INTELLIGENT MONITORING AND DIFFERENTIAL PROTECTION SYSTEMS FOR ELECTROCUTION PREVENTION IN MODERN ELECTRICAL INSTALLATIONS

Master's Student **Daria IONESCU,** University of Petroșani, daria.ionescu20@yahoo.com
Drd. Eng. **Dan Cristian LAZAR,** University of Petroșani, Dan-CristianLazar@upet.ro
Associate Professor PhD Eng. Adina TATAR, University "Constantin Brâncusi" of Târgu Jiu, adynatatar@gmail.com
Associate Professor PhD Eng. **Dragos PASCULESCU,** University of Petroșani, DragosPasculescu@upet.ro
Lecturer PhD Eng. **Teodora LAZAR,** University of Petroșani, TeodoraLazar@upet.ro

Abstract: *This paper proposes a technological transition in the field of electrical safety, shifting from purely reactive protection systems (RCD, MCB) to an intelligent mechatronic architecture capable of active diagnosis and prevention. Although classic residual current devices provide essential protection against electrocution, they present critical limitations caused by the lack of visual feedback and the inability to detect low-level leakage currents that precede insulation degradation. To overcome these barriers, we developed a digitized system based on a high-frequency sampled microcontroller that continuously monitors the residual current and classifies it into three risk tiers (Nominal Safety, Preventive Maintenance, and Imminent Danger). Experimental results demonstrate that the proposed prototype not only instantly isolates the circuit in under 30 ms upon exceeding the critical 30 mA threshold, but also introduces the concept of predictive maintenance through its OLED interface and acoustic alerts. This pre-alarm functionality prevents unplanned technological downtime and optimizes service interventions in industrial environments, transforming electrical safety from a last-resort mechanism into a transparent and manageable process.*

Keywords: differential protection, residual current, predictive maintenance, electrical safety, electrocution prevention, microcontroller, RCD

1. INTRODUCTION

Electrical safety represents a vital component in the design and operation of any modern infrastructure, whether referring to residential spaces or industrial complexes. Despite the remarkable technological progress of recent decades, the risk of electrocution remains a constant threat, often underestimated until the moment an incident occurs. Current statistics indicate that a significant proportion of fires and workplace accidents originate from insulation faults that remain "invisible" to conventional protection systems. This reality highlights a critical gap in electrical safety: most current devices are designed to protect equipment and wiring against fires caused by overcurrent, often neglecting the fine intensity thresholds that can be lethal to the human body [1].

The evolution of safety measures has gone through several stages, from simple fuses to the residual current devices (RCDs) found today in electrical distribution panels. However, there is a fundamental distinction between passive and active protection. While classic systems are reactive, intervening only when a major fault has already occurred, current technology allows us to transition towards proactive risk management. Table 1 summarizes this technological transformation, highlighting the necessity of shifting towards digitized solutions [2].

Table 1. Evolution of Protection Methods in Installations

Generation	Dominant Technology	Protection Type	Main Limitations
Generation 1	Fuses	Passive	Exclusively protects wiring; slow reaction time.
Generation 2	Miniature Circuit Breakers (MCB)	Passive	Reacts only to short circuits; insensitive to small leakages.
Generation 3	Classic Residual Current Devices (RCD)	Reactive	Trips after fault occurrence; provides no status data.
Generation 4	Smart Digital Systems	Active / Preventive	Real-time monitoring; early warning and diagnostics.

The central objective of this paper is to develop an advanced monitoring system that eliminates the "blind" nature of traditional protections. We aim to demonstrate how, through the integration of high-precision current sensors and digital processing logic, we can detect insulation degradation in its incipient stages.

Thus, the scope of this work is not limited merely to emergency power disconnection, but aims to create an intelligent interface that informs the user regarding the real status of the installation, transforming electrical safety from a hidden mechanism into a transparent and predictive process [3], [4].

2. PHYSIOLOGY OF ELECTROCUTION AND CRITICAL PARAMETERS

Understanding the mechanisms by which electric current interacts with the human body is essential for establishing the foundation of any protection system. The human body, being a medium composed largely of electrolytic solutions, behaves as a complex conductor whose integrity is severely compromised when traversed by an external flow of electrons. The severity of this phenomenon is not determined by a single variable, but rather by a critical combination of current intensity, duration of exposure, and the current path through the body. The most severe incidents are those in which the current crosses the cardiac axis or the respiratory center.

