Original Article

Design of Electronic Protection Modules, Voltage Monitoring, and Safe Reset for Industrial Electrical Equipment and Tools

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Abstract - This article presents the design and implementation of electronic modules for protection, voltage monitoring, and safe reset aimed at industrial applications that demand high reliability in terms of electrical safety. The developed system continuously monitors single-phase 220 VAC and three-phase (220 VAC, 380 VAC, and 440 VAC) voltage equipment and tools, integrating voltage measurement circuits and using an ATTiny 84 microcontroller for phase loss detection and protection processing, incorrect phase sequence in three-phase voltages, or abnormal power supply conditions with historical data in three-phase applications. It also enables safe reset reactivation, in addition to providing protection against incorrect rotation reversal in motors and faster short-circuit faults. The main objective is to prevent uncontrolled start-up when recovering a power supply lost due to external problems and to ensure that, after a power outage, power is restored only through a controlled and validated reset. The implementation of the proposed module reduces electrical incidents associated with unsafe resetting by up to 81.2%, thanks to the verification of phase failure or absence of power supply and manual validation prior to service restoration using safe resetting. In addition, the visual interface of LED indicators facilitates rapid identification of the operating status, reducing diagnostic times for problems external to the equipment. Experimental results and field tests demonstrate that the proposed solution constitutes a significant advance in the protection of industrial machinery, increasing workplace safety, the reliability of the electrical system, and the operational sustainability of power tools.

Keywords - Safe Reclosing Module, Electrical Protection System, Industrial Safety Automation, Voltage and Phase Monitoring, ATTiny84 Microcontroller Design.

1. Introduction

Currently, industrial electrical safety in companies in the metalworking sector and continuous manufacturing processes has become a fundamental aspect of production processes in Peru, where power outages and automatic resets in electrical equipment are one of the causes of workplace accidents involving operators, damage to machinery, and economic losses due to production downtime. In real-life situations involving the operation of three-phase motors, power tools, and interlocked control equipment, the absence of a protection system or module and safe reset can cause unexpected starts after a power restoration, putting both personnel safety and operational continuity at risk. It is also necessary to verify the correct electrical supply in terms of phases to avoid reverse rotation in electric motors.

To validate these indices, a survey is conducted on incident reports in industrial companies for data acquisition, indicating incidents due to activations after a power restoration or even phase failure in industrial companies in the metal-mechanical sector and workshops. In addition, reports from Peruvian entities such as the Instituto Nacional de Defensa Civil (INDECI), the Ministry of Energy and Mines (MINEM), and the Sociedad Nacional de Industrias (SNI), which estimate that between 18% and 25% of industrial electrical incidents during the last six months are associated with reconnection or uncontrolled reset failures due to the risk of electrocution, entrapment, or cuts from electric hand tools. These figures reveal the need to implement electronic solutions that integrate voltage detection, phase validation, short-circuit protection, and safe reset before restoring the corresponding power supply.

In response to this problem, the design of an electronic module for protection, voltage monitoring, and safe reset for electrical equipment and tools is proposed, aimed at industrial environments and workshops in the metalworking sector. The electronic module uses a microcontroller to perform the validations of the functions using integrated circuits for correct signal filtering and voltage configurations that allow

sensing of single-phase 220 VAC and three-phase (220VAC, 380VAC, 440VAC) voltages for selection of the same type of application in each piece of equipment. The module incorporates a visual interface using three LEDs to inform the operator of the operating status (operational, fault, or reset), allowing for safe and timely intervention, as well as generating a historical report on three-phase voltage incidents. This development seeks to offer an efficient, economical, and adaptable solution that contributes to reducing the incidence of electrical accidents, improving industrial safety standards, and increasing operational reliability in medium and low voltage electrical systems.

2. Related Works

Similar models to this design emphasize protection, industrial prevention, and process reliability, as in [1], where the design seeks to identify vulnerabilities and risks in industrial systems by analyzing real-time performance. However, traditional methods only consider observed data, limiting their accuracy in the face of unrecorded behavior. A zero-shot learning-based evaluation model is proposed, capable of analyzing both observed and unobserved performance, improving generalization and early fault detection capabilities. The results show an improvement of more than 65% in accuracy, providing an innovative solution to strengthen system security and reliability.

In [2], comparisons of articles and reviews are made, identifying the role of technologies such as Virtual Reality, Augmented Reality, Extended Reality (VR, AR, XR), the Internet of Things (IoT), Artificial Intelligence (AI), and Collaborative robots (Cobots), with the aim of providing electrical safety for today's industry. Likewise, in [3], certain variables are prioritized before startup, proposing a closed-loop startup strategy based on Dual Simple Phase Shift modulation (DSPS) adapted to the TAB converter. Three key contributions are introduced: a slope comparison method to detect the maximum current point, a partial derivative tracing method to calculate the optimal phase angles, and a safe and efficient start-up strategy that maximizes power while controlling current stress. Experimental results confirm a 34% improvement in starting speed compared to the DAB method, demonstrating the effectiveness of the DSPS approach in ensuring stable, fast, and safe starting in TAB converters.

