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A New Hybrid Intelligent Fractional Order Proportional Double Derivative + Integral (FOPDD+I) Controller with ANFIS Simulated on Automatic Voltage Regulator System

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ABSTRACT

In the dynamic realm of Automatic Voltage Regulation (AVR), the pursuit of robust transient response, adaptability, and stability drives researchers to explore novel avenues. This study introduces a groundbreaking approach—the Hybrid Intelligent Fractional Order Proportional Derivative^2+Integral (FOPDD+I) controller—leveraging the power of the Adaptive Neuro-Fuzzy Inference System (ANFIS). The novelty lies in the comparative analysis of three scenarios: the AVR system without a controller, with a traditional PID controller, and with the proposed FOPDD+I-based ANFIS. By fusing ANFIS with a hybrid controller, we forge a unique path toward optimized AVR performance. The hybrid controller, based on FOPID (Fractional Order Proportional Integral Derivative) principles, synergizes individual integral factors with ANFIS, augmenting them with a doubled derivative factor. The ANFIS design employs a hybrid optimization learning scheme to fine-tune the Fuzzy Inference System (FIS) parameters governing the AVR system. To train the fuzzy inference system, we utilize a Proportional-Integral-Derivative (PID) simulation of the entire AVR system, capturing essential data over approximately seven seconds. Our simulations, conducted in MATLAB/Simulink, reveal impressive performance metrics for the FOPDD+I-ANFIS approach: Rise time: 1.1162 seconds, settling time: 0.5531 seconds, Overshoot: 0%, Steady-state error: 0.00272, These results position our novel approach favorably against existing works, underscoring the transformative potential of intelligent creation in AVR control.

1. Introduction

Voltage regulation is crucial in electrical engineering, particularly power engineering. It measures the change in voltage magnitude between the sending and receiving end of a component, such as a transmission or distribution line. Voltage regulation describes the ability of a system to provide near constant voltage over a wide range of load conditions. It ensures that electronic devices receive the required voltage for proper operation. An Automatic Voltage Regulator (AVR) is an electronic device that maintains a consistent voltage level for electrical equipment connected to the same load. By regulating voltage fluctuations, the AVR ensures a reliable and stable power supply. Although the AVR cannot function optimally without a controller, when paired with the AVR system, the controller can address specific voltage issues. Additionally, the AVR finds applications in scenarios like voltage control for DC motors or robotic arms. The AVR operates as a circuit that generates and sustains a fixed output voltage, regardless of input voltage variations or load changes. It is commonly used in various motor vehicles to match the generator's output voltage with the electrical load and battery charging requirements. Different types of AVR systems exist, including Tap-changing AVR, Induction Motor AVR, Static AVR, and Digital AVR [1]. Efficient operation of electrical or electronic equipment relies on a specific voltage known as the nominal voltage. If the generator's output falls below this nominal voltage, the AVR adjusts the exciter's amplification current [2], increasing its strength. Conversely, if the generator's output voltage exceeds the nominal value, the AVR reduces the exciter's amplification current. In this way, the AVR automatically detects and stabilizes any changes in the generator's output voltage, preventing damage to devices caused by voltage instability. Fig. 1 illustrates the AVR's operation using power from a permanent magnet generator [3]. Özay Can, Cenk Andiç, Serdar Ekinci, and Davut Izci [4] introduces a new type of controller design for the AVR system. A novel controller named fractional order (FO) proportional-integral-derivative plus second-order derivative (FOPIDD 2) has been proposed for the first time, and an optimization method known as the reptile search algorithm (RSA) has been utilized to tune the six parameters of FOPIDD controller. A. Jegatheesh, V. Thiyagarajan, N. B. Muthu Selvan and M. Devesh Raj [5] presents a novel Seagull optimization algorithm based fractional order proportional integral derivative controller (SOA-FOPID) fed AVR system to regulate the voltage and enhance the stability of the power system. Othman A. M. Omar, Mostafa I. Marei, and Mahmoud A. Attia [6] illustrates various types of control systems used for AVR systems, along with their mathematical models, to demonstrate their improved terminal voltage responses. Abdulkerim Ali, Belachew Bantyirga, and Getachew Biru [7] discusses the design and control of Automatic Generation Control (AGC) and AVR for multi-area interconnected power systems.