2.1. Dynamics of Hazard Thresholds

The physiological effects of low-frequency alternating current (50 Hz) manifest gradually as its intensity increases. At very low levels, ranging between 0.5 and 1.5 mA, we encounter the perception threshold, characterized by mild tingling sensations which, although biologically harmless, can trigger dangerous startle reactions. Transitioning to the 10 – 15 mA range marks a critical point: the tetanization threshold (or the "let-go" threshold). At this stage, the electric current seizes control of the muscular system, causing involuntary contractions that prevent the victim from releasing their grip on the live source [5].

If the intensity continues to rise towards values of 20 – 30 mA, respiratory difficulties occur due to the contraction of the thoracic muscles. This is also the standard sensitivity threshold ($I_{\Delta n}$) at which residual current protection devices are calibrated to intervene. Beyond the 50 mA level, the organism enters the zone of imminent lethal risk, where ventricular fibrillation can be triggered. This condition represents a total disruption of the cardiac rhythm, causing the heart to cease pumping blood, which leads to death in the absence of immediate medical intervention [6].

2.2. Body Impedance and the Role of Environmental Factors

To quantify the actual risk in a fault situation, we must analyze the human body through the lens of fundamental electrotechnical laws. According to the specialized literature, the intensity of the current flowing through the body, termed touch current (I_b), is determined by the ratio between the touch voltage (U_C) and the total human body impedance (Z_B):

$$I_b = \frac{U_C}{Z_B} \tag{1}$$

where:

- I_b (Body Current): The current flowing through the human body.
- U_C (Touch Voltage): The voltage appearing between simultaneously accessible parts during a fault.
- Z_B (Total Impedance of the human body): The sum of internal resistance and skin impedance.

The impedance Z_B is not a fixed value, but a variable parameter heavily influenced by the condition of the epidermis and environmental factors. While dry skin offers considerable resistance, the presence of moisture drastically reduces this natural barrier, allowing the flow of currents that significantly exceed survival thresholds. Table 2 summarizes the impact of these variations on user safety [7].

Table 2. Variation of touch current I_b depending on environmental conditions (U_C = 230 V)

Skin Condition / Environment	Typical Impedance (Z_B)	Touch Curren (I_b)	Estimated Physiological Effect
Dry skin	5000 Ω	46 mA	Muscle contractions, fibrillation threshold
Wet skin	1500 Ω	153 mA	Definite ventricular fibrillation
Wet environment (immersion)	800 Ω	287 mA	Instantaneous cardio-respiratory arrest

This mathematical demonstration highlights the extreme vulnerability of the user, particularly in high-humidity environments. Since the touch current in these cases instantaneously exceeds the fibrillation threshold, it becomes evident that a protection system based on classic magnetothermal circuit breakers—designed to protect circuits against overcurrents on the order of amperes—is ineffective for saving human lives. Consequently, there is a vital need for a technology capable of monitoring these residual currents on the order of milliamperes and interrupting the power supply within a timeframe of milliseconds [8].

3. CURRENT PROTECTION TECHNOLOGIES (RCD)

To counteract the risks analyzed previously, electrical engineering developed the Residual Current Device (RCD). Currently, it represents the most effective barrier against electrocution via direct and indirect contact; however, despite its utility, it presents significant technological limitations within the context of an intelligent infrastructure [9].

3.1. Operating Principle of the RCD

The operation of an RCD is based on the continuous monitoring of the magnetic balance between the phase and neutral conductors. In an electrical installation in perfect working condition, according to Kirchhoff's circuit laws, the vector sum of the currents entering and leaving a circuit must be zero:

$$\sum I = I_L + I_N = I_\Delta \tag{2}$$

where:

- I_L- Line current (Phase).
- I_N - Neutral current.
- I_Δ - Residual Current (Differential current)

In a healthy circuit, $I_\Delta = 0$. In a fault condition (leakage), $I_\Delta \neq 0$. If I_Δ exceeds the rated residual operating current ($I_{\Delta n}$), typically **30 mA**, the device trips.