Also in [4], medical automation applications, which use an efficient geometric approach that evaluates the system's tolerance to initial placement errors. Through simulations in liver and lung scenarios, it was verified that the metric is applicable to various algorithms for planning the movement of steerable needles, allowing the selection of plans with greater margins for safe start-up. This advance improves human-robot collaboration in guided surgeries, increasing the accuracy of the procedure and patient safety. In [5], a precise and safe start-up application proposes model-free adaptive control for PSUs, eliminating dependence on the physical model and

improving system response. Based on a refined nonlinear model, an adaptive controller with parameter optimization was designed and evaluated in four start-up scenarios. Simulation results show a significant improvement in speed and water level control, achieving a reduction in regulation time of 5.53 s and a lower overshoot of 2.85% compared to traditional PID and predictive methods. In addition, the method reduces energy consumption and meets real-time control requirements, demonstrating its effectiveness, efficiency, and practical viability in modern hydroelectric systems. The results show that the integration of these tools allows the development of intelligent and immersive digital ecosystems aimed at safety training, real-time monitoring, and predictive risk prevention. A conceptual framework combining predictive analysis and immersive training is also proposed, contributing to a more efficient and human-centered OSH, although challenges related to data security, ethics, and technology adoption in industrial environments remain.

For [6], the proposed environment must be validated. A CDPR with four cables and limited spatial constraints was used, comparing its simulated performance with an industrial prototype. Both followed the same trajectory, evaluating delay and position errors. The results showed a maximum divergence of 0.27%, even considering data transmission latency, demonstrating high fidelity between simulation and physical environment. Consequently, the system is confirmed as an effective tool for trajectory control and testing of CDPR architectures, promoting research and development in advanced robotics.

In [7], comparing device sensing as a protection method, which investigates the stability characteristics of a Synchronous Motor-Generator Pair (SMGP) designed to improve the inertia of grid-connected renewable energy systems. Through bifurcation and nonlinear stability analysis, the study identifies safe and unstable operating regimes based on key parameters such as electromagnetic torque, damping coefficient, and inertia. For the first time, the research reveals the existence of bistable regimes, where the system can transition to unsafe operation even within linearly stable regions, demonstrating that conventional analysis based solely on eigenvalues does not guarantee total stability.

Likewise, globally stable and unstable regions are identified within the parameter space, providing valuable information for the design of robust SMGP systems capable of maintaining grid stability in the face of frequency fluctuations. Finally, the results define a safe operating range for system parameters, contributing to the reliable integration of low-inertia renewable energy sources into modern power grids.

Also in [8], an intelligent fault diagnosis method for angle grinders is proposed based on the hybrid ACD-DE-SVM algorithm, which combines chaos theory and adaptive

optimization. The system processes vibration signals using wavelet decomposition, generating feature vectors to identify faults with high accuracy. The experimental results show an accuracy of 98.81%, a recovery rate of 98.74%, and an F1 score of 0.9877, surpassing other diagnostic methods. This approach demonstrates high robustness and accuracy, constituting an effective solution for predictive maintenance and improving industrial reliability. In [9], some problems with industrial equipment are identified, and a robust conceptual design model is presented that addresses multiple uncertainties, focusing on improving customer satisfaction, performance, and production costs. A multi-criteria optimization model is developed that uses an improved NSGA-II genetic algorithm, based on a hybrid expectation-possibility-probability approach to obtain Pareto solutions.

3. Methodology

The design and implementation of electronic protection, voltage monitoring, and a safe reset module adaptable to hand-held power tools and industrial equipment is proposed in order to meet industrial safety and operator protection needs. The design is divided into five main stages: problems to be solved and scope of the module, design of hardware adaptable to any equipment, design of control software in terms of voltage and functionality, functional validation and simulation of the module, and experimental evaluation in the field. A block diagram of the stages of the proposed design is shown (see Figure 1).

The main features of the design are listed below:

- Lockout due to phase failure.
- Overvoltage detection in terms of the power supply to the equipment or power tool.
- Manual reset after fault indication.
- LED indicators for quick diagnosis.
- Adaptable to any equipment or power tool.
- Module adaptable to equipment or power tool according to supply voltage.
- Fault history and causes for the three-phase module.

Table 1. Components to be used

Type	Model	Quantity
Microcontroller	ATTiny84	01
Electronic module	PCB V1.0	01
LED	Red, green, blue	03
Integrated circuit	LM324	01
Integrated circuit	TL072	02
Integrated circuit	LM358	02
Optocoupler	H11AA1	03
Optocoupler	MOC3021	01
TRIAC	BTA26-600B	01
Zener diode	ZM4740	01
Switching power supply	220V/5VDC/200mA	02
Current sensor	WCS1600	01

Regarding the scope of the module, the first problem and objective to be addressed is to reset an electrical device or tool when power is restored. Detection should only be performed and validated when this device is working, or the power switch is activated. It detects the absence of voltage and waits for a manual reset. There are two situations of use: one uses 220VAC single-phase voltage for hand-held power tools such as grinders, drills, belt polishers, etc. The other uses three-phase voltages of 220VAC, 380VAC, and 440VAC, used in bench drills, lathe-type polishers, benders or rollers, power inverters, etc.

The PCB design, which controls the equipment or power tool, was created using the EAGLE 9.6 program, which integrates components such as operational amplifiers, optocouplers, thyristors, and microcontrollers, in addition to having a linear and switched power supply to ensure the module's robustness. A non-invasive current sensor will validate the work before the power is cut off and protect against short-circuit failures. This will also serve to generate a history of problems arising from surges or overcurrents.