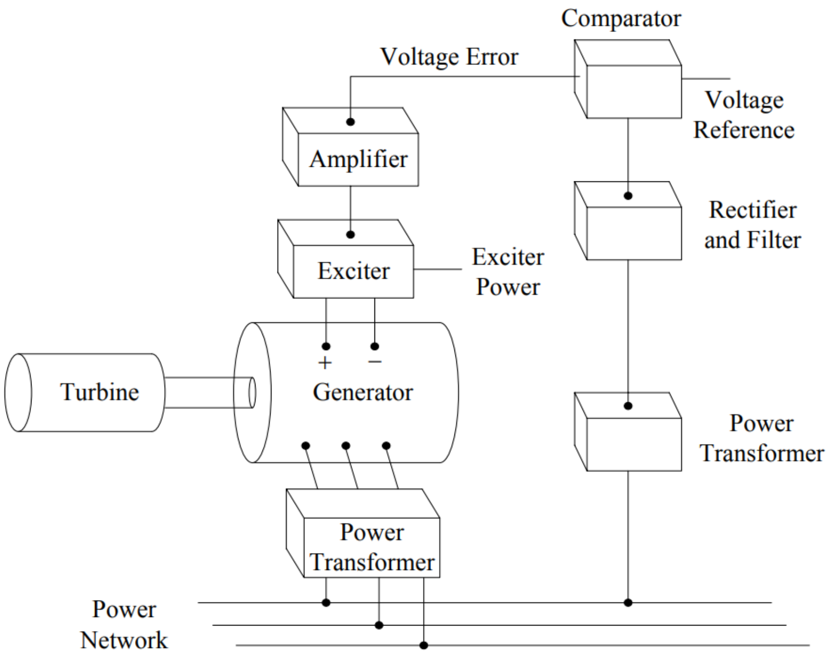

Fig. 1. How does an AVR system work [3]

The control unit in Automatic Voltage Regulator (AVR) systems plays a crucial role in maintaining the stability and efficiency of power systems. such as Voltage Regulation (VR), stability enhancement, and excitation control. In Automatic Voltage Regulator (AVR) systems, several types of control units are used to maintain and regulate the voltage as follows:

- Sensing Circuit: The three-phase generator voltage is supplied to the sensing circuit passing PT and 90R first, and the three-phase output voltage of 90R is lowered then transmitted by diode circuit, and leveled by capacitor circuit and resistor and this voltage can be adjusted with VR (Variable Resistant).
- Carbon Pile Regulator: a compact unit and connected as a resistance in series with the field circuit. The value of resistance of the carbon pile gets reduced as the pressure applied on it is increased. A solenoid coil connected across the supply controls the pressure applied and thereby the voltage developed by the generator.
- Fractional Order Proportional Integral Derivative Controller (FOPID): To increase the flexibility in design and to acquire accurate control the PID controller is replaced by a FOPID controller, and the FOPID controller parameters are tuned by Optimization Process.

To boost the closed-loop response for superior performance, a hybrid controller is considered essential. This research presents a Hybrid Intelligent FOPDD+I (Fractional Order Proportional Derivative^2+Integral) controller, which is based on (ANFIS). The approach combines an advanced FOPID controller with neural networks and (FIS). The emphasis is on utilizing the neural network's learning abilities to establish a set of rules for creating an efficient (FIS) to control the Automatic Voltage Regulator system. The contributions of this study are introduced as follows.

