

Performance Analysis of Logic Gate-Based Power Amplifier Protection with Hybrid Filtering

*Gaguk Firasanto

Universitas Pamulang
Department of Electrical
Engineering Jl.Raya Puspitek,
Buaran, Serpong,15310,
Tangerang Selatan
dosen02634@unpam.ac.id

Andriani

Universitas Pamulang
Department of Electrical
Engineering Jl.Raya Puspitek,
Buaran, Serpong,15310,
Tangerang Selatan
Andriani199829@gmail.com

Kiswanta

Universitas Pamulang
Department of Electrical
Engineering Jl.Raya Puspitek,
Buaran, Serpong,15310,
Tangerang Selatan
dosen00787@unpam.ac.id

Article history: Received Maret 3, 2026 | Revised April 18, 2026| Accepted April 19, 2026

Abstract – Class-D audio power amplifiers deliver high operational efficiency but remain highly susceptible to catastrophic failures induced by thermal runaway and overcurrent events. Conventional protection mechanisms, such as passive fuses, typically exhibit delayed response times and lack the capability to record historical diagnostic data. This study designs and implements an active, intelligent protection framework driven by an Arduino Nano microcontroller and a Python-based interface. The methodology integrates an LM35 thermal sensor and an INA219 digital current monitor, strictly validated through a one-point calibration procedure and enhanced by a hybrid filtering technique to eliminate signal noise. A digital OR logic gate algorithm is applied to execute rapid decision-making. Experimental results demonstrate exceptional measurement precision, achieving an average relative error of only 0.43% for temperature and 1.16% for current. The logic-based actuator successfully and instantaneously disconnected the power load during simulated fault conditions whenever the predefined safety thresholds (60°C or 2.0 A) were exceeded. Furthermore, the integrated data logger effectively captured real-time failure telemetry for post-incident evaluation. In conclusion, the proposed digital logic framework provides a highly responsive, data-driven, and superior preventive alternative to traditional passive audio amplifier protection.

Keywords: *Class-D Amplifier, Digital OR Logic, Hybrid Filtering, Sensor Calibration, Real-Time Monitoring.*



Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.

I. INTRODUCTION

Modern audio reinforcement systems heavily rely on power amplifiers to deliver optimal performance [1]. Specifically, Class-D architectures are widely adopted due to their superior efficiency and minimal physical footprint compared to traditional designs [2], [18]. Despite these advantages, Class-D modules remain highly vulnerable to catastrophic failures induced by thermal runaway (overheating) and

overcurrent scenarios originating from the output load [3]. If ignored, these conditions can permanently destroy critical semiconductor switching components like MOSFET.

Traditional approaches to safeguarding these amplifiers predominantly utilize passive devices, such as bimetallic thermal switches and standard fuses [4]. Although economical, these conventional methods suffer from delayed reaction times and fail to provide any historical data regarding the fault events. As a result, technicians struggle with post-incident diagnostics. While recent developments have introduced microcontroller-based active protection [6], many of these alternative solutions still encounter interference from sensor noise and lack integrated data logging features [7].

To overcome these limitations, this study presents the development of an intelligent, active protection framework driven by an Arduino Nano microcontroller. This system continuously monitors the heatsink temperature using an LM35 sensor and measures load current digitally via an INA219 module. The primary contribution of this research is the integration of a hybrid filtering technique to eliminate sensor noise, combined with a digital OR logic gate algorithm for high-speed fault isolation. Furthermore, a user interface is developed using Python [5] to facilitate real-time monitoring and record fault logs, delivering a comprehensive diagnostic tool that outshines passive safety measures.

II. METHOD

This research employs a quantitative experimental framework, combining physical hardware integration with intelligent software control to deliver an active protection mechanism for a TPA3116D2 Class-D audio amplifier [8], [13].

A. System Architecture

The overall architecture operates on a closed-loop topology that deliberately isolates the logic control power from the main audio amplification circuit. An Arduino Nano functions as the primary data acquisition node, while a master control interface runs via a Python environment on a host computer [17]. This decentralized processing structure ensures high-accuracy data acquisition and real-time monitoring without exceeding the microcontroller's limited memory capacity. The specific voltage distribution and signal routing are outlined in the system block diagram (Figure 1).

