Parsafar and Qaderi Baban
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Real-time fault diagnosis system for electrical panel using embedded systems

Parsa Parsafar[1] and Payam Qaderi Baban[2*]

*Correspondence: payamb4@gmail.com

[1] Department of Engineering, University of Mazandaran, Amol, Iran
[2] Faculty of Electrical, Biomedical and Mechatronics Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran

Abstract

Regular maintenance inspections are necessary for industrial electrical panels. The project incorporated an IoT system that leverages embedded systems to streamline and expedite this process. This implementation rendered the electrical panel in real-time, enabling more efficient maintenance procedures. The project utilized an Odroid embedded system board as the central system controller and designed an electronic circuit for data communication. Software design was completed using the C++ programming language, and Dataplicity Cloud Commander was used as an interface for accessing the electrical panel online via phones or computers. This design allows technicians to continuously monitor the panel's protective relays, temperatures, and power supply voltages. The system underwent testing for various operating conditions and potential errors, resulting in a low-cost intelligent system that significantly reduces troubleshooting time for electrical panels by providing essential information quickly and easily.

Keywords: Electrical panel, Odroid board, Cloud system, Fault diagnosis

Introduction

The electrical panel is essential to every industrial machine and production line. It plays a crucial role in ensuring the smooth operation and efficiency of the entire manufacturing process. Specifically, the electrical panel supplies energy and controls the various parts involved in the production process. Some of the equipment and components installed inside the switchboards include contactors and types of control relays, protection relays, industrial computers such as PLCs and network equipment, motor drivers and controllers, monitors, and power supplies. The set of equipment mentioned above forms a system that guarantees the machine's working process, machine safety, and operator safety. Failure of any part of the system can cause an industrial machine to shut down and thus slow down or completely stop the production process. Rapid and timely detection of breakdowns in industrial electrical boards reduces stoppage time and increases production efficiency.

The designed system automates the crash detection process and reduces troubleshooting time to zero. The purpose of the system is to continuously send technicians information about the operation of the electrical board equipment via a mobile phone or computer connected to the Internet. With this information, technicians can check the working status of selected sections of the electrical panel and take the necessary steps if a malfunctioning report is received. The result will be that reducing troubleshooting time and getting information about the state of the work of electrical relays and switching equipment will ultimately increase efficiency and reduce production costs in the industry. Intelligent fault detection systems are basically available for high-priced switchboards. But these systems are not economical for low-cost boards. One of the main goals of this project was to build an economical real-time crash diagnosis system to use in any type of electrical panel.

Research background

The process of troubleshooting and obtaining information on electrical panels is traditionally carried out manually using measuring instruments like multi-meters. Within panels featuring PLCs, the computer oversees the machine's operation and displays textual alarms on the screen based on data received from internal sensors [1]. It is worth noting that PLCs primarily regulate the machine's performance rather than controlling the equipment housed within the power panel itself. For instance, aspects such as DC power supply voltage levels, AC voltage levels, or residual current device functionality are not directly governed by the PLC. Consequently, technicians must rely on a combination of PLC-reported messages and manual measurements to troubleshoot the panel. However, this analysis and troubleshooting process is both time-consuming and necessitates physical presence. Thus, the speed of troubleshooting ultimately hinges on the expertise, experience, and technical knowledge of the repair technician. Considering that manufacturing plants often comprise multiple panels requiring continuous care and scrutiny, the implementation of an IoT system within a plant environment can enhance performance and accelerate the troubleshooting process for power panel boards [2, 3]. In this study, a single-board computer called Odroid performs the task of collecting data from relays and sensors, processing data, and sending results to the user's mobile phone [4]. The utilization of single-board computers, such as the Raspberry Pi, for process automation, has gained widespread popularity owing to its affordability, compact size, and extensive array of features [5]. The following inventions serve as examples of our inspiration to automate the process of fault detection for electrical panels, a task that has not been previously approached.

In 2018, Kumar and ShivaShankara conducted a system aimed to detect faults in railway tracks and provide an automated solution for fault detection. The system utilizes a combination of vibration monitoring sensors and ultrasonic sensors, along with programmable logic controllers (PLCs) and GSM communication elements.

The system significantly improves fault detection efficiency compared to manual methods. It can analyze vast amounts of data quickly and accurately, allowing for the early detection of faults that might otherwise go unnoticed. This helps prevent potential accidents, minimize disruptions, and reduce downtime [6]. The model's block diagram is shown in Fig. 1.