- The study developed an effective method for generating the training dataset, which is crucial for the learning process.
- A hybrid learning training algorithm was employed in this research, enhancing the learning and adaptation capabilities of the system.
- The performed criteria for various controllers allocated in the automatic voltage regulator system were compared in this study.
- The study examined many different configurations for the system: it operated without a controller, it used a PID controller, FOPID, FOPD-I and the proposed Hybrid Intelligent FOPDD+I based ANFIS.
- This research introduced a novel approach for the Automatic Voltage Regulator system that combines a hybrid learning algorithm with a FOPDD+I based ANFIS.
- The proposed approach demonstrated comparatively better results than alternative methods, proving its efficacy and efficiency.

This article is split into five sections where Part one covers the introduction, and Part two and three elaborates on the system design and modeling, and hybrid controller design based on ANFIS. Part four covers the results and discussion, and Part five contains conclusion and future studies.

2. System Design and Modelling

In MATLAB, transfer functions are used to mathematically represent the relationship between the input and output of linear time-invariant systems. Each component in a control or dynamic system can often be represented by a transfer function. Here's a brief explanation of representing an amplifier, exciter, generator, and sensor as transfer functions in MATLAB that shown as follows [8]:

1. Amplifier: An amplifier is a component that increases the amplitude or power of a signal. In the context of control systems, an amplifier is typically represented as a simple gain. A gain of 'k' means the output is 'k' times the input. In MATLAB, the representation of an amplifier with a transfer function using the *TF* function. For instance, the amplifier has a gain of 10 as depicted in Equation (1) [9]-[13]:

$$G_{amp} = tf([10],[0.1 \quad 1]); \tag{1}$$

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2. Exciter: An exciter introduces a controlled signal or excitation into a system. It could be modeled as a first-order transfer function, often representing a simple low-pass filter or a basic dynamics block. For example, a first-order exciter with a time constant of 1 as illustrated in Equation (2) [14], [15]:

$$G_{exciter} = tf([1],[0.4 \quad 1]); \tag{2}$$

3. Generator: The generator, in the context of a control system, could be represented by a transfer function that describes its dynamics. It might have second-order behavior, capturing its response to input signals. As an example, a second-order generator with poles at -1 and -2 as depicted in Equation (3) [16]-[23]:

$$G_{generator} = tf([1],[1 \quad 1]); \tag{3}$$

4. Sensor: A sensor measures and converts physical quantities into electrical signals. In many cases, a sensor's behavior can be approximated as a simple gain. For instance, a sensor with a gain of 1 as shown in Equation (4) [24]-[35]:

$$G_{sensor} = tf([1],[0.01 \quad 1]); \tag{4}$$

The Laplace transform is a powerful mathematical tool used to solve differential equations. It transforms a function of time, f(t), into a function of a complex variable s. The Laplace Transform of a function f(t) is defined in Equation (5):

$$F(s) = \int_0^\infty f(t)e^{-st}dt \tag{5}$$

For AVR systems, we often deal with differential equations. The Laplace Transform has some useful properties when applied to derivatives were shown in Equation (6), and Equation (7):

For the first-order derivative:

$$\mathcal{L}\{f'(t)\} = sF(s) - f(0) \tag{6}$$

For the second-order derivative:

$$\mathcal{L}\{f''(t)\} = s^2F(s) - sf(0) - f'(0) \tag{7}$$

Where F(s) is the Laplace transform for $f(t)$, and $f(0)$ and $f'(0)$ are the initial conditions. In the context of AVR, these equations allow us to transform differential equations describing the system into algebraic equations in the s domain, which are often easier to solve. After solving these algebraic equations, we can then apply the inverse Laplace Transform to get the solution in the time domain. Consider a simple AVR system represented by the following differential equation as depicts in Equation (8), Equation (9), and Equation (10):

$$T_e\frac{dE'(t)}{dt} + E'(t) = K_a(V_{ref} - V(t)) \tag{8}$$

Where:

$E'(t)$ is the output voltage of the exciter.

