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Optimizing Energy Use In An Open-Source Firmware Integrated Router Network Using The PID Method

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ABSTRACT

This research designs and implements a real-time power consumption control system on an OpenWRT-based MikroTik hAP ac² router using a PID Controller on an ESP32 microcontroller. The system utilizes the INA219 sensor to precisely measure power consumption and accesses network parameters such as throughput, latency, and the number of active users through the Open-WRT module to adjust power control to network conditions. The research method was carried out by testing nine PID parameter configurations and one uncontrolled configuration for comparison. Each configuration was tested under various network load scenarios, with power consumption and network performance data continuously recorded. The analysis was conducted using ITAE (Integral Time Absolute Error) calculations to evaluate control quality, and ANOVA statistical testing to determine the significance of differences between configurations. The test results showed that the optimal PID con-figuration (Kp = 1,5; Ki = 0,5; Kd = 0,2) was able to reduce average power consumption to 7,418 W with an ITAE of 2.419 and stable throughput. This research provides an effective contribution for implementation in small-to-medium scale energy-efficient networks.

ABSTRAK

Penelitian ini merancang dan mengimplementasikan sistem pengendalian konsumsi daya secara *real-time* pada router MikroTik hAP ac² berbasis *Open-WRT* dengan menggunakan PID *Controller* pada mikrokontroler ESP32. Sistem memanfaatkan sensor INA219 untuk mengukur konsumsi daya secara presisi, serta mengakses parameter jaringan seperti *throughput*, latensi, dan jumlah pengguna aktif melalui modul *OpenWRT* agar pengendalian daya dapat menyesuaikan kondisi jaringan. Metode yang digunakan adalah eksperimen dengan menguji sembilan konfigurasi parameter PID dan satu konfigurasi tanpa kendali sebagai pembanding. Setiap konfigurasi diuji pada berbagai skenario beban jaringan, dengan data konsumsi daya dan performa jaringan direkam secara kontinu. Analisis dilakukan menggunakan perhitungan ITAE (*Integral Time Absolute Error*) untuk mengevaluasi kualitas kendali, serta uji statistik ANOVA untuk mengetahui signifikansi perbedaan antar konfigurasi. Hasil pengujian menunjukkan konfigurasi PID optimal (Kp = 1,5; Ki =

0,5; Kd = 0,2) mampu menurunkan konsumsi daya rata-rata menjadi 7,418 W dengan nilai ITAE 2,419 dan *throughput* stabil. Sistem ini efektif untuk diterapkan pada jaringan hemat energi berskala kecil hingga menengah.

1. Introduction

The demand for efficient and energy-saving network devices is becoming increasingly urgent in line with the growth of modern communication infrastructure. Routers, as the core components of networks, operate continuously and contribute significantly to the overall network power consumption. This situation poses challenges in energy management, particularly in small-to-medium scale networks that often lack intelligent energy management systems.

Various approaches have been developed to optimize network energy efficiency, including algorithm-based traffic management, dynamic sleep mode settings, and adaptive control using intelligent controllers [2]. One widely adopted technique is the Proportional-Integral-Derivative (PID) controller, which has proven effective for real-time and adaptive regulation in various applications, including the control of energy consumption in network devices [3]. Demonstrated that optimal PID tuning can enhance power consumption efficiency in both network-based and industrial systems [6].

Previous studies have investigated energy efficiency in wireless sensor and IoT networks using event-based PID control, as well as the application of PID in industrial device energy consumption control systems [4]. The performance of routers using stock firmware and OpenWRT, showing that open-source firmware offers high flexibility for developing monitoring and control systems [3]. Developed a fuzzy-PID controller for TCP/AQM networks [5], and demonstrated the effectiveness of PID in distributed control systems [7].

However, the application of adaptive PID control systems integrated with open-source firmware on network routers remains very limited. The main contribution of this research is the design and implementation of a PID control system integrated with OpenWRT to optimize router energy consumption, along with an experimental evaluation of its effectiveness using comprehensive network performance parameters. This work is expected to provide a practical and adaptive solution for energy savings in small-to-medium scale networks.