In 2013, Iñigo Bediaga and colleagues conducted a study focused on fault detection in rolling element bearings of a milling machine tool's spindle head. The article delves into an extensive exploration of various advanced methods employed for detecting

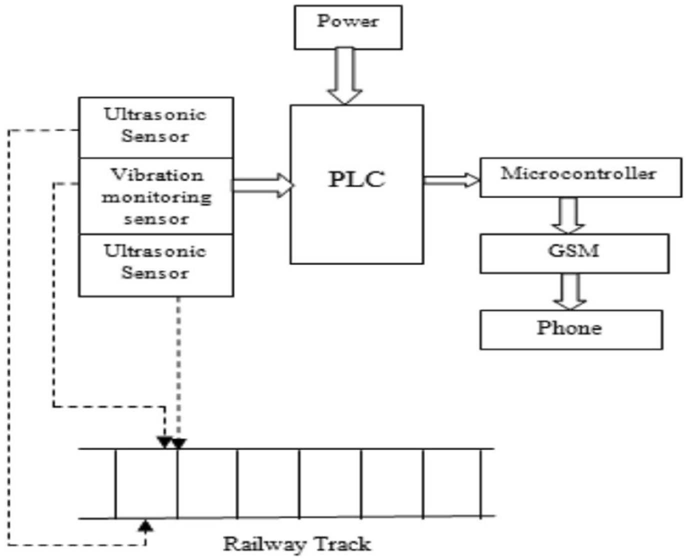

Fig. 1 Block diagram of automated fault detection system, provided in [6]

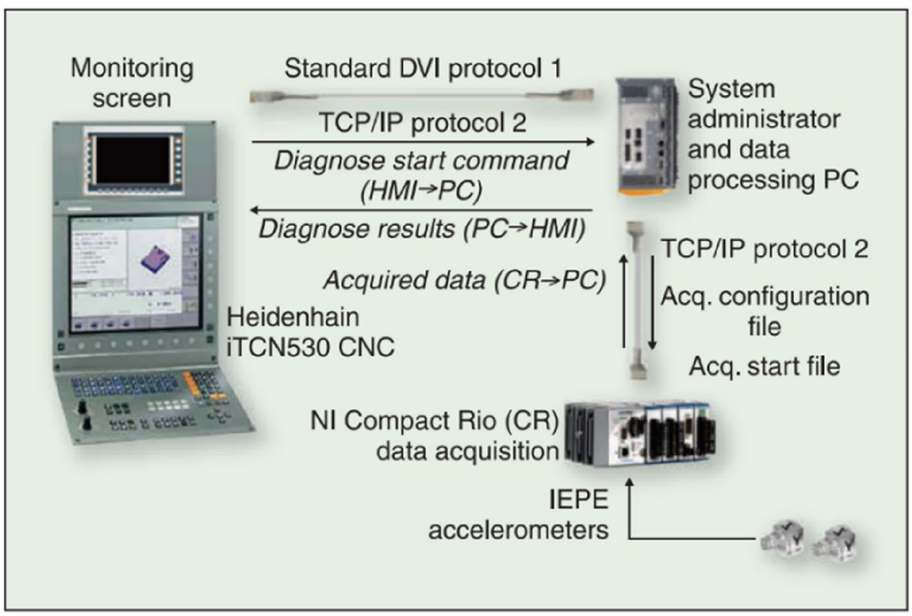

Fig. 2 Monitoring system communications diagram of [7] fault diagnosis system

faults in ball bearings, such as fuzzy classification and neural networks [7]. The details are provided in Fig. 2.

In 2017, Adhikaree and colleagues introduced a groundbreaking cloud-based battery condition monitoring platform designed for large-scale lithium-ion (Li-ion) battery systems. This innovative platform eliminates the requirement for extensive on-site infrastructure and hardware, as highlighted in their publication [8]. The figure illustrating a small-scale system, as presented in the original paper, is displayed in Fig. 3.

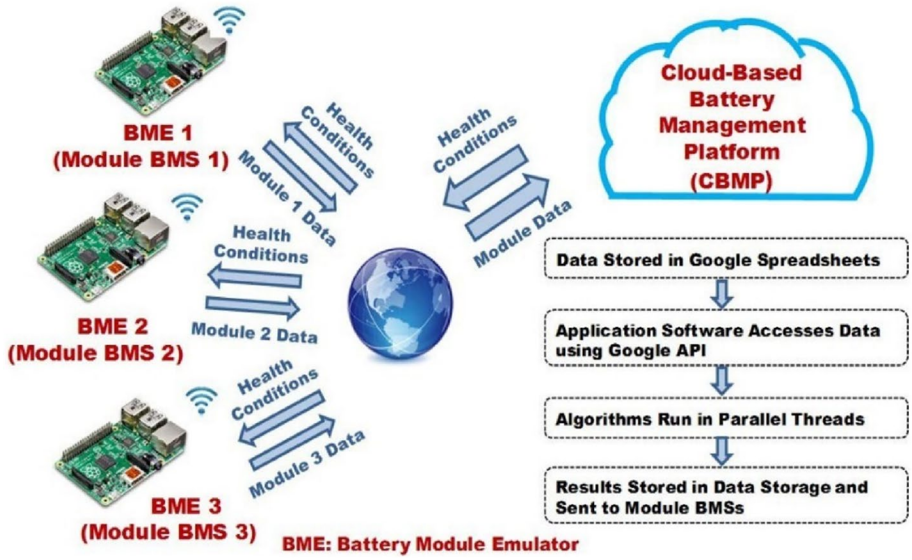

Fig. 3 Small-scale cloud-based BMS simulator, provided in [8]