Similarly, for three-phase modules, it will have a mini power supply occupying a small space to avoid conflicts with electrical components in a power switch or electrical control panels. Regarding the sizing of the card and its location in a power tool such as a grinder, simulations were carried out depending on the size and space in each power tool to be treated, according to models made in AutoCAD 3D. In addition, grinders of different brands were used to perform this internal sizing calculation, the location of terminal blocks for input voltage, current sensor, and LED indicator light.

The selection of the microcontroller, sensors, and electronic modules takes into account the range of precision and robustness, processing capacity, and required speed. For the electrical design of the system, a diagram is drawn up integrating the sensors, voltage sources, and electronic module case as protection for its subsequent final location and configuration of the sensors, their regulation, and activation of alerts.

The dimensions of the electronic module are 35x65mm, which fits perfectly in a space adjacent to the power switch, with the possibility of adding LED indicators for quick diagnosis in the equipment. As for modules for three-phase voltages, they have dimensions of 100x120mm, ideal for placement in 2-position ON-OFF selector switches. Both modules will be encapsulated with black epoxy resin to ensure their functionality and also to prevent contact with dust or particles that could damage the electronic board.

The electronic module can be adapted to any electrical equipment due to its small size. Its software was simulated in PROTEUS 8 and programmed in the Arduino IDE, which facilitated communication between the ATTiny84 microcontroller in ISP, using the same bootloader.

As for the operational tests, tests were carried out with an angle grinder to use the single-phase module and an industrial bench drill for the three-phase module. Reseating tests were also carried out to verify proper safety operation, with the respective LEDs lighting up green in normal operating mode, red when there is a malfunction in the equipment or external situations that affect its operation, and blue when awaiting manual reseating by the operator. Likewise, the electronic module will store records of overcurrents, overvoltages, manual resets, and the number of voltage losses due to external problems.
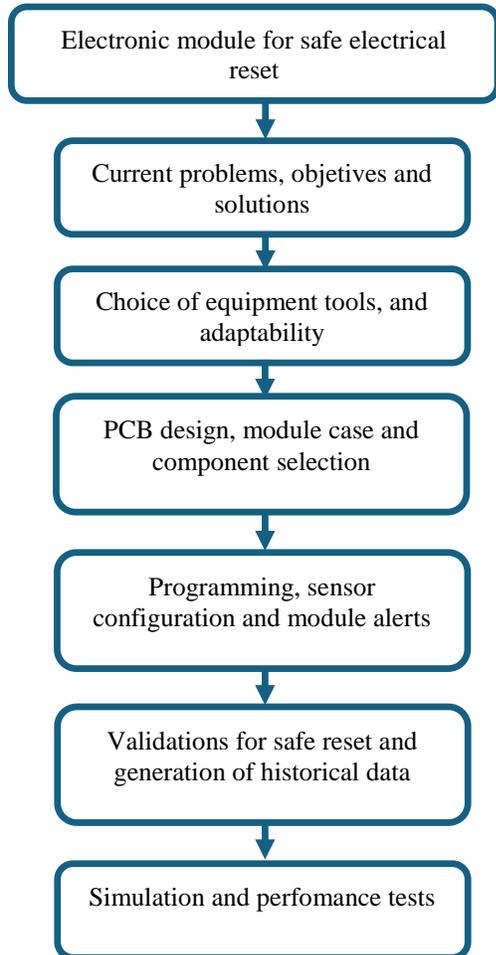
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┌─────────────────────────────────┐
│ Electronic module for safe       │
│ electrical reset                 │
└─────────────────────────────────┘
              │
┌─────────────────────────────────┐
│ Current problems, objetives and  │
│ solutions                        │
└─────────────────────────────────┘
              │
┌─────────────────────────────────┐
│ Choice of equipment tools, and   │
│ adaptability                     │
└─────────────────────────────────┘
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┌─────────────────────────────────┐
│ PCB design, module case and      │
│ component selection              │
└─────────────────────────────────┘
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┌─────────────────────────────────┐
│ Programming, sensor              │
│ configuration and module alerts  │
└─────────────────────────────────┘
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┌─────────────────────────────────┐
│ Validations for safe reset and   │
│ generation of historical data    │
└─────────────────────────────────┘
              │
┌─────────────────────────────────┐
│ Simulation and perfomance tests  │
└─────────────────────────────────┘
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Fig. 1 Stages of development of the proposed design