At the moment an insulation fault occurs or a person touches a live component, a portion of the current leaks to ground. This "fault current" (I_Δ) creates an imbalance within the device's measuring toroidal transformer. The resulting magnetic flux induces a voltage in a secondary winding which, if it exceeds the design threshold (typically 30 mA), triggers an electromagnetic release mechanism that interrupts the power supply in less than 40 ms [10], [11].

3.2. Limitations of Classic Electromechanical Systems

Although the electromechanical RCD is a robust and reliable device, it remains a "mute" and reactive instrument, presenting a series of disadvantages in modern operation:

- **Lack of visual feedback:** The device has only two states: ON (coupled) or OFF (tripped). The user has no information regarding the "health" of the installation. It is impossible to know whether the system is on the verge of tripping (e.g., a 25 mA leakage) or if the insulation is perfect.
- **Inability to detect slow degradation:** Cable insulation does not always fail abruptly. Moisture, conductive dust, or polymer aging produce gradual increases in the residual current. A classic RCD will ignore these signs until the critical threshold is reached, causing a sudden power interruption, which can be critical in certain processes.
- **Vulnerability to non-linear loads:** Many modern devices (switched-mode power supplies, dimmers) can generate fault currents with direct current or high-frequency components that can "blind" an AC-type RCD, rendering it incapable of tripping in the event of a real danger [12].

Table 3. Comparative analysis of operating states

Installation Status	Residual Current (I_Δ)	Classic RCD Reaction	Monitoring Need
Optimal	< 5 mA	No reaction	Visual confirmation of safety
Slight degradation	10 - 20 mA	Ignores the fault	Preventive alert for maintenance
Critical Threshold	30 mA	Sudden tripping	Emergency protection action

In conclusion, current systems are designed to save lives at the moment of the accident, but they do nothing to prevent it or to provide data regarding the status of the installation. This technological barrier necessitates the transition towards an active monitoring system, capable of transforming a protection device into an intelligent diagnostic instrument.

4. DESIGN OF THE "SMART" MONITORING SYSTEM

The innovative proposal of this paper consists of transforming differential protection from a purely reactive mechanism into an intelligent mechatronic architecture capable of preventive diagnostics. The core of this prototype lies in the harmonious integration of high-precision data acquisition and digital processing, a process that enables the visualization and management of electrocution risks before they reach lethal thresholds [13].

4.1. Hardware Architecture of the Prototype

The system is designed on a modular structure, where the data flow begins with the direct monitoring of the low-voltage network. The central acquisition element is represented by a high-sensitivity current sensor (based on the Hall effect or a toroidal transformer), capable of detecting the magnetic imbalance between the phase and neutral conductors. Unlike classic systems, this sensor delivers an analog signal proportional to the value of the residual current (I_{Δ}), providing a resolution on the order of milliamperes.

This signal is transmitted to the processing unit — a high-frequency sampled microcontroller — which interprets the data and coordinates the warning and execution peripherals. This architecture, detailed in Figure 1 below, highlights the connection between the power section of the installation and the low-voltage control logic, while also illustrating the continuous monitoring loop [14].

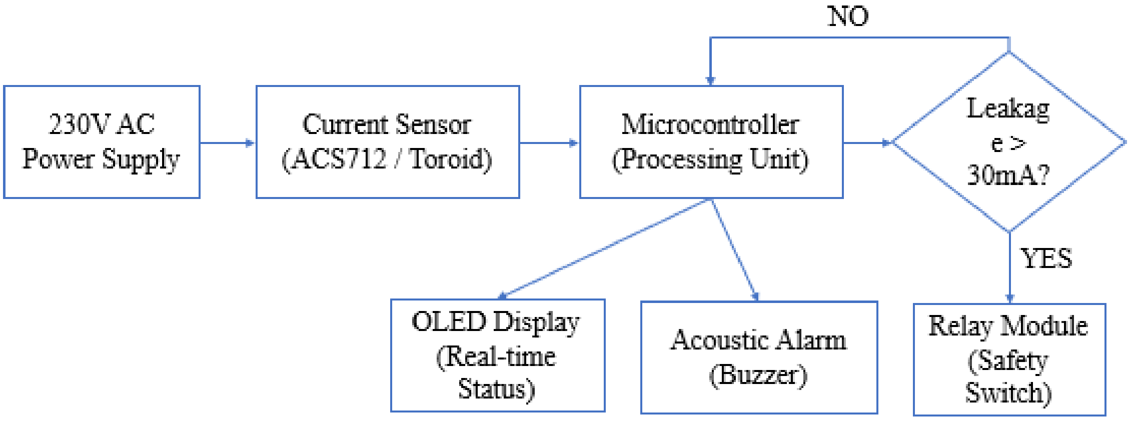

Figure 1. Block diagram of the information and decision flow for the Smart-RCD system