The Odroid board offers numerous advantages over the Raspberry Pi, making it a preferred choice in many studies. One notable example is the work of Christopher Chambers, who, in 2015, invented a crash notification device that utilizes a Raspberry Pi to receive crash information from sensors installed in a vehicle enabling prompt notification of accidents to families, insurance companies, and medical emergencies, facilitating necessary actions to be taken [9]. Some of these advantages include:

1. More powerful hardware, with typically more RAM and processors enables it to easily handle more demanding applications and multitask.
2. Odroid boards have more powerful graphics processors than Raspberry Pi boards, making them a better choice for graphics-intensive applications like gaming and video playback, and providing better graphics performance.
3. Odroid boards have more expansion options than Raspberry Pi boards, with more USB ports, and support for more add-on modules providing greater flexibility and options for users.
4. Odroid also has a growing community of developers and enthusiasts, and many popular software packages have been optimized for Odroid boards, making them a better choice for users seeking more optimized software support.
5. Odroid boards typically have better networking performance than Raspberry Pi boards, with support for faster Ethernet speeds and built-in support for Wi-Fi and Bluetooth, providing better connectivity options for users.

Methodology

In order to automate the troubleshooting process and determine the working status of the equipment within the panel, first, the equipment and parameters need to be selected. These equipment can include protective relays, such as electric motor thermal relays, phase control relays, residual current device. The desired parameters can include the temperature inside the panel, and the voltage fluctuations of the DC power supply. Moisture levels, smoke levels, and diagnosis can also be monitored if needed. The system requires a computer to obtain information on the selected equipment and parameters, to analyze the data obtained and to generate results from the analysis results. One of the options could be the single-board computers available on the market. Single-board computers (SBCs) are compact, cost-effective, and easily installable components that can be incorporated within the power panel [10]. Once the computer is programmed, it is connected to the user's smart phone or computer via the Internet. The user can access the single board computer information or monitor the computer's performance through the Internet of Things platforms. The electrical panel illustration is shown in Fig. 4. The hardware industrial embedded platform, (Odroid), along with the fault diagnosis experimental platform, is illustrated in Fig. 5.

Control system

Odroid board is a small Linux single board computer invented for education [11]. Its small size and low cost make it an ideal tool for manufacturers and electronics enthusiasts, in projects and designs involving more than the usual microcontrollers [12]. Odroid board has a robust and durable structure, which makes it even suitable for use in industrial environments [3].

ODROID-C4 is a single board computer (SBC) developed by Hardkernel. It is based on the Amlogic S905X3 quad-core ARM Cortex-A55 processor with a Mali-G31 MP2 GPU. The board comes with 4 GB of LPDDR4 RAM, gigabit ethernet, 802.11ac Wi-Fi, Bluetooth 5.0, and supports up to 4Kp60 video output. ODROID-C4 also features four USB 3.0 ports, one USB 2.0 port, and a microSD slot for storage. It has a 40-pin GPIO header and supports various expansion boards such as the ODROID-N2+ compatible HATs. The SBC is powered by a 5 V/4A DC power input, and supports various operating