4. Development System

The electronic module is developed based on the ATTiny84 microcontroller, which processes and executes variables such as voltage, current, reset, LED indicators, and historical data. This is incorporated into integrated circuits and modules to perform this task according to the programming firmware. The conditions are the same in terms of variable reading for a single-phase system as for a three-phase system, differing only in voltage sensing and diagnostic alerts. The architecture of this module is shown in (See Figure 2).
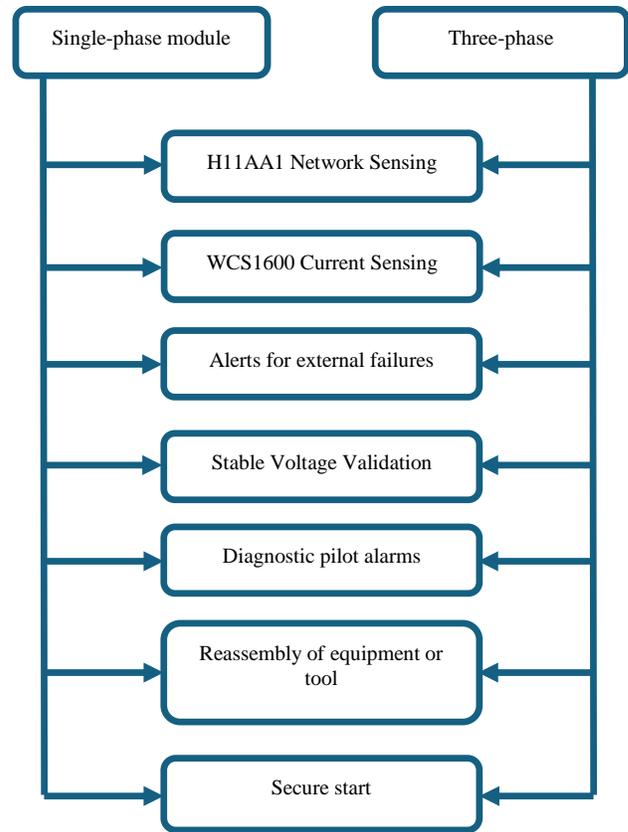
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┌──────────────────┐    ┌──────────────────┐
│ Single-phase     │    │   Three-phase    │
│ module           │    │                  │
└──────────────────┘    └──────────────────┘
       │      ┌──────────────────────┐      │
       ├─────▶│ H11AA1 Network        │◀─────┤
       │      │ Sensing               │      │
       │      └──────────────────────┘      │
       │      ┌──────────────────────┐      │
       ├─────▶│ WCS1600 Current       │◀─────┤
       │      │ Sensing               │      │
       │      └──────────────────────┘      │
       │      ┌──────────────────────┐      │
       ├─────▶│ Alerts for external   │◀─────┤
       │      │ failures              │      │
       │      └──────────────────────┘      │
       │      ┌──────────────────────┐      │
       ├─────▶│ Stable Voltage        │◀─────┤
       │      │ Validation            │      │
       │      └──────────────────────┘      │
       │      ┌──────────────────────┐      │
       ├─────▶│ Diagnostic pilot      │◀─────┤
       │      │ alarms                │      │
       │      └──────────────────────┘      │
       │      ┌──────────────────────┐      │
       ├─────▶│ Reassembly of         │◀─────┤
       │      │ equipment or tool     │      │
       │      └──────────────────────┘      │
       │      ┌──────────────────────┐      │
       └─────▶│ Secure start          │◀─────┘
              └──────────────────────┘
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Fig. 2 Operating architecture

Depending on the single-phase and three-phase voltages for which the single-phase module is designed to operate, it starts by evaluating the mains voltage using the H11AA1 optocoupler to verify the single-phase voltage entering the equipment. For a single-phase configuration, the line and neutral are used to perform this sensing. In a three-phase network, the reading of each line R-S, S-T, and R-T is taken into account to evaluate the absence and detection of phase. The permissible voltage value for the tool is commonly 220V AC, so an overvoltage value of no more than ±5% is taken to protect internal components such as the main motor in single-phase mains power tools. In a three-phase network, an overvoltage value of no more than 5% per phase is used to prevent components from overheating. The reading of these voltages will be configured with TL074 operational amplifiers so that the alternating signal will be converted into an analog pulse voltage by phase shift every 120°, ranging from 0 to 4.5V DC for the ATTiny84 reading.

Current sensing in the equipment, whether three-phase or single-phase, is performed by the WCS1600 sensor with a follower configuration for signal filtering or a comparator, depending on whether it is a specific blocking or sensing current configuration. The reading is 22mV/A with a proportional output range from 0.3V to 4.7V in this case. The power supply of the electronic module for single-phase power tools consists of an array of resistors that provide the

appropriate voltage for the polarization of the power Zener diode responsible for supplying power to the module. An EMI line filter is also incorporated to prevent electrical noise, thus avoiding system reboots or equipment failures due to interference problems. For three-phase equipment, there is an external switched-mode power supply using the rectified voltage, similarly reduced through two mini 200mA power supplies incorporated in each phase, as well as phase detection and a switched voltage regulator for regulating the main voltage in the module.

Regarding the generation of historical data, the appropriate reading of voltage and current values will be taken into account, generating the first historical data for low or overvoltage, preventing the equipment from starting up and causing it to overwork. If the thermomagnetic circuit breakers are incorrectly sized, this module will be able to sense the equipment's current and disable it due to excessive demand in the event of overwork, obtaining the current value as a second history.

In terms of the disconnection and safe reset wait functionality, the module will obtain a voltage from a capacitor when it is not powered, obtaining sufficient time to perform the respective evaluation and activating the interlocked off mode to wait for a safe reset when it receives power again and evaluating the condition in which it was turned off, since if there is a disconnection with the switch off, it will not evaluate the reactivation. Similarly, when the equipment is connected to the network while the switch is on, it will not turn on immediately, but will activate the reset function in the module. Only when the equipment is connected to the network and is turned off will it be able to turn on without any problems, without waiting for any other event.