2. Methods

2.1 Electronic System Design

The system developed in this research comprises several key components that are integrated to optimize energy consumption on the MikroTik hAP ac² router running OpenWRT firmware. The main components include an ESP32 microcontroller as the primary controller, an INA219 sensor for real-time current and voltage measurements, and LM2596 and MOSFET modules serving as power supply regulators for the router. The ESP32 microcontroller implements the PID controller algorithm, which computes the control signal based on the error between the actual power consumption measured by the INA219 sensor and the desired reference value [2].

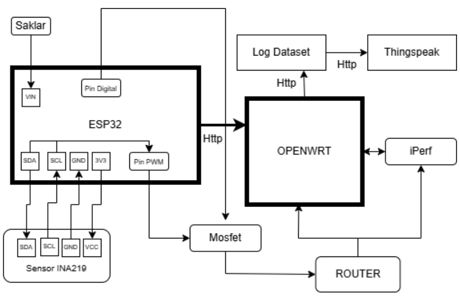

Fig. 1 Electronic System Design

Fig. 1 is an example of an electronic system design. Accurate measurement of power consumption using the INA219 sensor is essential for providing precise feedback to the control system. Additionally, network

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performance parameters such as throughput, latency, and the number of active users are obtained in real time via the OpenWRT API integrated into the router. This network performance data serves as an additional input to adjust the PID control output, enabling adaptive power regulation according to current traffic conditions [5]. Fig. 2 is an example of a Schematic of the research tool.

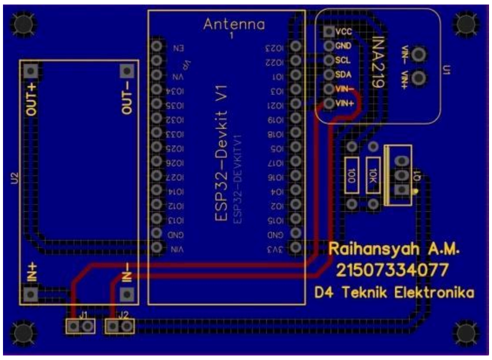

Fig. 2 Schematic Of The Research Tool

The PID controller is implemented on the ESP32 microcontroller in a closed-loop configuration, where the generated control signal is used to regulate the output voltage of the LM2596 and MOSFET modules that supply power to the router. With this configuration, the system can dynamically adjust the router's power consumption, reduce energy waste during periods of low network load, and maintain optimal network performance during high loads. This approach achieves better energy efficiency compared to static methods and offers a practical solution for energy management in small-to-medium scale networks [1].

2.2 Data Acquisition and Integration

Power consumption measurement in this system is performed using the INA219 sensor, which can measure current and voltage in real time with high accuracy. The INA219 sensor is installed on the MikroTik hAP ac² router's power supply line to obtain actual power consumption data, which serves as the main feedback for the PID control system. The current and voltage data obtained from this sensor are then processed by the ESP32 microcontroller to continuously calculate power consumption during the test period. Fig. 3 is an example of a data acquisition integration process ESP32 via Arduino IDE.

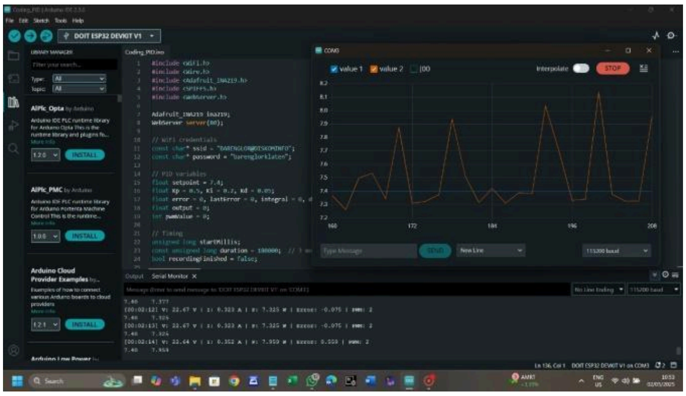

Fig. 3 Data Acquisition Integration Process ESP32 via Arduino IDE

In addition to power consumption measurement, the system also integrates network performance monitoring obtained through the OpenWRT firmware running on the router. OpenWRT provides APIs and monitoring modules that enable real-time retrieval of network parameters such as throughput, latency, and the number of active users. These parameters are essential as indicators of network service quality and serve as additional inputs in power consumption regulation to enable adaptive control according to actual traffic conditions. Fig. 4 is an example of a data acquisition integration process OpenWRT via VM oracle.