$V(t)$ is the terminal voltage of the generator.

$V\_\{ref\}$ is the reference voltage.

K_a is the gain of the amplifier.

T_e is the time constant of the exciter.

Taking the Laplace transform of both sides gives:

$$T_e s E'(s) + E'(s) = K_a (V_{ref}/s - V(s)) \tag{9}$$

Rearranging terms, The Automatic Voltage Regulator system's transfer function is derived here:

$$E'(s) = \frac{K_a}{T_e s + 1} (V_{ref}/s - V(s)) \tag{10}$$

Once translated these elements into transfer functions within MATLAB, you can mathematically combine them using fundamental arithmetic operations (* for cascading, + for parallel combination, etc.). This merged transfer function encapsulates the connection between the input and output of the complete system, incorporating these distinct components [36]-[46]. The conceptual illustration of the AVR system within MATLAB, Hybrid Intelligent FOPDD+I Controller based ANFIS, and Hybrid Intelligent FOPDD+I Controller based ANFIS with Load (LTI System) are depicted in Fig. 2, Fig. 3, and Fig. 4 respectively.

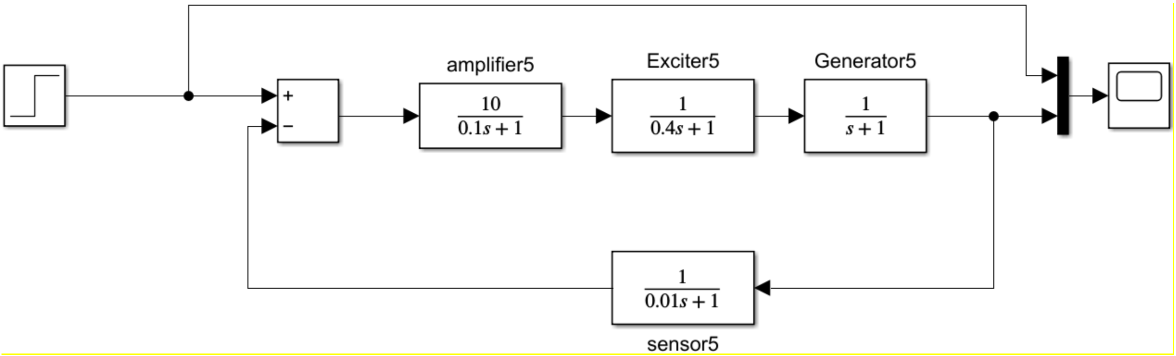


Fig. 2. AVR system components in MATLAB simulink

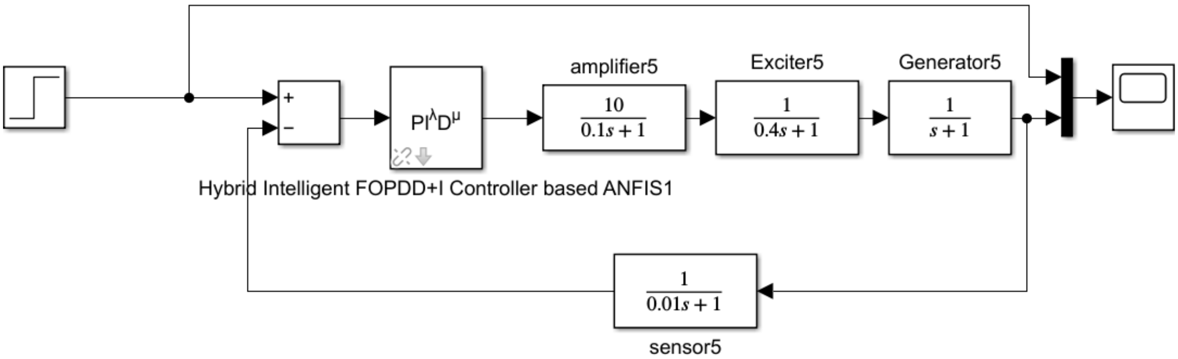


Fig. 3. AVR system components with hybrid intelligent FOPDD+I controller based ANFIS in MATLAB simulink without load