For the module design stage, the correct and appropriate selection of components was made according to the integrated circuits dedicated to tasks such as the LM324, LM358, and TL074 in terms of analog reading accuracy. The ATTiny84 microcontroller is used for the operating logic, considering that it is a microcontroller with sufficient speed to evaluate these required parameters of less than 2.5MHz.

The single-phase module operates at a stable 5V voltage regulated by a linear regulator and a 1W ZM4740 Zener diode and a resistor array, together with a phase input EMI filter for protection from external electrical noise (see Figure 3) and for three-phase voltages, it is obtained through the rectification of a three-phase diode bridge and switched-mode power supply for the regulation of ±5VDC voltages; The first function of the module responsible for voltage sensing and phase validation for both modules is shown in (See Figure 4), where the H11AA1 optocoupler senses the supply voltage in parallel with the isolated input voltage from the power cable of the hand tool to the microcontroller in single-phase and three-phase voltages. The R-S, S-T, and R-T phase sensing,

according to each evaluation, the module also acquires analog values from line sensing for the validation of adequate operating voltage. It uses the TL074 operational amplifier to validate the analog value of the rectified mains voltage entering the module, from which pulse validation through the microcontroller activates a relay that allows manual reset, enabling the transition to a second stage.
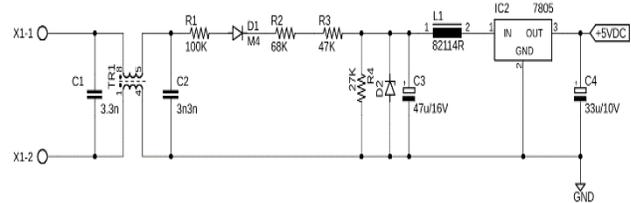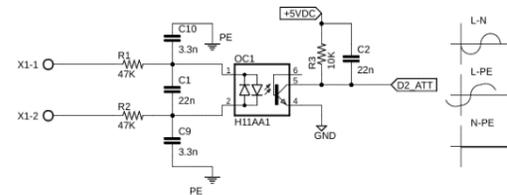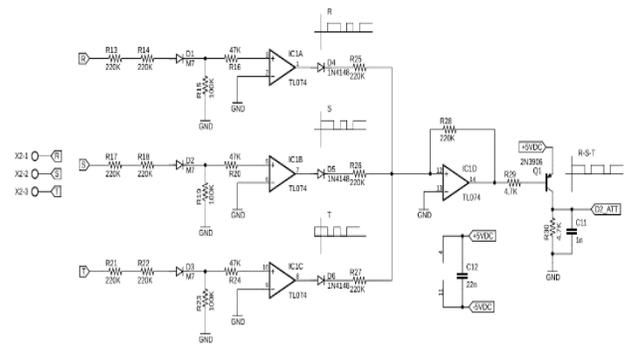

Fig. 3 Linear source of a single-phase electronic module

(a)

(b)

Fig. 4 Voltage validation circuit (a) Single-phase, and (b) Three-phase.

For the second stage of current sensing, the module uses the WCS1600 sensor, capable of reading up to 70A in VAC, using one for single-phase voltage and three for three-phase voltage, where the LM358 operational amplifier configuration evaluates the maximum current comparison, obtaining a digital output of 0-5VDC for evaluation by the microcontroller (see Figure 4). Likewise, the sensor offers a voltage proportional to the current obtained with a variable analog voltage of 0.7 to 4.7VDC, which is filtered by the LM358 itself. Overcurrent in single-phase tools will be detected through a red LED diode, indicating that the equipment has suffered an overcurrent as a protection system. This is followed by a manual reset after this 30-second protection is deactivated until another similar event is evaluated. The equipment's protection current is given

according to the manufacturer's design in a range of 1500-1900W from 6 to 9 amps of maximum sensing proportional to a continuous execution time of 1 minute.
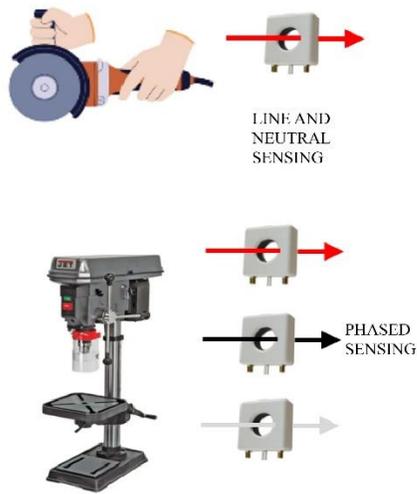

Fig. 5 Current sensing and maximum limitation

As for the manual reset stage, the electronic module will evaluate the previous stages, mainly the voltage stage, because in the metalworking industry, mains voltages are variable and unstable, and the module would not be able to work properly. That is why a standard fixed voltage of 5% or a variable analog input voltage in three-phase voltages is selected. The reset function is activated when the equipment or tool is disconnected from the network, either by human manipulation or a network disconnection due to imperfections in an electrical panel or voltage anomalies. In this case (see Figure 5) the equipment or power tool will remain on after the operator's impression, who will first carry out an inspection to find out why the equipment or tool shut down and may even check external consumables such as cutting discs, grinding discs, polyfan discs, in the case of a grinder, or jams in the drill bit of a bench drill, roller, or bender in three-phase voltages.

