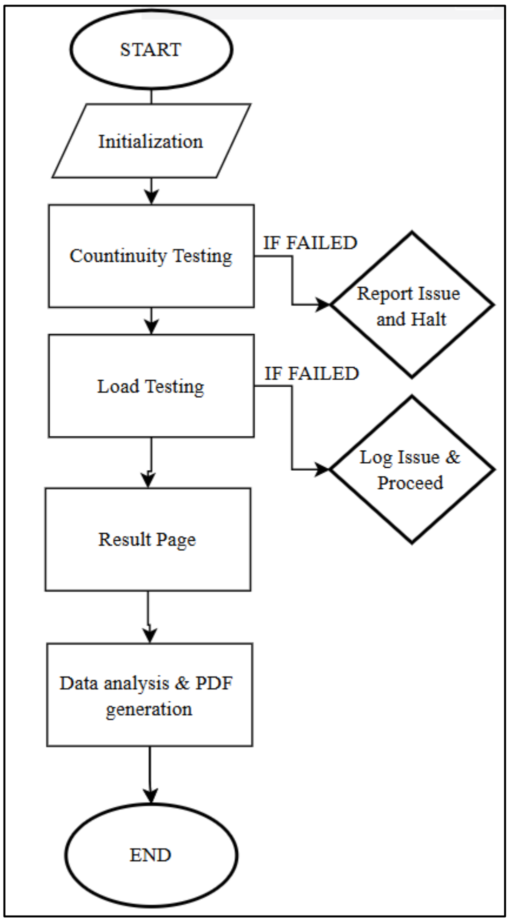

Figure 3:

Testing Workflow for PDU Evaluation [1]

The flowchart illustrates the step-by-step process involved in the automated testing sequence designed to evaluate the functionality and performance of the system under test. Each stage is outlined as follows:

1. Start

The testing procedure is initiated at this stage. It marks the beginning of the overall sequence and sets the system into operational mode.

2. Initialization

During initialization, all necessary hardware and software components are configured. This includes setting up communication interfaces, configuring input/output ports, and ensuring that all sensors and actuators are in their default states. This step ensures that the system is prepared for consistent and reliable testing.

3. Continuity Testing

In this phase, the system verifies electrical continuity between designated terminals to ensure that connections are intact and functional. Relay configurations are applied to establish circuit paths, and continuity is checked using appropriate measurement techniques.

If a discontinuity is detected, the process moves to a fault-handling step where the issue is recorded and the testing operation is halted. This prevents further procedures from being conducted on a potentially defective unit.

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4. Load Testing

After confirming continuity, the system proceeds to evaluate performance under electrical load. This involves applying a predefined current or voltage and monitoring system response. Key parameters such as voltage levels, current flow, and relay switching are observed to assess behavior under working conditions.

If a failure is identified during this stage, the system logs the error but continues the testing sequence. This approach allows non-critical issues to be documented without interrupting the entire process.

5. Result Page

Upon completion of the test phases, a results summary is generated. This includes pass/fail outcomes, key measurements, and any anomalies observed during testing. The result page provides a clear overview of the system's performance.

6. Data Analysis and PDF Report Generation

The gathered data is analyzed to detect trends, verify parameter thresholds, and confirm overall system behavior. A detailed report in PDF format is automatically created, documenting all test results, timing details, and any identified issues. This report serves as a record for quality control and traceability purposes.

7. End

The sequence concludes at this point, indicating that all testing operations have been executed. The system can now be powered down or reset for future use.

RESULTS

The implementation of the Power Distribution Unit (PDU) test jig yielded reliable and consistent results, validating the success of the project's objectives. The system accurately verified continuity across all power lines, including R, Y, B, Neutral, and Earth, and successfully identified open or missing connections. During load testing, each PDU handled the applied 4A system voltage without any faults, demonstrating strong performance under expected operating conditions. The jig also effectively detected wiring errors such as phase-neutral, phase-earth, and earth-neutral reversals, ensuring safety and connection integrity. The relay switching mechanism operated smoothly, enabling dynamic control of test scenarios without any failures. The ATmega328P-AU microcontroller, in combination with I2C expanders, maintained reliable communication and precise control of the entire testing sequence. Additionally, the jig supported scalable panel testing, proving its usefulness for multi-unit validation. Overall, the project concluded with a fully functional, automated testing solution that significantly enhances quality assurance in PDU deployment while minimizing manual intervention and increasing operational efficiency. The results are presented in table 1.