The user interface is implemented using an OLED display and an acoustic warning device (buzzer), elements that eliminate the "mute" nature of traditional electrical switchboards. In the final stage, the system features a power relay module, which acts as an actuating element capable of isolating the load from the power supply upon the detection of an imminent hazard [15].

To provide a comprehensive overview of the hardware resources utilized in the implementation of the prototype, the main components and their specific roles within the mechatronic ecosystem are summarized in Table 4.

Table 4. Specifications of the Smart system components

Component	Model/Type	Functional Role
Current sensor	ACS712 / Toroid	Transformation of the residual current into an analog signal.
Processing unit	Microcontroller (e.g., ESP32)	ADC acquisition, sampling, and logical analysis.
Visual Interface	I2C OLED Screen	Displaying the I_Δ value and status messages.
Actuating Element	5V/230V Relay Module	Automatic load disconnection upon fault detection

4.2. Software Logic and Monitoring Algorithm

The software novelty lies in the algorithm's capability to segment risk according to the severity of the detected leakage. Instead of ignoring the fault until the critical threshold is reached, the microcontroller processes the signal through digital filters to eliminate network noise and categorizes the I_Δ value into three distinct safety tiers:

- **Green Tier (Nominal Safety):** For values of $I_\Delta < 5$ mA, the system confirms insulation integrity, providing the user with psychological comfort currently non-existent in standard electrical installations.
- **Yellow Tier (Preventive Maintenance):** In the $10 \text{ mA} \le I_\Delta \le 20$ mA range, the system activates acoustic and visual warnings. This tier is crucial as it signals incipient insulation degradation or a hazardous presence of moisture, allowing for human intervention before an electric shock occurs.
- **Red Tier (Imminent Danger): $I_\Delta \geq 30$ mA**, the algorithm identifies an imminent risk of ventricular fibrillation. At this moment, the microcontroller commands the instantaneous tripping of the relay, interrupting the power supply within time parameters compliant with international safety standards [16].

To provide a clear visual perspective on how the algorithm evaluates and segments risk, this decision logic is illustrated in Figure 2. The risk scale highlights the dynamic transition of the system's operational states, which is directly proportional to the intensity of the fault current—ranging from the confirmation of optimal insulation, through the preventive warning stage, to the execution of the critical disconnection command.

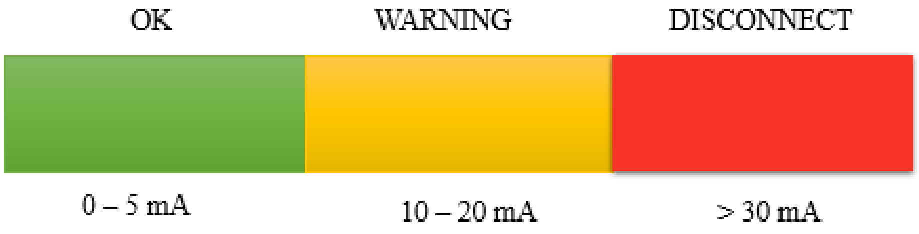

Figure 2. Graphical representation of the risk tiers and monitoring algorithm decisions

Through this approach, the proposed system does not merely "save" lives at the last second, but transforms electrical safety into a visible and manageable process, granting the user the opportunity to intervene in the installation before a critical fault occurs.

5. COMPARATIVE STUDY AND EXPERIMENTAL RESULTS

To validate the performance of the prototype and the efficiency of the proposed monitoring algorithm, the system was subjected to a set of rigorous experimental tests.

The primary objective was to evaluate the reaction speed and the preventive diagnostic capability in comparison with the known limitations of miniature circuit breakers (MCB) and classic residual current devices (RCD) [17].