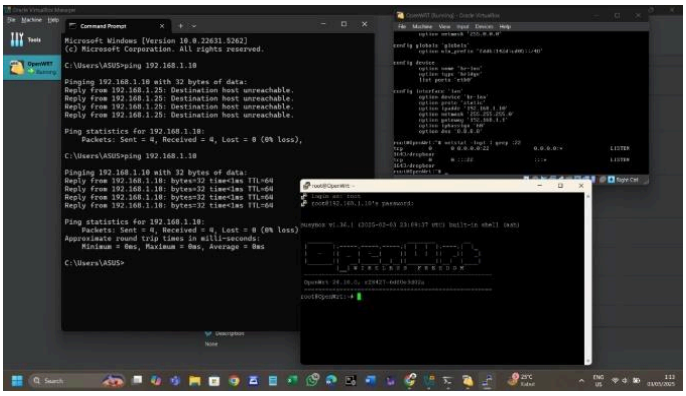

Fig. 4 Data Acquisition Integration Process OpenWRT Via VM Oracle

Power consumption data from the INA219 sensor and network performance data from OpenWRT are then combined and processed integratively by the ESP32 microcontroller. With this integration, the PID control system can dynamically adjust the power supply to the router, optimizing energy usage without compromising network service quality. This data acquisition and integration process is carried out continuously and in real time during testing under various network load scenarios to ensure the effectiveness of power consumption control.

2.3 System Implementation and Deployment

The power optimization system was physically implemented using a custom-built embedded hardware module housed in an acrylic enclosure. The system comprises an ESP32 microcontroller, INA219 precision power sensor, MOSFET-based switching circuitry, and supporting voltage regulation modules. The design emphasizes modularity and compactness to facilitate integration with existing networking infrastructure.

Fig. 5 Power optimization controller built with ESP32 and INA219, enclosed for protection.

For deployment, the device was installed alongside a MikroTik hAP ac² router and connected directly to its power supply line. The router operates using OpenWRT firmware, which communicates with the ESP32 module via serial connection for real-time power control based on network conditions. The entire system was configured to operate continuously, with power monitoring and adjustment handled autonomously by the embedded controller.

Fig. 6 Deployment of the PID controller alongside the MikroTik hAP ac² router in a real network setup.

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The implementation of the hardware controller and its integration with the network infrastructure confirm the feasibility of applying embedded power management systems in real-world networking environments. The compact design allows for minimal intrusion in existing setups, while the deployment near the router ensures accurate sensing and efficient control. As depicted in Fig. 5, the assembled controller is securely housed to protect against physical interference and environmental factors. Furthermore, Fig. 6 demonstrates the successful integration of the device into an operational setting, highlighting its practicality and potential for broader deployment in small to medium-scale network systems.

2.4 PID Configuration and Implementation

Nine PID parameter configurations (Kp, Ki, Kd) were tested along with one baseline configuration without control. PID parameters were determined based on trial and error tuning methods and initial testing to achieve an optimal response range. PID implementation on the ESP32 is performed in a closed-loop manner, where the control output is used to regulate the router's input voltage via LM2596 and MOSFET. It calculates the control output by considering the weighted sum of the proportional, integral, and derivative terms of the error with respect to time, as shown in (1).

$$u(t) = K_{p'}\ e(t) + K_i \int_0^t e(\tau), d\tau\ + K_{d'}\ \frac{de(t)}{dt} \quad (1)$$

Where:

u(t) is the control output at time t,

e(t) is the error signal (the difference between setpoint and process variable),

Kp is the proportional gain,

Ki is the integral gain,

Kd is the derivative gain.