Explanation of the Socket Voltage and Load Current Table:

The following section outlines the results obtained from the functional testing of a Power Distribution Unit (PDU) designed for a three-phase, four-wire star-connected system. The system operates at a nominal phase-to-neutral voltage of 230V, and the testing was performed after confirming the continuity and load-handling capability of each output point. The PDU includes nine output sockets, labeled Socket 1 through Socket 9. Each socket was assigned to one of the three phases—Red (R), Yellow (Y), or Blue (B)—with a neutral connection, identified as RN, YN, and BN respectively. These represent standard phase-to-neutral combinations used in a balanced three-phase setup.

The assessment involved verifying the status of phase, neutral, and earth connections for every socket. All three parameters were found to be properly connected, as indicated by a consistent "OK" status across all test points. Voltage readings were recorded under load conditions and ranged between 217.5V and 221.5V. This variation is well within the allowed range for a 230V nominal system, where typical standards accept deviations of up to ±10%, translating to a safe operating range of 207V to 253V. Such slight differences in voltage can occur due to load distribution, conductor resistance, terminal losses, or internal impedance in the system, but in this case, all measurements stayed within acceptable limits.

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Current drawn by each load varied across the sockets, with values ranging from 1.748 A to 4.278 A. These variations reflect the different load conditions applied during testing. To quantify the power delivered at each socket, the standard formula for single-phase power was applied as shown in equation 1.

Power (W) = Voltage (V) × Current (A) × Power Factor (PF). …………(1)

Since all test loads were purely resistive, the power factor remained at 1.0 throughout, indicating no reactive component and perfect alignment between voltage and current. For instance, if Socket 5 registered 220.2V and a load current of 3.422 A, the power consumed can be calculated as mention in equation 2.

P = 220.2 × 3.422 × 1 = 753.66 W…………..(2)

These results highlight the PDU's ability to support loads close to 1 kilowatt per socket without any signs of voltage drop or instability.

Table 1 – Generated after successful connection & Load test,

PDU type: 3 Phase star 230 [1]

Socket No.	Phase	Phase Connection	Neutral Connection	Earth Connection	Voltage (V)	Load Current (A)	Power Factor
1	RN	OK	OK	OK	218.305	1.748	1
2	RN	OK	OK	OK	219.066	4.278	1
3	RN	OK	OK	OK	217.576	4.252	1
4	YN	OK	OK	OK	219.26	4.278	1
5	YN	OK	OK	OK	218.694	4.273	1
6	YN	OK	OK	OK	220.11	3.98	1
7	BN	OK	OK	OK	221.505	2.652	1
8	BN	OK	OK	OK	220.876	3.127	1
9	BN	OK	OK	OK	219.985	3.945	1

The consistency of a power factor value of 1 across all sockets also indicates that the entire test was conducted with non-reactive (resistive) loads, making it ideal for evaluating the efficiency of pure power transfer without interference from inductive or capacitive elements. Additionally, the proper earthing verified during the test confirms adherence to safety standards, ensuring protection against electrical faults, leakage currents, or insulation failures.

The performance evaluation of the Power Distribution Unit (PDU) across nine output sockets demonstrates its high reliability, efficiency, and compliance with electrical safety standards. Each socket was verified for proper Phase, Neutral, and Earth connections, all of which were found to be correctly established, ensuring safe and secure operation. Voltage levels recorded across the sockets ranged from **217.576 V to 221.505 V**, indicating consistent and stable voltage regulation under varying conditions. The PDU successfully handled load currents between **1.748 A and 4.278 A**, confirming its capability to support a wide range of operational demands without voltage drops or instability.

Furthermore, all sockets maintained a **power factor of 1.0**, reflecting optimal energy efficiency with minimal reactive power losses. This level of performance across different phase connections (RN, YN, BN) underscores the system's balanced design and effective load distribution. Overall, the results validate that the PDU is not only functionally sound but also robust and dependable for deployment in practical scenarios where stable, safe, and efficient power distribution is essential—such as industrial environments, testing facilities, and critical infrastructure systems.