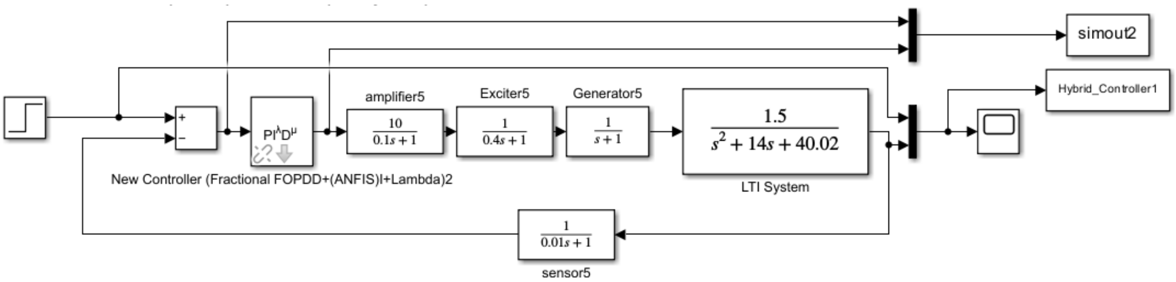


Fig. 4. AVR system components with hybrid intelligent FOPDD+I controller based ANFIS in MATLAB simulink with load (LTI System)

3. Hybrid Controller Design based on ANFIS

The proposed AVR control system involves a Fractional PID controller with two derivative terms and a proportional term all operating in the forward path. The integral term operates separately in the forward path and connects to an Adaptive Neuro-Fuzzy Inference System (ANFIS) with its derivative factor. This configuration essentially creates a Hybrid Intelligent FOPDD+I Controller based ANFIS [47]. AVR systems are often modeled and simulated in MATLAB Simulink for several reasons:

- Comprehensive Analysis: MATLAB Simulink provides a comprehensive environment for modeling, simulating, and analyzing dynamic systems12. It allows engineers to create a detailed model of the AVR system, including all its components, and analyze its behavior under different conditions.
- Visual Representation: Simulink offers a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. This visual approach makes it easier to understand the system's operation and identify any potential issues.
- Control Design and Implementation: MATLAB Simulink is widely used for designing and implementing control systems. In the context of AVR systems, control algorithms (like PID or FOPID controllers) can be designed, tested, and optimized within the Simulink environment.
- Performance Evaluation: By simulating the AVR system in Simulink, engineers can evaluate the system's performance, such as its response time and stability. This helps in fine-tuning the system's parameters for optimal performance.
- Educational Tool: MATLAB Simulink is also an excellent tool for teaching and learning.

The utilization of fractional derivatives alongside the conventional PID components allows for enhanced control over systems with complex dynamics and non-linear behavior. By incorporating ANFIS into the integral term, the system gains adaptive capabilities, enabling it to adjust the integral gain and its derivative factor based on the system's behavior and performance [48]-[52].

(ANFIS) uses neural networks innate capacity for learning to extract the if-then rules that govern the fuzzy system. These guidelines are used by the system's core fuzzy inference algorithm to estimate a novel fuzzification sets conclude from the past sets that served such a preface. Five interconnected layers make up an ANFIS setup; Fig. 5 illustrates this structure, which is the same as the one employed in this study. There is a specific logical order in which it runs [53]-[57]. The input features are converted into input membership functions.