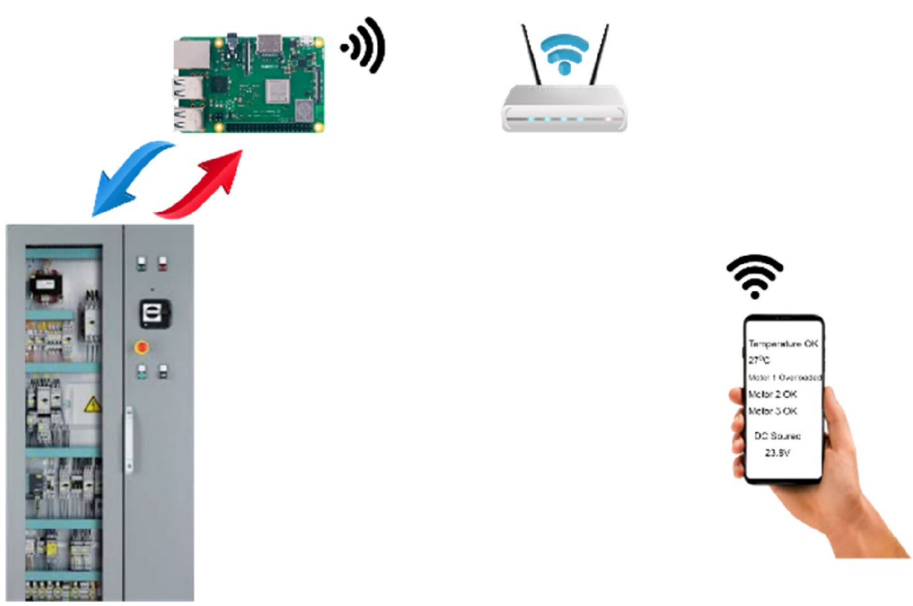

Fig. 4 Fault detection system electrical panel using Odroid

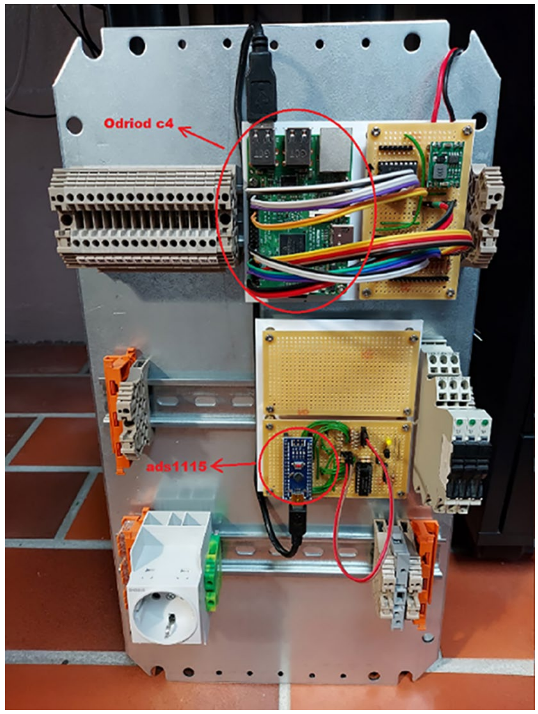

Fig. 5 Implemented hardware platform

systems including Ubuntu 20.04 LTS, CoreELEC, and Android 9 Pie. ODROID-C4 also supports Docker and Kubernetes, making it a suitable choice for edge computing and IoT applications. Overall, ODROID-C4 offers powerful computing capabilities in a compact form factor, making it a versatile option for various projects and applications [13]. Using these specifications, Odroid-C4 can be used as a fast, high-performance controller with the network installations required for the IoT system.

Selection of devices and parameters

Electrical devices and parameters that were taken into account in this project include the thermal overload relay, the phase control relay, the residual current device (RCD), the cooling temperature, and the DC supply voltage of the panel. Thermal overload relays have an electromechanical system that protects the motor in case of overload or phase failure [14].

Three-phase control relays, also known as protection relays, protect electric motors and equipment against voltage outages in three-phase systems. When voltage errors such as phase loss, phase inversion, phase imbalance, undervoltage, and overvoltage occur, the circuit will shut down. The Residual Current Device (RCD) serves as an electrical protection system designed to automatically disconnect circuits in the event of an electric shock or ground fault. Regularly check the difference between the live current and the return current of the neutral conductor. The difference between these two currents means that the current leaks to the ground, causing the RCD to break the circuit.

DC power supplies in electrical panels are used to supply industrial automation devices such as sensors, PLCs and relays. Most automation systems are powered using

24 VDC. If a power supply deviation occurs at the set point, the working system performance will malfunction. Electrical panels for automation include many electronic devices such as PLCs, DC power supplies, motor controllers, networking equipment, and monitors. These equipment are sensitive to heat and humidity in industrial environments. Such panels use air conditioning to protect the equipment from both heat and humidity.

Analogue to digital converter

Relays are common in automatic control systems [15]. Most relays provide additional normally open (NO) and normally closed (NC) switches that operate when the relay is operating. These switches on the relay were used to provide the digital inputs needed for the GPIO (Odroid Input/Output) pins. Parameters such as temperature and DC power level fluctuation are analog data. An analog-to-digital converter interface must be used to transfer this information to the computer. Analog to Digital converters are available in different types depending on resolution, speed, channel number, and communication protocol.

Adafruit's ADS1115 breakout has 16-bit resolution, an I2C interface, and a 4-pin selectable address, which allows you to program the sample rate and output gain to the desired range, making it one of the best choices as an ADC [16]. An illustration of this converter breakout is shown in Fig. 6.

In this study, the temperature inside the power panel is measured using the LM35 sensor. The advantage of this sensor lies in its simplicity, as well as the linear output it provides in terms of temperature. It is a 3-pin sensor that uses two pins to supply power capable of handling 4–40 V. The third pin is the sensor output, which changes 10mv per degree Celsius.