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DISCUSSION

The development and deployment of the Power Distribution Unit (PDU) test jig marked a significant advancement in the application of embedded systems for automated electrical diagnostics. This project was designed with the primary objective of streamlining the testing process of PDUs by integrating multiple electrical test parameters into a unified, programmable system. The implementation resulted in a reliable and efficient platform capable of executing continuity checks, load current validation, connection integrity assessments, and reverse polarity detection with minimal human intervention.

The transition from manual procedures to automated testing not only improved operational efficiency but also ensured consistency, accuracy, and repeatability across all test cycles.A major technical milestone was the successful orchestration of multi-point electrical testing through embedded control. The system employed the ATmega328P-AU microcontroller as the central controller, selected for its robust performance and compatibility with industrial-grade applications. To address the limited native I/O capacity of the microcontroller, I2C-based port expanders (PCF8575DW) were utilized. This architecture allowed scalable expansion of input and output lines essential for relay operation, test status indicators, and signal acquisition. The use of I2C communication also minimized wiring complexity and improved layout flexibility on the printed circuit board.

During development, several design-level and signal-integrity challenges emerged. Electrical noise from relay actuation, occasional I2C bus instability, and voltage dips during load switching were some of the primary issues encountered. These were addressed through both hardware and firmware improvements. Hardware-level solutions included the integration of decoupling capacitors (0.1 µF and 1 µF, 0805 package), flyback diodes for inductive load protection, and refined grounding schemes to reduce electromagnetic interference. On the firmware side, optimized signal timing, retry mechanisms in communication routines, and state machine-based logic control were implemented to enhance system resilience and response accuracy.

Modular design principles played a central role in structuring the test jig. The system was partitioned into discrete blocks—controller, input/output interface, relay drivers, and power management—allowing easier debugging, maintenance, and reconfiguration. This approach also facilitates future upgrades or adaptations for different PDU layouts or expanded test requirements, making the platform suitable for both prototyping and volume production environments.

Electrical performance testing was carried out under various loading scenarios, with load currents ranging from approximately 1.75 A to 4.28 A per socket and operating voltages maintained between 217.5 V and 221.5 V. These figures fall within the permissible range of ±10% for a nominal 230 V system. Real power consumption was calculated using the formula: $\mathbf{P = V \times I \times PF}$,

where all tests were conducted with purely resistive loads, resulting in a power factor (PF) of 1. For instance, a socket with 220.5 V and 3.85 A draws approximately 849.43 W. The accuracy of these values validates the effectiveness of the measurement system and its ability to support moderate load conditions with high fidelity.

Safety considerations were meticulously integrated throughout the design. Fuse protection, electrical isolation, and adherence to grounding best practices were implemented to mitigate risks such as short circuits, overcurrent, or accidental human contact. These measures ensured the device's compliance with standard electrical safety norms and enhanced its reliability in industrial settings.

In conclusion, the PDU test jig successfully demonstrated how embedded systems can be leveraged to create a structured, scalable, and safe testing framework for complex electrical systems. The combination of intelligent control, modular hardware, and automation capabilities has enabled a significant leap in the quality, efficiency, and reliability of the testing process. This project serves as a strong foundation for future innovations in automated electrical testing and showcases the pivotal role embedded technology plays in modern industrial applications.

CONCLUSION

The design and implementation of the Power Distribution Unit (PDU) Test Jig have demonstrated a comprehensive and systematic approach to ensuring the functional reliability of PDUs prior to deployment. By integrating embedded control systems, such as microcontrollers, I/O expanders, relay drivers, and standard communication protocols like I²C and RS485, the test jig effectively automates continuity and load testing procedures. The modular hardware architecture allows for scalable testing across various voltage levels and socket configurations, thereby improving test coverage and operational efficiency. This solution not only reduces human error and testing time but also enhances the consistency and accuracy of validation processes. Moving forward, incorporating features such as data logging, remote diagnostics, and advanced analytics could further optimize performance and support broader quality assurance standards in industrial applications.

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