This is because if the power is restored, this equipment could cause incidents such as cuts, entrapments, or even mutilations due to the sudden start-up of this equipment. In the event of this problem, the manual reset of the module will act under certain conditions. First, it will validate whether the equipment had a voltage loss while it was operating, using the first stage of voltage detection and current sensing of the tool or equipment, saving the detection variable in the microcontroller; second, it will evaluate the reset position when reconnecting the equipment to the mains, for which, if the switch is in the ON position and power is supplied again, the equipment will be blocked and manual reset will be required. Third, the equipment must be used correctly, with the switch in the OFF position and connected to the mains voltage to operate normally without resetting. Given these indications, the microcontroller will act by sending light signals to indicate the status of the equipment after reset, or

while waiting for manual reset. A blue light indicates that the equipment has been reset after reconnection or restoration of the mains voltage. In the case of three-phase voltage, there will be an additional audible alert on the card indicating faults, as this module is designed for more robust and larger equipment. For each established function, a history is generated that can be viewed through the microcontroller's serial port connection. This port is covered and is only allowed to change the voltage and current configuration parameters of the equipment to be configured. In addition, the activation of the tool or equipment will be controlled by a BTA26-600B triac.
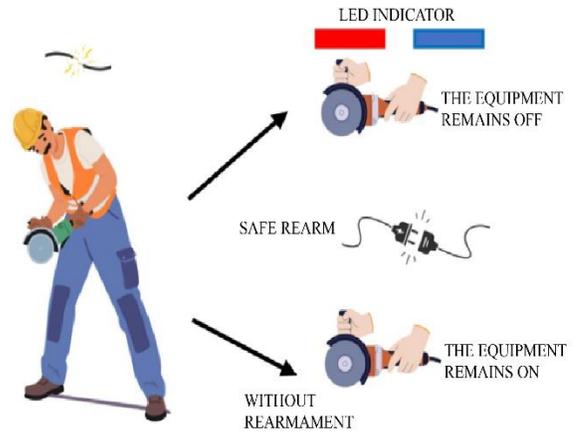

Fig. 6 Safe and unsafe reset process

The LED indicators will perform a diagnostic function in different tools or equipment, depending on their application for tools (see Figure 7). For single-phase voltages, the following is obtained:

- Green LED: functionality and correct status of the equipment.
- Red LED: Maximum overcurrent fault counter, which blocks the equipment until a technical inspection is performed due to excessive detection of this problem.
- Red LED (double flash): Overcurrent detected exceeding the maximum working cycle of 1 min at maximum amperage.
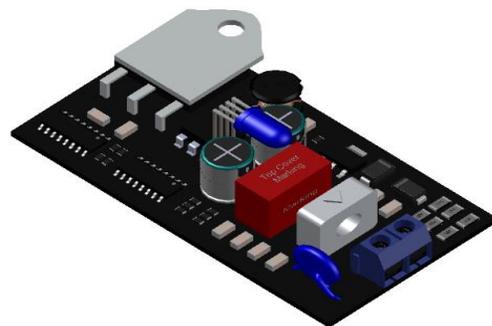- Blue LED: Reset the power tool for safe start-up.

Fig. 7 Single-phase module for power tools

Similarly, the LED indication for three-phase voltages (see Figure 8), since some functions are added in parallel, such as:

- Green LED: functionality and correct status of the equipment.
- Red LED (fully lit) and buzzer: Excessive current in the equipment, lockout with audible alert when the duty cycle is exceeded.
- Red LED (double flash) and buzzer: Equipment phase failure, check the electrical input connection.
- Red LED (triple flash) and buzzer: Low or high voltage in the equipment, perform operation evaluation.
- Blue LED (double flash for 2 seconds) and buzzer: Reset performed before connection or voltage restoration.
- Blue LED: Equipment reset for safe start-up.

Fig. 8 Three-phase module for industrial equipment

Depending on the size and location of the electronic module in the tools or equipment, there are two different scenarios: the first has functionality for power tools, and the second for three-phase equipment.

The design of the first module is based on the space available in a grinder or angle grinder, reaching a dimension of 35x65mm, located inside the equipment. In this case, a 7" grinder was used as an example (see Figure 8). This module is covered with epoxy resin (see Figure 9) because it needs rigorous protection of the electronic components, as it is exposed to contaminants such as metal dust, paint, grease, etc.
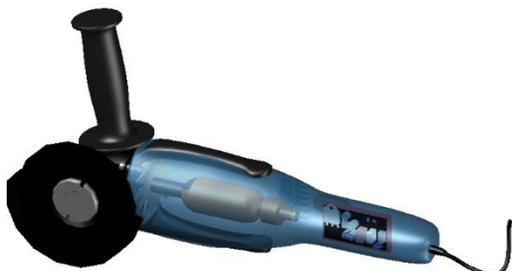

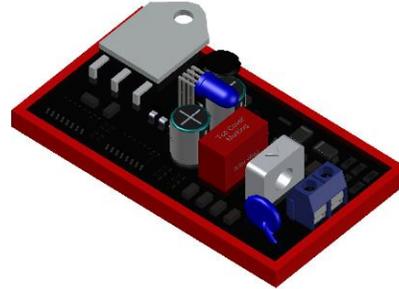
Fig. 9 Grinder with internal module

Fig. 10 Single-phase module with epoxy

Similarly, for the second module for three-phase voltages, a 2-position button panel was used, locating the module in this component using AutoCAD 3D software to adapt the respective space. This module will have dimensions of 100x120mm. In the case of the previous module, it will only be covered by dielectric varnish, as more operating parameters need to be configured, such as voltage and current range, in addition to having an audible alert included.