In this case study, the output voltage of the DC power supply is 24 V. Odroid can only read analog data from 0 to 5 V. Therefore, an attenuator circuit was used to reduce the size of the power supply output to an acceptable range for the Odroid input pins, as shown in Fig. 7.

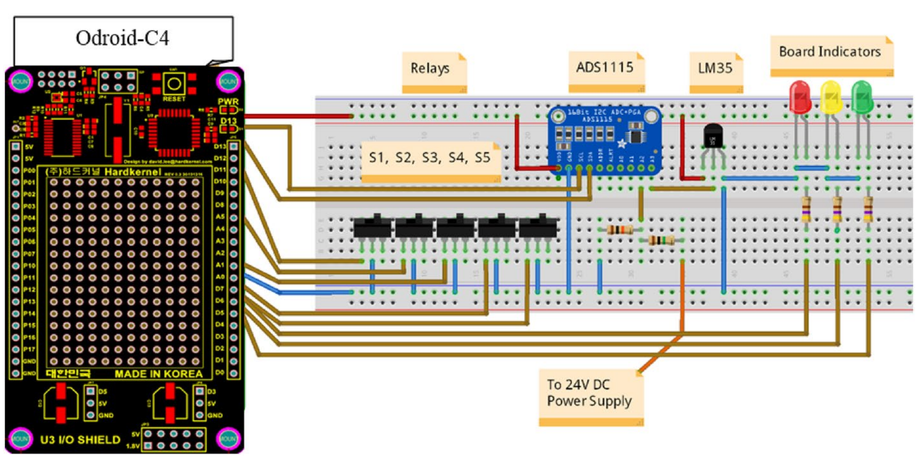

Fig. 6 The circuit design and connections of the system

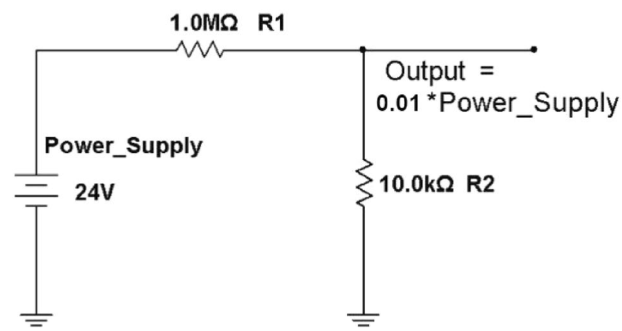

Fig. 7 The voltage divider circuit (attenuator)

$$V_{\mathrm{Out}} = \frac{R_2}{R_1} V_{\mathrm{In}} \tag{1}$$

Equation 1. Relation between the output and input voltage in this circuits depends on two resistors ($R1$ and $R2$) connected in series.

If necessary, humidity sensors such as HCZ-H8 and smoke detection sensors such as MQ135 can be used [17]. The way these two sensors are installed is similar to how the temperature sensors are installed (Fig. 8).

Circuit setup

One of the Odroid ports is a 40-pin port called GPIO that allows users to connect this computer to input and output devices [18]. Two pins on this port are for I^2C type serial communication. Figure 9 shows how the Odroid connection is connected to the circuit of this project.

This circuit uses the odroid-C4 as the system controller. The Odroid scheme only shows power and GPIO connections. Pins 19, 26, and 21 are connected to the red, yellow, and green LEDs through 470Ω resistors, respectively. The LED was used as a local alarm in the circuit. The Adafruit ADS1115 analog-to-digital converter was used to transfer analog data to the controller. The SCL and SDA pins of the controller are connected to terminals of the same name on the ADS1115 converter. Each device's power pins were connected to 5 V and ground. To transfer DC source oscillation data to the controller, we first reduced the voltage level to 1/10 using an attenuator circuit. This design assumes that the monitored power panel has a 24 V DC power supply. In this case, the 24 V DC supply voltage was lowered to 2.4 V, which is a suitable range for the controller. The output of the attenuator was connected to input channel 2 of the ADC converter. The LM35 sensor was used to measure the temperature of the panel. The V_{out} pin of the LM35 was connected to input channel 3 of the analog-to-digital converter.

Other equipment selected for monitoring include thermal overload relays for three motors, three-phase monitor relays, and residual current device relays. The NO (normally open) switch of each relay shown in the circuit labeled $S1$, $S2$, $S3$, $S4$, and $S5$ is connected to the input pins 18, 25, 12, 16, and 20 of the controller, and the other end of each switch is grounded.