The configuration and implementation of PID in this study were carried out by designing nine variations of PID parameters (Kp, Ki, Kd) that were experimentally tested on the power consumption control system of the MikroTik hAP ac² router based on OpenWRT. Parameter determination was performed through the trial and error method, referring to the system's initial response to obtain the optimal control range.

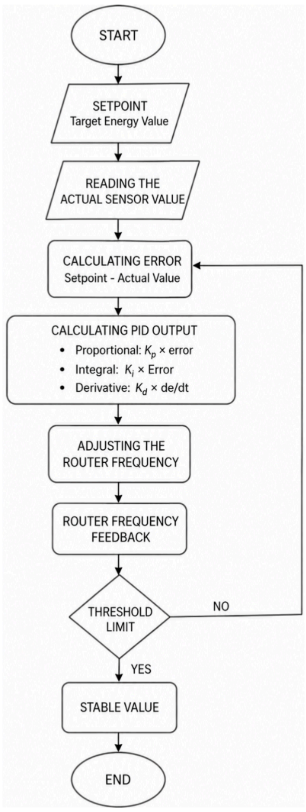

Fig. 7 Flowchart The Implementation Of PID

Fig. 7 above is a system flow diagram of the configuration and implementation of PID. Each configuration was tested along with one baseline configuration without control as a comparison, to determine the effectiveness of adaptive power consumption regulation against changes in network load. During testing, the system automatically records power consumption and network performance data for each PID configuration.

The data acquisition process runs continuously throughout the test period so that the system's response to various load scenarios can be analyzed comprehensively. With this approach, the effectiveness of PID control in reducing power consumption while maintaining network performance can be evaluated objectively and measurably. Fig. 5 above is a system flow diagram of the configuration and implementation of PID.

2.5 Experimental Design

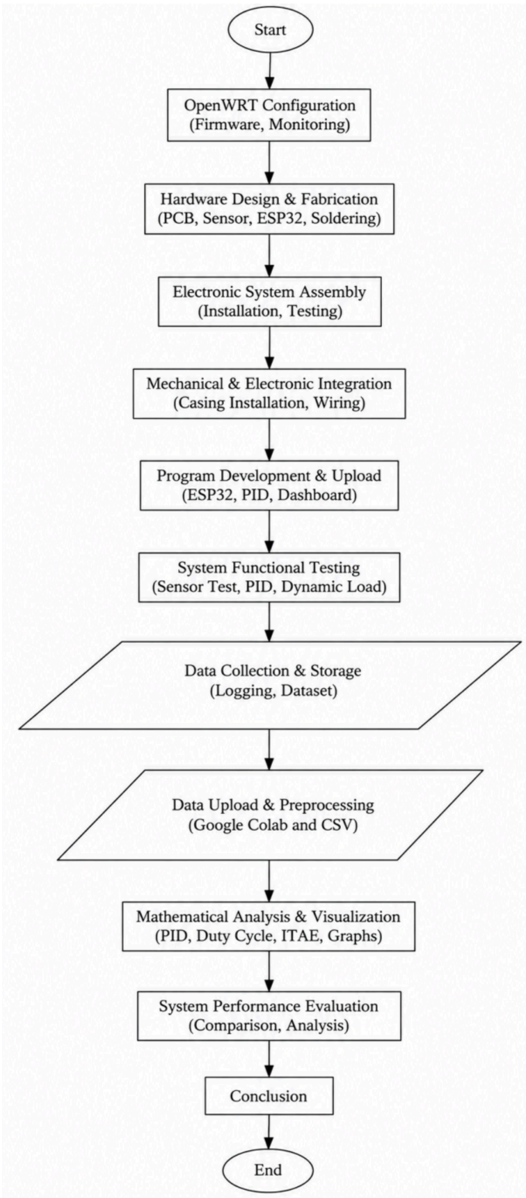

Fig. 8 Flowchart The Experimental Design

The experimental design involved applying varying traffic loads to the router using iPerf to simulate real network conditions. Each PID configuration was tested under several load scenarios (low, medium, and high) for a specified period. Power consumption and network performance data were recorded simultaneously for each configuration.