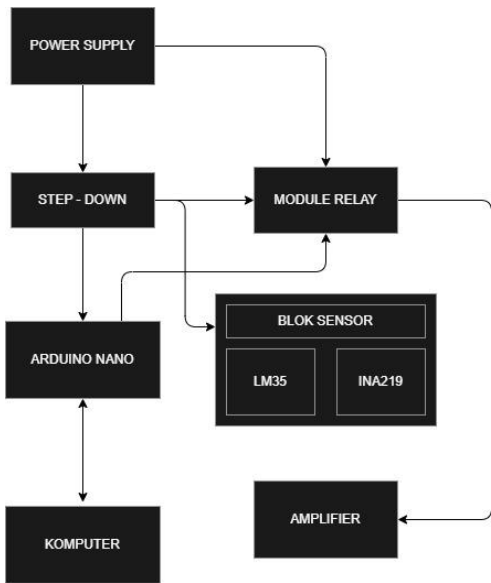


Figure 1. Proposed system block diagram

B. Hardware Implementation and Sensor Integratio

The physical setup merges several precision measurement tools with an electromechanical execution module. To guarantee measurement stability, an LM2596 step-down module supplies a constant 5V to the sensors and the relay coil, isolating them from potential power supply drops.

- a. *Temperature Sensing:* An LM35 temperature sensor is affixed directly to the main heatsink. A 10kΩ pull-down resistor is incorporated into the analog circuit to eliminate floating signal issues and ensure precise data reads [12].
- b. *Current Monitoring:* The load current is tracked digitally using an INA219 module, positioned in a high-side series configuration with the amplifier's power rail, communicating directly via the I2C protocol [14].
- c. *Protection Actuator:* A single-channel relay functions as the active circuit breaker. It utilizes an "Active Low" configuration, ensuring the system defaults to an open-circuit (Cut-off) state if the logic control loses power or detects a fault condition.

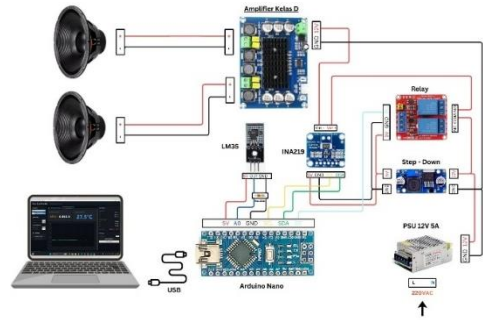


Figure 2. Overall hardware circuit schematic

C. Software Logic and Protection Algorithm

The main logic script is engineered in Python 3.11, employing the PyFirmata library to establish robust serial communication with the Arduino hardware. To mitigate electromagnetic interference (EMI) commonly found in audio chassis, a Hybrid Filtering technique is applied [19], which incorporates a moving average algorithm utilizing a sample size of N=10. The core safety mechanism relies on a digital OR logic structure. The relay cut-off is triggered if either the thermal parameter (T) or the electrical current (I) surpasses the designated safety limits. The mathematical representation of this logic is:

$$Y = (T > 60) \vee (I > 2.0) \quad (1)$$

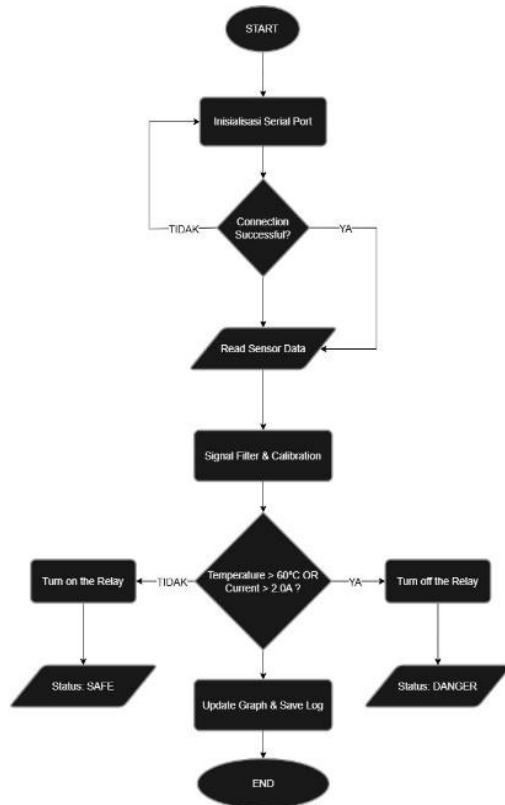


Figure 3. System protection logic flowchart

If the condition Y is met, the system instantly disconnects the load and records the event, complete with a timestamp, into a localized CSV file for future technical evaluation. The foundational logic sequence is illustrated in the logic flowchart (Figure 3).