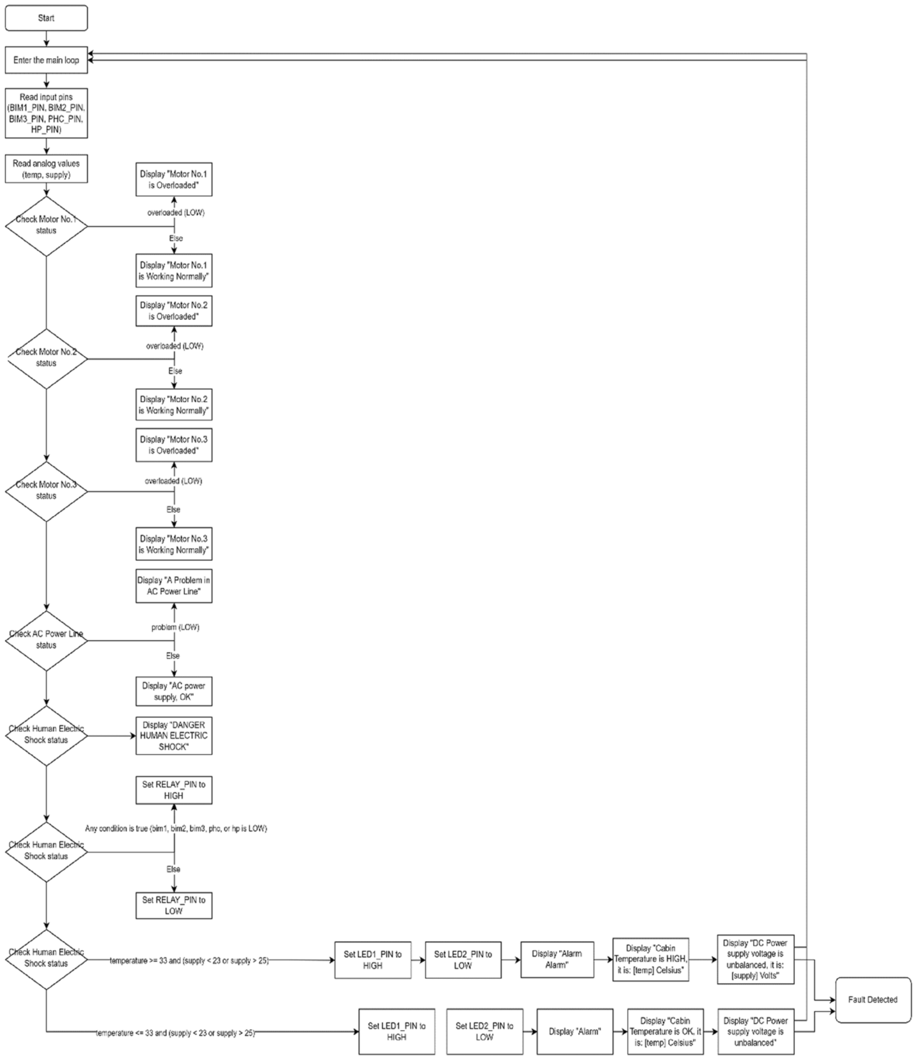

Fig. 8 Code procedure flowchart

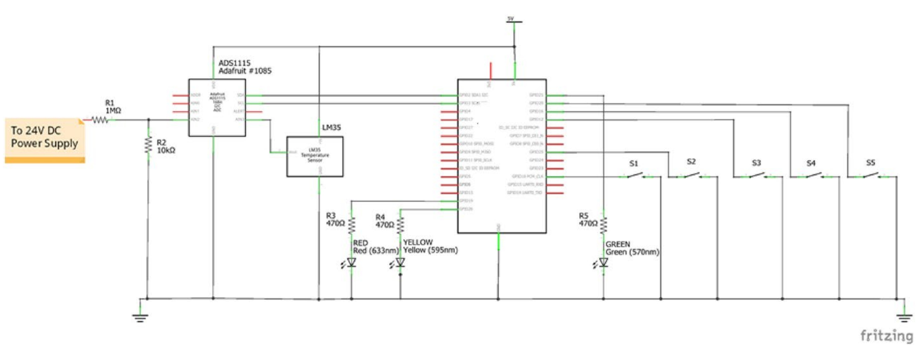

Fig. 9 Schematic diagram of the circuit

Controller setup

In the case study of this project, three bimetallic relays, phase control relays, residual current devices, room temperature, and DC power voltage fluctuations are controlled by the Odroid. C++ was used for controller programming. In addition, programming must call the required libraries into the program, including those needed for ADS1115 converter programming. Detailed procedure is outlined in Fig. 8, providing comprehensive instructions.

As shown in the program description, the relay's controller input pins are defined in pull-up mode. Therefore, in order for the controller to detect the activation of the protective relay, for each relay, the corresponding input pin of the controller is connected to ground through the NO switch of the relay. In this case, when each protective relay is activated, the controller sends a message corresponding to the generated fault.