Data collection was performed in real time using the INA219 sensor for power consumption measurements and the OpenWRT monitoring module for network parameters. The acquired data were subsequently

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processed and visualized as power consumption versus time graphs and performance comparison tables among configurations. This approach enabled direct observation of the impact of PID implementation on the stability of power consumption and the quality of network services under different load conditions.

Fig. 8 above is a system flow diagram of the experimental design. Each test was conducted in a controlled and repeated manner to ensure the consistency of results. The testing procedure also included evaluation of possible overshoot, system recovery time, and network performance stability. These results served as the basis for determining the optimal PID configuration that provides the best energy efficiency without degrading network service quality.

2.6 Data Analysis

Data analysis in this study focused on evaluating the performance of the PID control system using the Integral Time Absolute Error (ITAE) metric. The ITAE metric is used to measure the accuracy and speed of the system's response in reaching the desired power consumption target. A low ITAE value indicates that the system can quickly adjust power consumption with minimal cumulative error, making it the main indicator of control quality achieved in each PID configuration. It calculates the ITAE formula as shown in (2).

$$ITAE = \int_{0}^{T} t.\,|e(t)|dt \tag{2}$$

where e(t) is the error between the reference and actual power consumption at time t, and T is the observation period. In addition to ITAE, the analysis also involved comparing the average power consumption and network performance, such as throughput and latency, for each configuration. Test data were visualized in the form of graphs and tables to facilitate interpretation. The power consumption versus time graph was used to observe system response, stability, and the occurrence of overshoot or undershoot during the control process.

Network performance analysis was conducted by comparing throughput stability and latency variation between PID configurations. This is important to ensure that the achieved energy efficiency does not compromise network service quality. Thus, data analysis provides a comprehensive overview of the effectiveness and impact of PID Controller implementation in optimizing power consumption of OpenWRT-based routers.

3. Result and Discussion

3.1. Power Consumption Test Results

Test results showed that PID configuration 1 with parameters Kp = 1, 5; Ki = 0, 5; Kd = 0.2 provided optimal performance with an average power consumption of 7,418 W and an ITAE value of 2.419. This configuration successfully reached the 7,4 W setpoint with minimal error and stable response. Compared to the baseline without PID control, which consumed 7,964 W, there was an energy saving of 6,86% or about 0,546 W. The low variance 0,116 in the optimal configuration indicates good power consumption consistency during the test period.

Table 1. Average Test Results For PID Configurations And OS Router

No.	K_p, K_i, K_d	Setpoint (W)	Power (W)	Latency (ms)	Throughput (Mbps)	ITAE
1.	OS Router	-	7,964	14,81	18,10	-
2.	1,5; 0,5; 0,2	7,4	7,418	15,04	17,82	2.419
3.	0,6; 0,15; 0,03	7,4	7,562	14,73	18,14	4.607
4.	0,4; 0,25; 0,07	7,4	7,757	14,48	18,47	6.344
5.	0,8; 0.1; 0,01	7,4	7,510	14,82	18,02	3.651
6.	0,5; 0,2; 0,05	7,4	7,481	14,88	18,04	2.612
7.	1,0; 0,5; 0,2	7,4	7,478	14,93	17,99	3.601
8.	1,5; 0,7; 0,3	7,4	7,441	14,88	17,94	2.774
9.	1,5; 0,7; 0,3	7,2	7,427	14,97	17,88	3.662
10.	1,5; 0,7; 0,3	7,6	7,536	14,81	18,10	6.681

Table 1 is the result of a comparison of the PID Configurations and baseline without PID control. Analysis of the nine PID configurations showed that the integral parameter (Ki) significantly affects system stability. PID configuration 8 with parameters Kp = 1, 5; Ki = 0, 7; Kd = 0, 3 resulted in a power consumption of 7,427 W with the lowest variance 0,097, but its ITAE value was higher 3.662. This indicates a trade-off between power consumption stability and system response speed. Configurations with too high a Ki tend to experience overshoot, while too low a Ki causes a slow response in reaching the setpoint.