5.1. Testing Methodology and Response Times

The testing was conducted through the controlled simulation of insulation faults. Using a set of variable resistors introduced into the test circuit, leakage currents (I_{Δ}) of predetermined values were generated, thus simulating the gradual degradation of an installation.

The system was monitored to record the elapsed time between reaching the critical threshold and the physical opening of the power relay contacts.

The obtained data were compared with the tripping standards of commercial equipment, with the results summarized in Table 5. It is observed that the classic 16 A circuit breaker is completely insensitive to lethal currents on the order of milliamperes, while the proposed system reacts within optimal safety parameters.

Table 5. Comparative analysis of reaction times to fault currents

Simulated Leakage Current	Siguranță Clasică (MCB 16A)	RCD Standard (30mA)	Sistemul Smart Propus
15 mA (Insulation degradation)	Does not trip	Does not trip	OLED Warning + Audible alarm
35 mA (Electrocution hazard)	Does not trip	Trips in ≈ 40 ms	Relay disconnection in < 30 ms
500 mA (Massive leakage)	Does not trip	Trips in ≈ 20 ms	Relay disconnection in < 15 ms

5.2. Graphical Analysis of Tripping Performance

To visually illustrate this superiority, the tripping performance of the systems has been transposed into Figure 3. The graph clearly highlights the three logical operating zones of the Smart system (Safety, Alarm, Disconnection) overlaid on the time-current curves.

It is observed that, unlike a classic miniature circuit breaker (MCB 16A)—which requires currents on the order of thousands of milliamperes to trip, placing it entirely outside the physiological safety scale—and compared to a standard RCD that acts at approximately 40 ms, the proposed prototype instantaneously isolates the circuit in under 30 ms upon reaching the critical threshold.

Furthermore, the representation emphasizes the added value of the "Alarm" zone (Yellow Tier), demonstrating the existence of a prevention window that is completely absent in traditional protection diagrams [18], [19].

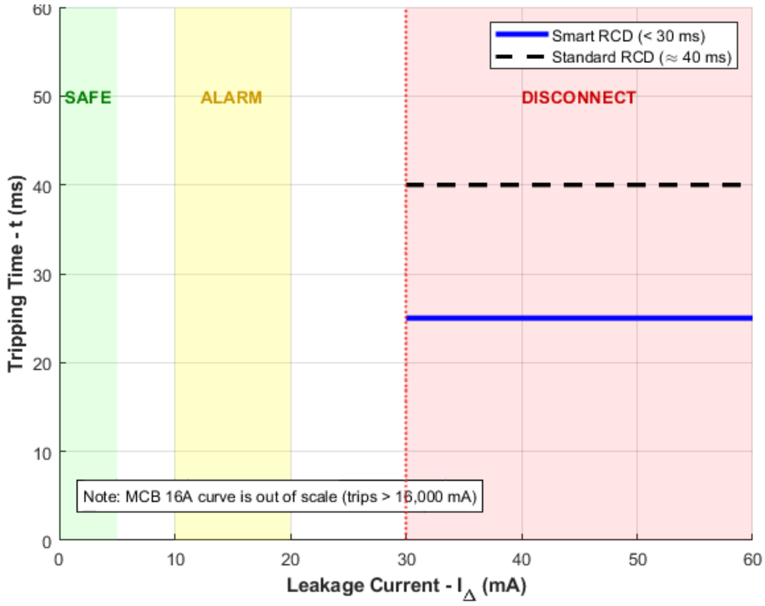

Figure 3. Comparison between tripping curves: Smart System vs. Conventional Protection

5.3. The Role of Prevention: Diagnosis via OLED Interface and Predictive Maintenance

Moving beyond simple reaction speed, the most significant experimental advantage observed was the utility of the visual interface in the transition toward predictive maintenance. In a testing scenario simulating the operation of industrial equipment (e.g., a driving electric motor or a recirculation pump) whose insulation is progressively degraded due to moisture and a corrosive working environment, a classic RCD proved limited [20], [21]. It would have allowed the equipment to operate without any warning until reaching the 30 mA critical threshold, causing an accidental and unplanned shutdown of the technological process (downtime) and exposing the operator to imminent risk upon touching the metallic casing [19].