Both control modules were simulated in PROTEUS 8 software to verify their functionality. The simulation is carried out based on configuration values for each tool or piece of equipment. In the case of a grinder, the simulation is performed with the sensing of digital and analog signals according to their characteristics, in this case, using the DWALT brand with 1200W power and working amperage from 3Amp to 6.5Amp. Similarly, for power equipment such as a bench drill with a 2HP three-phase motor, 1.5KW power, and 6Amp amperage, a 2-position switch was used.

Both electronic modules were tested for 30 days to monitor faults due to malfunction or even power losses due to network instability, excessive use in terms of the work cycle, and improper use of tools or equipment, used in a metalworking workshop located in the industrial area of Cerro Colorado, Arequipa.

5. Results and Tests

To validate the operation and performance of the electronic protection, monitoring, and safe reset module, initial tests were carried out with an external module implemented in a PCB prototype, progressive shutdown and startup tests, and abnormal voltages due to electrical noise typical of workshops and industrial plants in the metalworking industry. Tests were carried out to evaluate its capacity in terms of voltage and current fault detection, response time, and the main objective of safe reset in the absence of electrical disturbances.

Results were obtained from tests carried out on industrial equipment over a period of three months after implementation. The most critical results were phase loss, polarity reversal in electric motors, overvoltage of more than 15% maximum, safe resets, and electromagnetic tests.

Table 2. Results in single-phase tests

Tests	Parameter	Result	Equipment
Detection of phase or line loss	Constant loss counter	Source cable check	Straight and angle grinders, polishers, and heat guns
False contacts	Equipment lockout	Safe reset activation	Straight and angle grinders, circular saw
Voltage measurement	Maximum permissible voltage of 230VAC	Overvoltage lockout	Angle grinders, portable welding equipment.
Switching cycles	Failure is only due to overload	No switching limit	All hand tools installed
Fault history	Historical counter via UART connection	Critical fault counter until lockout due to check	All hand tools installed

Table 3. Speed of action in response to external problems

Tests	Time	Result	Equipment
Detection of phase or line loss	10ms	The tool was forced to shut down	All hand tools installed
False contacts	15ms, counter of 2 consecutive times	Safe reset activation	
Voltage measurement	Constant 1ms	Overvoltage lockout	
Switching cycles	Each detected event	Safe reset without switching limit	
Fault history	Each detected event history is generated in 10ms	Review via UART connection	

The module was subjected to constant testing in three companies in the metalworking sector and maintenance workshops, FACTORIA JJA, FRISMET, and INCARD, located in the Cerro Colorado industrial park in Arequipa.

Satisfactory results were obtained from the first month of implementation when compared to incidents of unsafe reloading.

Table 4. Results of incidents with the single-phase module

Type of Equipment	Without Module	With Module	Event Reduction %
Bench grinder	18	4	78%
Angle grinders	10	2	80%
Straight grinders	20	3	75%
Portable welding equipment	30	2	93.4%
Hand polishers	10	2	80%
Heat guns	4	0	100%
Circular saw	2	0	100%
Cut-off saw	2	0	100%
Hand jigsaw	15	1	93.4%
Hammer drill	10	1	90%

Likewise, the three-phase electronic module offers certain advantages in terms of electrical protection, the main one being safe reset, uncontrolled activations due to not having an interlock activation system and only having a switch, followed by phase failure, reverse rotation of a motor designed for a single purpose such as automatic polishers, since reverse rotation of the motor could cause the roughing stone to break, cooling pumps, and hydraulic drive units.

Table 5. Results of incidents with the three-phase module

Type of Equipment	Without Module	With Module	Event Reduction %
Hydraulic drive	2	0	100%
Bench drill	10	3	70%
Automatic polisher	5	2	60%
Grinder	10	2	80%
Acid pump	3	1	66.6%
Tape sealer	5	2	60%
Turntable	14	4	71.4%
Electric key	5	1	80%

An average effectiveness rate of 88.9% was obtained for the use of the single-phase electronic module in power tools, which are the most critical at the industrial level, and 73.5% for the use of the three-phase module in critical industrial equipment, thus offering an improvement over the considerable number of reports according to entities such as the National Civil Defense Institute and the Ministry of Energy and Mines, with an incidence rate of 18 to 25%, improving by 81.2% based on the results obtained in both modules.

The Ministry of Energy and Mines, which reports 18 to 25% of incidents, improved by 81.2% based on the results obtained in both modules. The probable diagnosis time for