The distribution of power consumption across all configurations ranged from 7,418 W to 7,757 W, indicating that all PID configurations successfully reduced power consumption compared to the baseline. PID configuration 3 with parameters Kp = 0, 4; Ki = 0, 25; Kd = 0, 07 resulted in the highest consumption 7,757 W with an ITAE of 6.344, confirming that a too low Kp parameter leads to a less responsive system. This pattern is consistent with PID control theory, where an optimal proportional parameter is required to achieve a balance between response speed and system stability.

3.1 Network Performance Analysis

The network throughput parameter in the optimal PID configuration showed a value of 17,82 Mbps with latency of 15,04 ms, proving that power consumption optimization does not compromise network service quality. Comparison with other configurations showed throughput variations in the range of 17,82-18,47 Mbps and latency of 14,48-14,97 ms, indicating consistent network performance stability. PID configuration 3 achieved the highest throughput 18,47 Mbps, but with the trade-off of higher power consumption and slower control response.

The correlation between PID parameters and network performance shows that configurations with moderate Ki (0,5-0,7) provide the optimal balance between energy efficiency and service quality. PID configuration 2 with Ki = 0, 15 produced a throughput of 18,14 Mbps but with slightly higher latency (14,73 ms) and ITAE of 4.607. This confirms that a too low integral parameter can slow the system's adaptation to changes in network load, although it still maintains good throughput.

Latency stability across all configurations showed a low standard deviation (<0,5 ms), proving that PID implementation does not cause significant latency fluctuations. PID configurations 4 and 5 showed the best latency performance (14,48 ms and 14,88 ms) while maintaining competitive throughput. This consistency is very important for real-time applications and maintaining Quality of Service (QoS) in small to medium-scale networks.

3.2 Duty Cycle Adjustment in PID-Based Power Control

In the proposed system, the adjustment of power delivery is achieved through Pulse Width Modulation (PWM), where the duty cycle plays a pivotal role in determining the average energy supplied to the router. The duty cycle, defined as the ratio of the ON time to the total period of the PWM signal, directly influences the output voltage and thus the power consumed by the device.

The output of the PID controller dynamically modifies the duty cycle in response to real-time deviations between the actual power consumption (Pactual) and the predefined setpoint (Pset), as described in Equation (1). The average power delivered to the load (Pavg) is linearly proportional to the duty cycle and the maximum power (Pmax), as shown in Equation (3):

$$P_{avg} = D \, x \, P_{max} \tag{3}$$

where D is the duty cycle in decimal form. Experimental results demonstrated that the PWM signal ranged from 219 to 255, corresponding to a duty cycle of approximately 85.88% to 100%. For instance, at D = 0.8588, the system output voltage was 22.40 V with a power of 8.61 W, whereas at D = 1.00, the voltage slightly increased to 22.61 V, maintaining an average power of around 7,34-7,38 W.

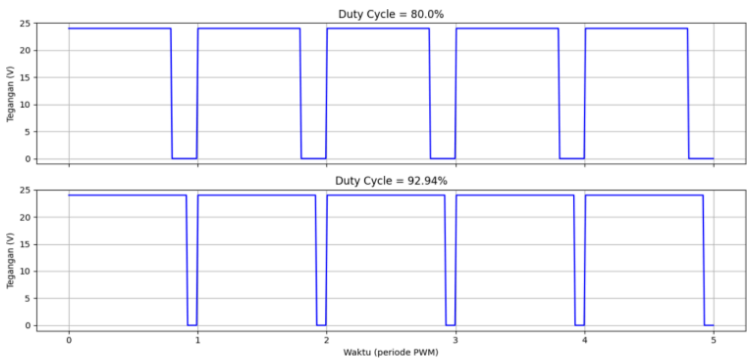

Fig. 9 Waveform Observations Of PWM Signals

Fig. 9 waveform observations of PWM signals at 80% and 92.94% duty cycles fig. reveal that increased duty cycle extends the MOSFET's conduction period, thereby increasing the effective energy supply. Nevertheless, the PID controller compensates dynamically to ensure that the average power remains stable,

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effectively maintaining energy efficiency even under variable loads.