In contrast, the Smart system assumed the role of an active diagnostic tool. As environmental factors generated leakage currents of 12 mA, the OLED screen immediately displayed the transition to the "Yellow Tier," accompanied by an intermittent audible alert. This functionality practically demonstrates how the interface assists maintenance personnel in identifying an incipient insulation fault before it becomes a lethal hazard or generates a destructive short circuit [22], [23]. Consequently, maintenance becomes predictive: the equipment can be decoupled in a controlled manner and repaired safely, avoiding both the risk of injury and unscheduled interruptions in the technological flow, which involve significant economic losses.

6. CONCLUSIONS AND PERSPECTIVES

This paper has demonstrated that the transition from a purely reactive (mechanical) protection mechanism to a digitalized mechatronic architecture represents a necessary evolution in the field of electrical safety. By integrating microcontrollers and low-voltage signal processing, the digitalization of electrical protection redefines safety standards, eliminating the "blind spot" of classic equipment regarding lethal fault currents.

The main contributions and advantages of the proposed system can be summarized as follows:

- Increased safety through prevention: Unlike a standard residual current device, the

Smart system transforms protection from a last-resort process into an active diagnostic tool. The real-time display of insulation degradation enables human intervention before a short circuit or electric shock occurs.

- Economic efficiency and modularity (Retrofit): From a practical and commercial perspective, the proposed prototype is highly cost-effective. Due to its modular architecture, it does not require the replacement of the existing power infrastructure and can be easily implemented as an extension (retrofit module) in residential or industrial electrical panels already in service.
- Facilitation of predictive maintenance: In industrial environments, early warning (the Yellow Tier) prevents untimely trippings and unscheduled shutdowns of the technological flow, significantly reducing economic losses associated with downtime.

As future research directions, the prototype can be expanded by integrating a wireless communication module (e.g., Wi-Fi / LoRa), enabling data transmission to Cloud platforms or SCADA systems. Thus, the Smart-RCD system could integrate seamlessly into Smart Home and Smart Grid ecosystems, facilitating fault history recording (data logging) and the remote alerting of maintenance teams directly on mobile devices.

7. REFERENCES:

[1]. **Pasculescu, D., Lupu, L., Pasculescu, V., Inisconi, I., & Suvar, M.**, *Study of electrocution hazards in three-phase electrical networks with ground-isolated neutral point*. Environmental Engineering and Management Journal, 11(7), 1267-1271, 2012.

[2]. **Pasculescu, D., Fita, D. N., Popescu, F. G., Grigorie, E., Lazar, T., Pupaza, C.,** *Risks assessment in terms of electrical safety for power substation from national power grid.* Research Developments in Science and Technology, 4, 1-28, 2022.

[3]. **Riurean, S., Fîță, N. D., Păsculescu, D., & Slușariuc, R.**, *Securing Photovoltaic Systems as Critical Infrastructure: A Multi-Layered Assessment of Risk, Safety, and Cybersecurity*. Sustainability, 17(10), 4397, 2025.

[4]. **Pasculescu, D., Riurean, S., Ilieva-Obretenova, M., Lazar, T., Tatar, A. M., & Fita, N. D.,** *Intelligent modeling of PV–BESS microgrids for enhanced stability, cyber–physical resilience and blackout prevention*. Energies, 19(1), 148, 2026.

[5]. **Malina, V. D., Andraş, A**., *Critical minerals in the context of the energy, green and digital transition: implications for sustainable development and applied research*. Annals of the University of Petrosani Mechanical Engineering, 27, 2025.

[6]. **Dragos Pasculescu, Sorin Mihai Radu, Teodora Lazar**, *Management energetique*, ISBN: 978-2-487467-00-2, Edition DUMAS, 2025.

[7]. **Lazăr, D. C., Petrilean, D. C., Păsculescu, D., Lazăr, T., Mija, N.**, *Smart Utilization Of Electrical Energy In Industry Using Iot Sensors And Machine Learning*, Fiability & Durability/Fiabilitate si Durabilitate, 35(1), 2025.

[8]. **Pasculescu Dragos, Lazar Teodora, Popescu Florin Gabriel**, *Electrical Risks Prevention*, ISBN: 978-620-7-80874-8, LAP LAMBERT Academic Publishing, 2024.