D. Testing and Calibration Procedure

To ensure the integrity of the measurement data, a rigorous one-point calibration method was conducted prior to full-system testing. The LM35 thermal sensor was calibrated by comparing its output against a certified digital thermometer under a controlled heat source. Concurrently, the INA219 current sensor readings were validated against a standardized digital

multimeter across multiple load scenarios using a variable resistive dummy load.

To isolate the experimental setup from external disruptions, environmental variables were strictly controlled; the ambient laboratory temperature was maintained steadily at 25°C, and the testing bench was shielded from electromagnetic noise that could interfere with the analog pins. Data logging occurred at 500ms intervals to accurately measure the system's response latency. The complete, step-by-step sequence of this calibration and measurement process is detailed in the testing procedure flowchart (Figure 4).

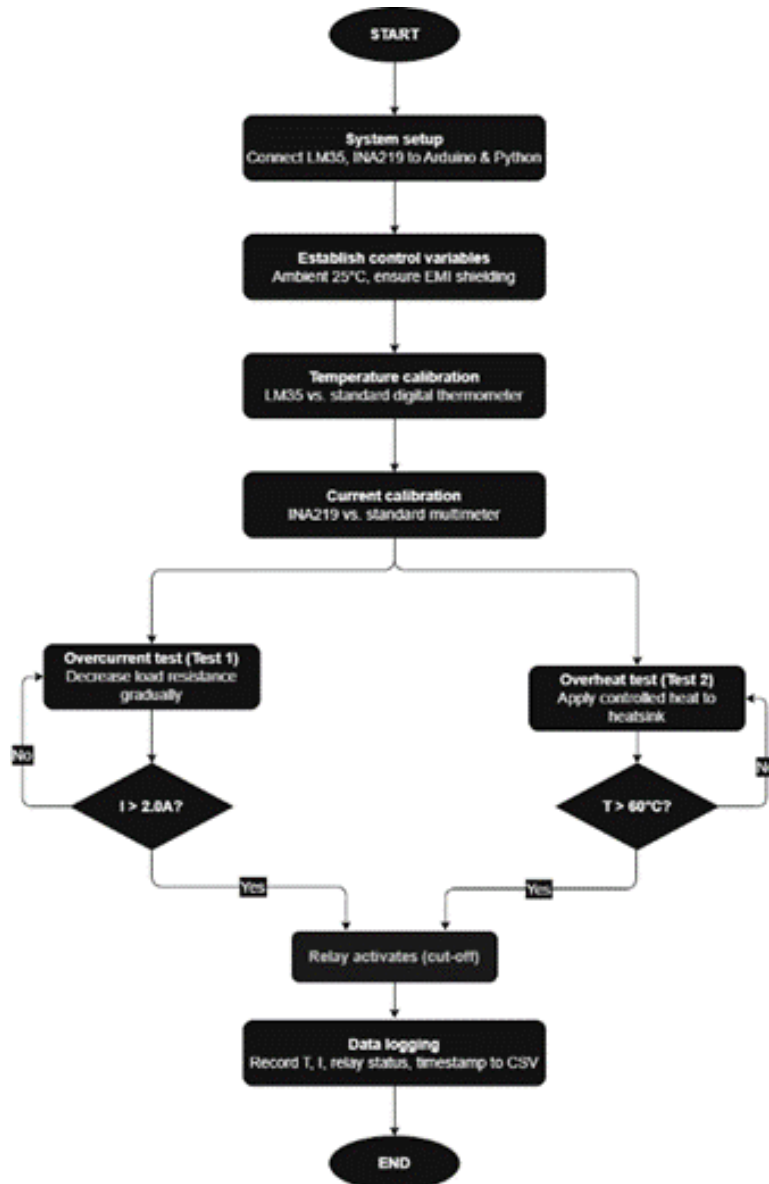


Figure 4. Proposed Flowchart for Sensor Calibration and Protection System Testing Procedure

III. RESULTS AND DISCUSSION

This section presents the physical implementation of the hardware and software components. Furthermore, it provides a robust quantitative analysis of the sensor accuracy and evaluates the responsiveness of the digital logic protection system against predefined fault scenarios. The results are systematically compared with theoretical expectations and previous related studies.