The temperature inside the panel is constantly measured by the temperature sensor and the temperature information is displayed to the user along with the necessary warnings and messages. Fluctuations in the output voltage of a 24 V DC power supply are reported similarly to the user. Three color LEDs are also mounted on the controller board for local reporting. A red LED light indicates that one or more protective relays are active. The yellow LED lights up when the temperature rises or the DC power supply voltage is out of the set point, otherwise the green LED lights up.

Experimental results and analysis

Experts can use IoT to easily access and supervise Odroid and its functions through Smart devices over the Internet [19]. The IoT platform used in this case study is called Dataplicity. Dataplicity provides a connection between Odroid and any computer that can connect to the internet [20]. It is free and easy to use and install. Users can remotely access the Odroid command line via Cloud Commander. Dataplicity gives the users full control over all Odroid features. According to this study, technicians can conveniently access information or receive alarms from the electrical panel through their smartphones or PCs. Figure 10 is a screenshot of the Dataplicity Cloud Commander environment, which displays a comprehensive report on the device and parameter conditions within the test project's electrical panel.

The report depicted in the figure indicates that the temperature, DC power supply, two thermal relays, and three-phase control relays are functioning within normal parameters, while a human shock event has been detected and the thermal relay for motor number 2 has been triggered. These reports play a crucial role in ensuring the safety of both humans and machines.

Experimental results

Figure 11 illustrates the proposed system designed for fault detection in an oscilloscope. Upon occurrence at time t_1, a fault manifests as a sudden spike in the measured values, indicating an anomaly. The method presented continuously monitors the oscilloscope's output in real-time and conducts data analysis. At time t_2, the fault detection algorithm identifies the abnormal behavior and triggers an error report. This report contains comprehensive details regarding the error type and severity, enabling swift troubleshooting. Subsequently, at time t3, the error is resolved through the activation of a fuse or the implementation of suitable corrective measures. As a result, the oscilloscope regains its normal functionality, as depicted by the stabilized values in the graph. By implementing