[9]. **Lazar, D. C., Petrilean, D. C., Lazar, T., Popescu, F. G., Ionescu, D., Tatar, A. M., Buica, G., Pasculescu, D.**, *Real-Time Energy System Optimization and Resilience Analysis in*

Low-Voltage Networks Using Intelligent Edge Computing. Processes, 14(4), 660, 2026.

[10]. **Dragos Pasculescu, Remus Dobra and Mohammad Ayaz**, "*Dosimetric Quantity System for Electromagnetic Fields Bio-effects*", International Journal of Scientific Research (IJSR) 5.2, pp. 28-32, 2016.

[11]. **Andras, A., Popescu, F. D., Radu, S. M., Pasculescu, D., Brinas, I., Radu, M. A., Peagu, D.,** *Numerical simulation and modeling of mechano–electro–thermal behavior of electrical contact using comsol multiphysics*. Applied Sciences, 14(10), 4026, 2024.

[12]. **Pasculescu, D., T. Niculescu, and L. Pana.**, "*Uses of Matlab software to size intrinsic safety barriers of the electric equipment intended for use in atmospheres with explosion hazard*" International Conference on Energy and Environment Technologies and Equipment (EEETE'10),"Politehnica" Univ.Bucharest, Pub. by WSEAS Press ISSN. Vol.5095.1790, 2010.

[13]. **Lazăr, D. C., Petrilean, D. C., Utu, I., Tătar, A., Pasculescu, D., Lazăr, T.**, *Optimizing Energy Consumption In Smart Homes With Iot And Home Assistant*, Annals of'Constantin Brancusi'University of Targu-Jiu. Engineering Series/Analele Universităţii Constantin Brâncuşi din Târgu-Jiu. Seria Inginerie, (2), 2024.

[14]. **Arad, Susana, et al.** "*Aspects of the electric arc furnace control.*", Proceedings of the International Symposium on Advanced Engineering & Applied Management, Hunedoara, Romania, 2010.

[15]. **Fîţă, N. D., et al**., "*Security risks assessment on the 400/275/25 kV Elvanfoot power substation from Scotland in order to ensure resilience and energy security.*", 2023 International Conference on Electrical, Computer and Energy Technologies (ICECET). IEEE, 2023.

[16]. **Pasculescu, V. M., Radu, S. M., Pasculescu, D., & Niculescu, T.,** *Dimensioning the intrinsic safety barriers of electrical equipment intended to be used in potentially explosive atmospheres using the SimPowerSystems software package*, International Multidisciplinary Scientific GeoConference: SGEM, 1, 417, 2013.

[17]. **Fîță, N. D., Marcu, M. D., Utu, I., Pasculescu, D., Popescu, F. G., Lazăr, T.,** *Critical analysis of the 220/110/20 kV Sardanesti power substation from Romania in the context of identification elements of instability and insecurity.,* International Conference on Artificial Intelligence, Computer, Data Sciences and Applications (ACDSA) (pp. 1-6). IEEE, 2024.

[18]. **Lazar, T., Ionescu, D., Lazar, D. C., Popescu, F. G., Tatar, A. M., Buica, G., Pasculescu, D.,** *Impact of Triplen Harmonics Generated by Modern Non-Linear Loads on Neutral Conductor Overheating in Low-Voltage Smart Buildings*. Energies, 19(7), 1743, 2026.

[19]. **Popescu, Florin Gabriel, et al.**, „*Principles of effective energy management and power control system*", Annals of the Univ. of Petrosani, Electrical Engineering, 24: 111-118, 2022.

[20]. **Lazăr, T., Marcu, M.D., Uțu, I., Popescu, F.G. and Păsculescu, D.**, „*Mașini electrice - culegere de probleme*", 2023.

[21]. **Popescu, Florin Gabriel, et al.** „*Analysis of filtering and correction of the power factor in distorted balance*", Annals of Univ. of Petrosani, Electrical Engineering, 23: 77-82, 2021.

[22]. **Petrilean D. C.**, *Transmiterea căldurii*, Editura Universitas, 2016.

[23]. **Pasculescu, Dragos, et al.**, „*Modeling and simulation of lighting of a road with 2 strips per direction to en 13201: 2015 Standard*", Annals of the University of Petrosani, Electrical Engineering, 24: 65-74, 2022.