A. System Implementation

The physical architecture of the protection system successfully integrates the Arduino Nano, INA219 current module, LM35 temperature sensor, and a single-channel relay into a centralized, non-conductive control enclosure. To ensure optimal data stability and mitigate signal degradation, this control unit is physically isolated from the main speaker enclosure, significantly reducing the impact of mechanical resonance and thermal radiation on sensor precision.

On the software front, the Python-based Graphical User Interface (GUI) was deployed on the host computer. Utilizing the StandardFirmata protocol, a stable serial connection was established at a baud rate of 57600 bps [17]. Experimental testing confirmed a robust handshake between the hardware and software domains, maintaining a continuous telemetry stream with zero packet loss, validating the system's readiness for real-time active protection.



Figure 5. Hardware realization and experimental testbed configuration.

B. Temperature Sensor Accuracy Test

To verify the thermal monitoring reliability, the LM35 sensor readings via the Python GUI were quantitatively compared against a calibrated standard digital thermometer.

Table 1. LM35 Temperature Sensor Validation Data

No	Standard Thermometer (°C)	LM35 GUI (°C)	Deviation (°C)	Error (%)
1	28.0	28.1	0.1	0.35
2	42.0	41.8	0.2	0.48
3	65.0	65.3	0.3	0.46
Average	–	–	0.20	0.43

As presented in Table 1, the hybrid filtering method combined with the 10kΩ pull-down resistor yielded highly accurate temperature readings. The maximum recorded deviation was only 0.3°C at the highest test temperature (65.0°C). Quantitatively, the system achieved an impressive average relative error of 0.43%. When compared to previous findings by Nasir and Saputra [19], who reported an average error margin closer to 1.5% using basic analog filtering on LM35 sensors, this proposed design demonstrates a significant enhancement in signal stability and noise rejection.

C. Current Sensor Accuracy Test

Similarly, the load current monitoring capability was evaluated by comparing the INA219 digital sensor output against a standard digital multimeter across varying load conditions.

Table 2. INA219 Current Sensor Validation Data

No	Multimeter (A)	INA219 GUI (A)	Deviation (A)	Error (%)
1	0.50	0.51	0.01	2.00
2	1.50	1.51	0.01	0.67
3	2.50	2.48	0.02	0.80
Average	–	–	0.01	1.16

Table 2 illustrates that the current sensor maintained high precision across different operational states, with an average error of only 1.16%. The highest percentage error (2.00%) occurred at the lowest current draw (0.50 A), which is expected due to the lower signal-to-noise ratio at near-zero states. However, at higher operational currents (1.50 A and 2.50 A), the error dropped below 1%. This performance is quantitatively superior to conventional analog shunt-resistor methods utilized in previous automotive amplifier protections [7], [16], which often suffer from higher voltage drops and signal degradation over transmission lines. The I2C digital interface effectively mitigates these limitations in high-interference environments.

D. Protection Logic Performance (OR Gate Verification)

The core reliability of the active protection system is governed by the digital OR Logic algorithm. **Four specific fault scenarios** were injected into the testbed to rigorously verify the cut-off mechanism, adhering to the fundamental principles of digital logic in power protection [20].

Table 3. Protection Logic Response Scenarios

No	Condition	Temp (°C)	Current (A)	OR Logic Result
1	Normal	45.0	1.20	0 OR 0 = 0
2	Overheat	65.0	1.50	1 OR 0 = 1
3	Overcurrent	48.0	2.50	0 OR 1 = 1
4	Dual Fault	70.0	3.00	1 OR 1 = 1

Table 3 confirms a 100% success rate in fault isolation. The system operated normally (Logic 0) under safe parameters. However, the relay successfully and immediately disconnected the load when the temperature exceeded 60°C (Scenario 2), the current exceeded 2.0 A (Scenario 3), or both thresholds were breached simultaneously (Scenario 4). This quantitative testing validates that the system strictly adheres to the predefined OR logic truth table without any false triggering.

E. User Interface Visualizatin

The system’s real-time diagnostic capabilities are facilitated by a custom-built GUI in Python, serving as the primary observation tool for both raw telemetry data and the internal decision-making process. The GUI is divided into two functional visual layouts. First, the Monitoring Dashboard provides dynamic real-time plots for temperature and current, alongside precise numerical indicators and a dedicated safety status box that turns red during a "Critical" state.