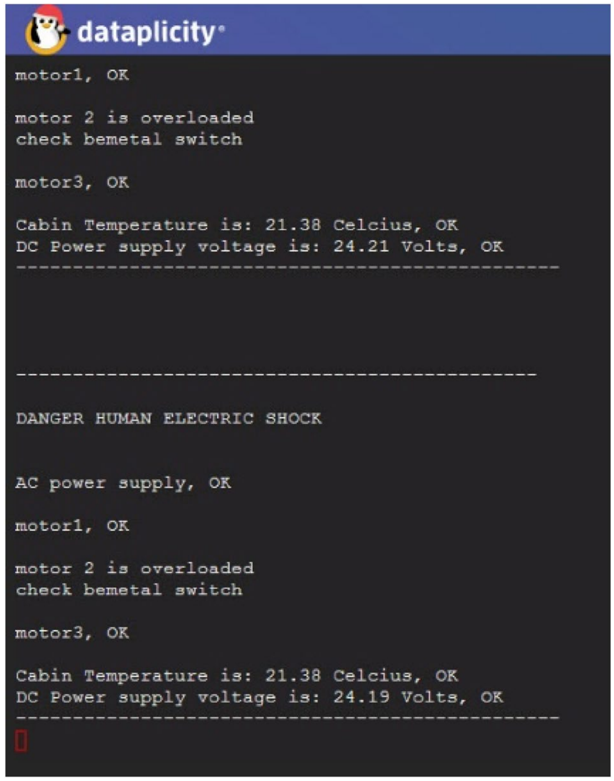

Fig. 10 Dataplicity cloud commander display

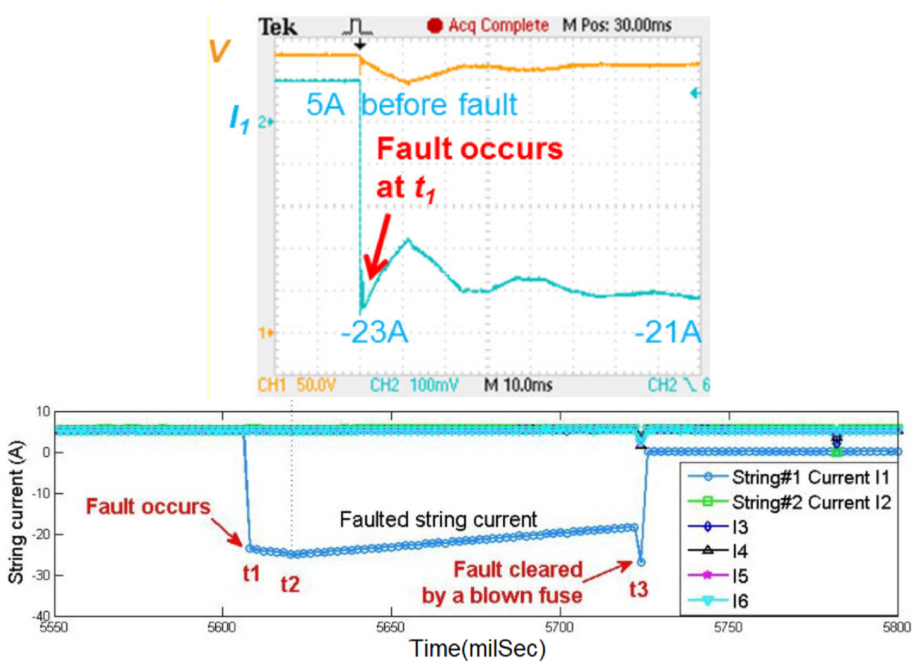

Fig. 11 Post-fault steady state captured by monitoring board

this system, errors can be promptly detected and addressed, ensuring accurate and reliable measurements in subsequent operations.

Comparison to similar models

It should be noted that since there is no similar implementation or even model for electrical panel fault diagnosis in the published articles so far, comparing the speed and accuracy of our proposed implementation of this component with similar models was not possible. So we compared our fault detection system with other electrical systems in the table below.

In this brief comparative analysis, we will evaluate the fault detection speed and accuracy of the proposed fault diagnosis in comparison to other articles mentioned in the Research Background section.

In [6], by utilizing sensors, PLCs, and GSM communication, the system aims to enhance railway safety by reducing the occurrence of accidents and minimizing the loss of life and property. However, the system relies on vibration monitoring sensors and ultrasonic sensors for fault detection. While these sensors are effective in detecting certain types of faults, they may have limitations in terms of accuracy, sensitivity, and the ability to detect hidden or intermittent faults. External factors like weather conditions or environmental noise can also impact the performance of these sensors. Furthermore, although the model demonstrates promising speed and accuracy in fault detection, it has not yet been implemented in practical applications.

In [7], early fault detection can lead to cost savings. By addressing issues promptly, the need for expensive repairs or component replacements can be minimized. Additionally, scheduled maintenance based on diagnostic information can help optimize maintenance costs.

The developed strategy for detecting and diagnosing faulty bearings in a heavy-duty milling machine tool's spindle head has been implemented in a real machine. This suggests that the system has been successfully applied in a practical. But the challenge mentioned in the article is to not only be capable of diagnosing faults automatically but also to generalize the process regardless of the measured signals. This suggests that the system may face difficulties in adapting to different types of signals or variations in operating conditions, which could limit its overall effectiveness and reliability. In fact the systems may sometimes generate false alarms, indicating a fault where none exists. This can result in unnecessary maintenance or disruptions in the production process, leading to inefficiencies.

In [8], the model allows for real-time monitoring of battery health conditions, such as state of charge (SOC) and state of health (SOH), enabling early fault detection and prediction of remaining useful life. By utilizing cloud resources, the platform reduces overall system and maintenance costs. However implementing a cloud-based system involves integrating various components, such as IoT devices, cloud storage, analytics tools, and visualization. This complexity may require expertise and additional resources for development and maintenance. Additionally this model has not been implemented in practical applications too.

By combining the speed and accuracy aspects, our proposed implementation outperforms the other methods mentioned in Table 1, ensuring rapid identification and

Table 1 The comparison of Fault detection criteria in electrical devices between some selected methods utilized in published papers

Article methods	Fault detection speed	Fault detection accuracy	Absolute error	Implemented
Proposed	High	High	0.007	Yes
[6] method	High	Moderate	0.082	No
[7] method	High	low	0.129	Yes
[8] method	High	Moderated	0.026	Yes

response to electrical panel faults with a high degree of accuracy. The system's ability to detect faults quickly and accurately contributes to increased operational reliability and safety, reducing the risk of equipment failure and potential hazards in electrical panel systems.

Conclusion

The goal of the paper was to provide a monitoring system that allows users to observe the condition of equipment and parameters of electrical panels. The project revolved around utilizing an Odroid minicomputer as the primary system controller. The case study included three thermal overload relays, three-phase monitor relays, residual current circuit breakers, panel temperature, and a DC power supply. Project case studies show that the Odroid can regularly monitor panel devices and parameters through the I/O port, and report the required data and alarms to the user via messages. It also shows how industrial IoT system applications can benefit technicians through fast and accurate troubleshooting. Based on system tests, users have the capability to exercise complete control over the system through their smartphones or PCs. As a future study, the system can be redesigned for the electrical panel network to control the entire plant's electrical system.

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Author contributions
PP: Writing—original draft, software. PQB: Writing—original draft, reviewing, and editing.

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Declarations

Competing interests
I declare that I have no conflicts of interest related to this work.

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