This relationship between PWM modulation and power regulation substantiates the critical role of duty cycle adjustment in energy-aware embedded systems, particularly in real-time power management for network devices.

3.3 Statistical Test and Discussion

The single factor ANOVA test results confirmed a relevant difference between PID configurations and the baseline without control (F = 17.9; p-value = 1.11E-28 < 0.05; F critical = 1.9). The F-statistic, which is much greater than the critical F, indicates that the difference in power consumption between groups did not occur by chance, but as a real effect of the applied PID parameters. The Sum of Squares Between Groups (49) is greater than the error variance, indicating relevant variability between configurations with a 99,99% confidence level.

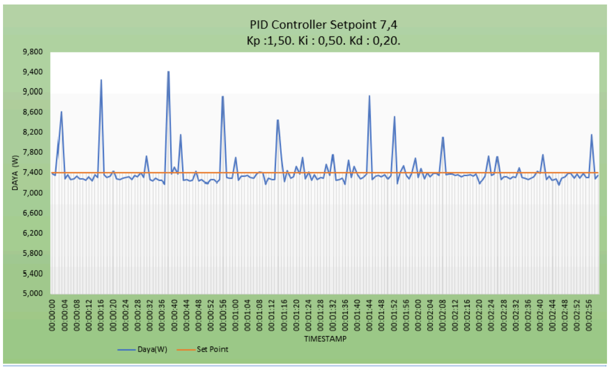
Table 2. The Single Factor ANOVA Test Results Confirmed

Groups	Count	Sum	Average (W)	Variance	Throughput (Mbps)	ITAE
NON PID	180	1433	7,964	0,995	18,10	-
PID 1	180	1335	7,418	0,116	17,82	2.419
PID 2	180	1361	7,562	0,279	18,14	4.607
PID 3	180	1396	7,757	0,433	18,47	6.344
PID 4	180	1352	7,510	0,259	18,02	3.651
PID 5	180	1347	7,481	0,124	18,04	2.612
PID 6	180	1346	7,478	0,224	17,99	3.601
PID 7	180	1339	7,441	0,116	17,94	2.774
PID 8	180	1337	7,427	0,097	17,88	3.662
PID 9	180	1356	7,536	0,376	18,10	6.681

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	49	9	5,40	17,9	1,11E-28	1,9
Within Groups	540	1790	0,30			
Total	589	1799				

Table 2 is the result of a single factor ANOVA test. Post-hoc analysis of variance within each group showed that PID configuration 8 had the lowest variance (0.097), followed by PID 1 and PID 7 with a variance of 0.116. This indicates very good power consumption stability in these configurations. In contrast, the baseline without PID showed the highest variance (0.995), proving the instability of power consumption without a control system. The relatively small Mean Square Within Groups (0.30) confirms the consistency of measurements within each configuration.

The discussion of statistical results emphasizes the effectiveness of adaptive PID control systems in optimizing router energy consumption. The large effect size (η2 ≈ 0.83) shows that PID implementation provides a relevant practical impact on energy savings. These findings are in line with the research of [6] which demonstrated the effectiveness of PID in energy control applications. For practical implementation, PID configuration 1 is recommended as it provides the optimal combination of energy efficiency (lowest ITAE), system stability, and consistent network performance, making it an ideal solution for small to medium-scale networks requiring energy optimization without sacrificing service quality.



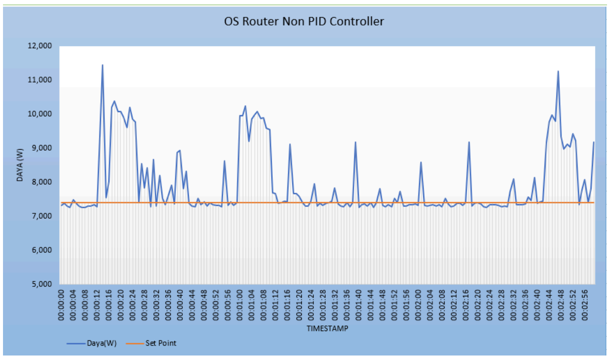


Fig. 10 Comparison of power consumption responses between the PID-controlled system (top) and the non-PID system.