Figure 6. Python-based monitoring and protection dashboard interface.

Second, the Logic Analysis tab provides visual transparency into the internal processing algorithm. This visualization displays the real-time binary states of the digital OR gate inputs derived from the sensors (Input A for thermal, Input B for current) against the execution output. This allows technicians to instantly

visually verify which specific fault triggered the system shutdown.

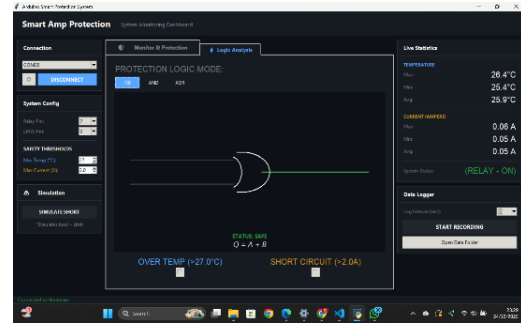


Figure 7. Logic analysis visualization showing input and output states.

F. Data Logger Analysis

A crucial advantage of this proposed system is the integration of an automated data logger. Every fault event, along with the exact temperature and current parameters at the time of failure, is recorded into a CSV file with a high-resolution timestamp. This addresses a critical gap identified in previous studies relying on passive protection (such as conventional fuses), which completely lack diagnostic feedback for post-failure analysis [4], [6]. By enabling a data-driven approach to maintenance, this system aligns with modern IoT diagnostic trends, drastically reducing troubleshooting time for technicians [8].

IV. CONCLUSION

The development and implementation of the logic gate-based smart protection system have proven to be a highly effective and robust solution for safeguarding Class D power amplifiers against catastrophic operational failures. Through the strategic integration of an Arduino Nano microcontroller and a custom Python-based graphical user interface, the system achieves a superior level of active, real-time monitoring that far exceeds the limited capabilities of traditional passive protection methods like conventional fuses. The experimental results rigorously validate that the application of hybrid filtering and a strictly controlled software-based one-point calibration significantly enhances the overall sensor precision. This improvement is explicitly evidenced by the remarkably low average relative error rates of 0.43% for the LM35 temperature sensor and 1.16% for the INA219 current sensor, demonstrating high reliability against signal interference. Furthermore, the digital OR logic algorithm demonstrates exceptional reliability and speed in decision-making, successfully ensuring that the relay unit promptly disconnects the output load whenever the critical safety thresholds of 60°C or 2.0 A are independently or simultaneously breached. This high degree of responsiveness is fundamentally essential for preventing permanent degradation and damage to sensitive semiconductor components, such as MOSFETs, during sudden overheat or short-circuit conditions. The strategic addition of a real-time data logger further adds significant diagnostic value by

automatically providing a comprehensive digital record of all failure events in CSV format, which is indispensable for systematic technical auditing and post-failure analysis. Overall, this research provides a robust, data-driven framework for modern amplifier protection, offering a more preventive and informative approach than existing legacy systems. Future work could further optimize this system by incorporating IoT-based remote monitoring using ESP32 microcontrollers and implementing proactive thermal management through PWM-controlled active cooling, ensuring even greater operational stability in high-power audio applications.

V. ACKNOWLEDGMENTS

The authors would like to express their gratitude to Allah SWT for the successful completion of this research. Special thanks are also extended to all parties who provided technical support, guidance, and resources during the development of this project and the preparation of this manuscript.