each piece of equipment has also been reduced due to the LED indicator that allows the number of times it flashes when reconnected to be identified. Only a comparison of times is made based on a previous report by the operator, along with the task to be performed and an adjacent situation, giving an inaccurate diagnosis of the possible cause.
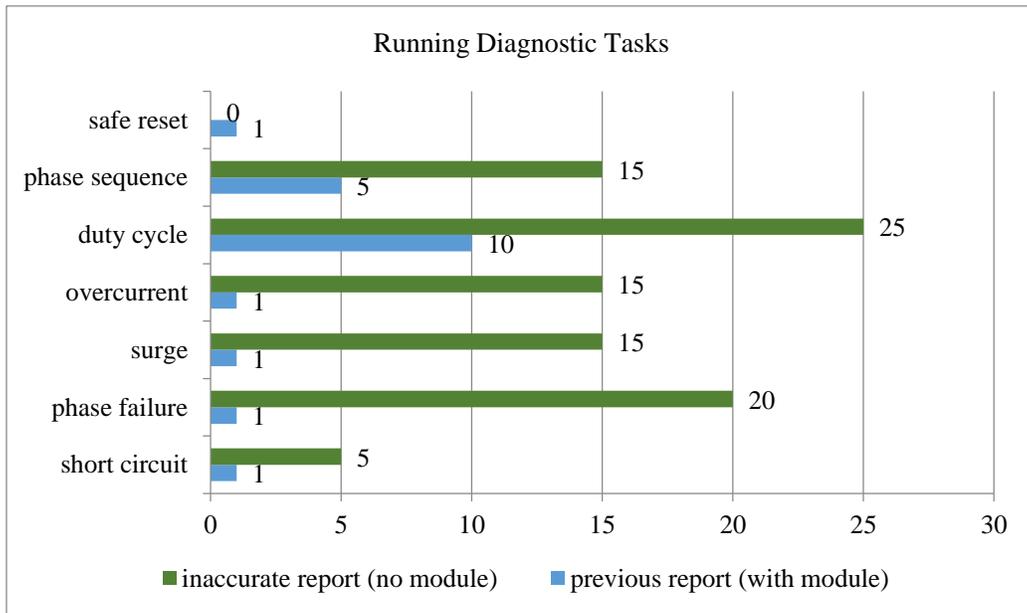

Fig. 11 Diagnostic runtime

Finally, the results show minor events, since the type of use of this equipment is not always routine or ideal for the application; that is, they are sometimes used for other purposes, exceeding their usual work cycle several times over. Due to these problems, adaptations were made to the equipment, such as soft start with capacitors to suppress a voltage spike that causes the inertia breakage of single-phase motors in hand tools, and snubber filters for three-phase contactors and rotation selectors.

6. Conclusion

The development and implementation of electronic protection, voltage monitoring, and a safe reset module proved to be an effective and necessary solution for improving operational safety in industrial environments and workshops in the metalworking sector. Experimental results and field studies showed an average reduction of 81.2% in incidents caused by uncontrolled ignitions, as well as a 92% decrease in diagnostic time, thus increasing productivity and reducing downtime due to inspections of industrial equipment and tools caused by shutdowns for maintenance. The module also contributes to compliance with international electrical safety standards (IEC 60204-1 and NTP IEC 60364), promoting the adoption of smart, low-cost technologies in the industrial sector. Its compact design, reliability, and easy integration position it as a viable, economical, and highly reliable alternative to traditional systems that are unsafe and lack controlled resetting.

In conclusion, the electronic protection, monitoring, and safe reset module developed represents a significant technological advance in industrial electrical protection, integrating compact SMD electronics for safety, efficiency, and operational reliability. Its implementation makes a difference in terms of reducing minor and serious workplace incidents, as well as protecting assets such as production and industrial safety in accordance with international safety regulations. Its design promotes future developments aimed at predictive maintenance and the digitization of electrical and electronic equipment.

Acknowledgments

References

[1] Mingda Zhai et al., "A Safety Evaluation method based on Gating Model and Generalized Zero-Shot Learning for Industrial Process," *Reliability Engineering & System Safety*, vol. 265, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[2] Arslan Zahid et al., "Exploring the Role of Digital Twin and Industrial Metaverse Technologies in Enhancing Occupational Health and Safety in Manufacturing," *Applied Sciences*, vol. 15, no. 15, pp. 1-51, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[3] Yuxuan Li et al., "A Safe and Fast Closed-Loop Start-Up Strategy for Triple-Active-Bridge Converters under DC Microgrip Application," *IEEE Transactions on Power Electronics*, vol. 40, no. 9, pp. 12676-12689, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Janine Hoelscher et al., "Safe Start Regions for Medical Steerable Needle Automation," *IEEE Transactions on Robotics*, vol. 41, pp. 2424-2440, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[5] Dong Liu et al., "Model-Free Adaptive Optimal Control for Fast and Safe Start-Up of Pumped Storage Hydropower Units," *Journal of Energy Storage*, vol. 87, pp. 1-29, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Julio Garrido Campos et al., "Integrated Simulation and Control Environment for the Development and Safe Start-Up of Cable Driven Parallel Robots," *International Journal of Computer Integrated Manufacturing*, vol. 38, no. 7, pp. 876-892, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[7] Rajesh Tanna et al., "Detecting Safe Operational Regimes of Synchronous Motor-Generator Pair for Wind Integration: A Non-Linear Perspective," *IET Energy Systems Integration*, vol. 5, no. 4, pp. 430-443, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] Jiangming Jia et al., "Fault Diagnosis Analysis of Angle Grinder based on ACD-DE and SVM Hybrid Algorithm," *Mathematics*, vol. 10, no. 8, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Zhenyu Liu et al., "Selection of the Optimal Scheme for the Conceptual Design of a Polisher Considering Multi-Source Uncertainties," *Journal of Mechanical Science and Technology*, vol. 38, no. 8, pp. 4261-4276, 2024. [CrossRef] [Google Scholar] [Publisher Link]