Visual analysis of Fig. 10 reinforces the statistical findings previously discussed. The graph representing the system with PID control (Kp = 1,5; Ki = 0,5; Kd = 0,2) demonstrates significantly lower power fluctuations, with consumption values closely following the 7,4 W setpoint throughout the testing period. In contrast, the system without PID control exhibits substantial oscillations, with power spikes exceeding 11 W, indicating a lack of regulation and energy inefficiency. These fluctuations suggest that in the absence of adaptive control, the system fails to respond effectively to dynamic network conditions, leading to excessive and unstable energy usage.

Overall, the implementation of the PID controller successfully reduced power consumption variance and brought actual values closer to the target with minimal error, as confirmed by the ITAE value of 2.419 and variance of 0.116. In comparison, the uncontrolled system exhibited a significantly higher variance of 0.995, highlighting its inconsistency. The correlation between statistical results and the graphical representation clearly demonstrates that the PID-based control system not only performs better numerically, but also offers practical improvements in energy stability and efficiency without compromising network service quality.

4. Conclusion

This research successfully developed and implemented a PID controller-based power consumption control system on the MikroTik hAP ac² router using OpenWRT firmware. The use of the ESP32 microcontroller and INA219 sensor enabled accurate real-time power consumption measurement, as well as adaptive control of the router's power supply based on network traffic conditions. By testing nine PID parameter configurations and one configuration without control, the optimal configuration was identified, which significantly reduced power consumption without compromising network performance.

The experimental results show that the PID configuration with parameters Kp = 1.5, Ki = 0.5, and Kd = 0.2, achieved an average power consumption of 7,418 W with an ITAE value of 2,419, indicating high control quality. Furthermore, network throughput and latency remained stable throughout the tests, demonstrating that the control system effectively maintains network service quality while optimizing energy usage. Statistical analysis using ANOVA also confirmed that the differences in power consumption among the tested PID configurations were statistically significant.

This adaptive PID control system is highly suitable for small- to medium-scale networks that require energy efficiency without sacrificing service quality. This research opens up opportunities for further development, such as integrating IoT and machine learning technologies for network load prediction and automatic adjustment of control parameters. Thus, the proposed solution can support the development of more energy-efficient and sustainable networks in the future.

Author Contribution:

All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

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Conflicts of Interest:

The authors declare no conflict of interest.

References

[1] H. E. Alami and A. Najid, "Optimization of energy efficiency in wireless sensor networks and internet of things: A review of related works," in G. P. Gupta (Ed.), Nature-Inspired Computing Applications in Advanced Communication Networks, IGI Global, pp. 89–127, 2020.

[2] N. M. Ramadhan, S. M. Raafat, and A. M. Mahmood, "Optimized event-based PID control for energy-efficient wireless sensor networks," Mathematical Modelling of Engineering Problems, vol. 11, no. 1, 2024.

[3] E. Haryanto, "Performance comparison of Xiaomi Mi Router 4A with stock firmware and OpenWRT in optimizing functionality," Empiricism Journal, vol. 4, no. 2, pp. 343–347, 2023.

[4] B. A. Pramudita, "Utilization of PID controller to optimize energy consumption in hybrid forced convection dryer," JURNAL INFOTEL, vol. 16, no. 3, pp. 614–625, 2024.

[5] M. Oudah, M. Q. Sulttan, and S. W. Shneen, "Fuzzy type 1 PID controllers design for TCP/AQM wireless networks," Indonesian Journal of Electrical Engineering and Computer Science, vol. 21, no. 1, pp. 118–127, 2021.

[6] T. George and V. Ganesan, "Optimal tuning of PID controller in time delay system: a review on various optimization techniques," Chemical Product and Process Modeling, vol. 17, pp. 1–28, 2020.

[7] V. R. Dahake, M. D. Patil, and V. A. Vyawahare, "Analysis of networked control system with integer-order and fractional-order PID controllers," International Journal of Control, Automation and Systems, vol. 22, no. 2, pp. 373–386, 2024.