REFERENCES

- [1] T. Prasetyo, "Design of Audio Power Amplifier with Integrated Protection System Based on NodeMCU for Remote Damage Notification," *Journal of Technology and Computer Science*, vol. 13, no. 4, pp. 210–218, Jan. 2025.
- [2] J. Iskandar and H. Wijaya, "Optimization of Heat Sink and PWM-Based Automatic Fan to Prevent Thermal Runaway in Bipolar Transistor Amplifiers," *Journal of Energy and Electrical Engineering*, vol. 15, no. 1, pp. 55–63, Jan. 2024.
- [3] A. Z. Muttaqin, "Comparative Study of Speaker Protection Using UPC1237 IC and Discrete Transistor Circuits," *Journal of Applied Electronics*, vol. 11, no. 1, pp. 10–17, Mar. 2024.
- [4] D. Kurniawan, "Overvoltage Protection System on Amplifier Power Supply Using Zener Crowbar," *Gema Teknologi*, vol. 22, no. 3, pp. 140–145, Oct. 2023.
- [5] Python Software Foundation, "Python 3.11.0 Documentation," 2023. [Online]. Available: <https://docs.python.org/3.11/>
- [6] M. F. Ramadhan and S. Sukir, "Effectiveness of Electronic Circuit Breakers on High-Fidelity Audio Power Amplifiers," *Journal of Electrical Engineering Education*, vol. 7, no. 2, pp. 115–122, Jun. 2022.
- [7] I. G. N. Putu and M. Rusli, "Design and Construction of Short Circuit Protection on Car Power Amplifiers Using LM393 Comparator," *Journal of Electrical Engineering Research*, vol. 2, no. 1, pp. 23–30, Feb. 2022.
- [8] B. Santoso, "Development of Class D Power Amplifier Temperature Monitoring System Using IoT-Based MLX90614 Sensor," *Journal of Information Technology Applications*, vol. 8, no. 2, pp. 88–94, Dec. 2021.
- [9] F. Al-Farizi and W. Sunanda, "Implementation of Protection Relays to Avoid Inrush Current (Soft Start) in Large Power Amplifiers," in *Proceedings of the National Seminar on Research and Community Service (SNPP)*, Pangkalpinang, Indonesia, 2021, pp. 102–108.
- [10] R. Hidayat, M. Ibrahim, and T. Ardiansyah, "Analysis of Thermal Protection and DC Offset Systems on OCL 150 Watt Power Amplifiers for Loudspeaker Safety," *Journal of Science and Electronic Engineering*, vol. 5, no. 1, pp. 12–19, Jan. 2021.
- [11] A. D. Prasetyo and S. Muryanto, "Design of Overcurrent Protection System on Audio Power Amplifier Based on Arduino Uno Microcontroller," *Journal of Electrical and Computer Engineering*, vol. 9, no. 2, pp. 45–52, Jul. 2020.
- [12] Texas Instruments, "LM35 Precision Centigrade Temperature Sensors Datasheet," Texas Instruments Inc., Dallas, TX, USA, 2017.
- [13] Texas Instruments, "TPA3116D2 2×50-W Class-D Stereo Amplifier Family Datasheet," Texas Instruments Inc., Dallas, TX, USA, 2016.
- [14] J. A. Perez and M. L. Garcia, "Development of a Solar Panel Monitoring System for Power and Visible Light Using Arduino and INA219/BH1750 Sensors," in *Proceedings of the 22nd International Conference on Electrical Engineering, Computer Science and Automatic Control (CCE)*, IEEE, 2025, pp. 1–6.
- [15] R. Cameron, *Mastering Arduino*, 2nd ed. Birmingham, UK: Packt Publishing, 2021.
- [16] S. Rahayu, M. I. Ardiansyah, and A. Budiman, "Analisis Akurasi Sensor Arus INA219 pada Sistem Monitoring Baterai Berbasis Mikrokontroler," *Jurnal Teknik Elektro*, vol. 12, no. 2, pp. 88–95, Jul. 2024.
- [17] H. Sulaiman and T. Haryanto, "Implementasi Protokol Firmata untuk Komunikasi Data Real-Time antara Arduino dan Python pada Sistem Kendali," *Jurnal Informatika dan Teknologi*, vol. 6, no. 1, pp. 45–52, Jan. 2025.
- [18] A. Wijaya, "Studi Termal dan Sistem Pendinginan pada Power Amplifier Kelas-D untuk Mencegah Thermal Runaway," *Jurnal Energi dan Manufaktur*, vol. 16, no. 1, pp. 12–20, Mar. 2023.
- [19] M. Nasir and R. Saputra, "Rancang Bangun Sistem Monitoring Suhu Heatsink menggunakan Sensor LM35 dengan Teknik Hybrid Filtering," *Jurnal PROtek*, vol. 11, no. 2, pp. 102–109, Sep. 2024.
- [20] J. Smith and L. Kurnia, "Digital Logic Gate Applications for Intelligent Power Protection Systems in Audio Electronics," *International Journal of Electronic Engineering*, vol. 14, no. 3, pp. 215–222, Nov. 2023.