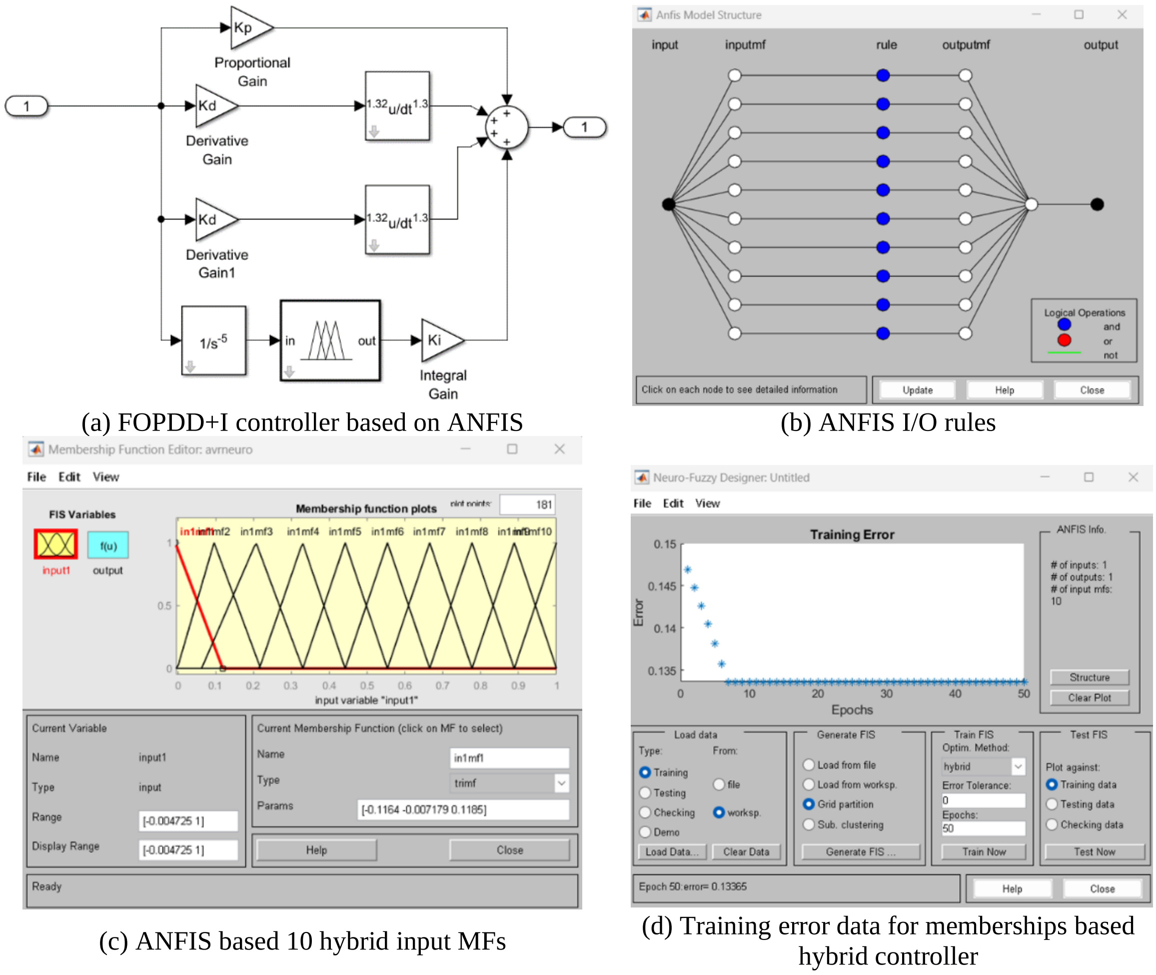
- Creates a relationship between the if-then rules and the input's membership function.
- Connects the output features to the if-then rules.
- Converts the output features into the output's membership functions.
- Links the outcome memberships function for the outcome ultimate result nor related decisions.

As a result of this configuration could potentially offer improved control performance, especially in systems with uncertainties, nonlinearities, or time-varying characteristics. The adaptive nature of ANFIS allows the controller to adapt its parameters in real-time, optimizing the system's response to changes and disturbances. However, the specific performance and effectiveness of this control system would depend on various factors like the system dynamics, tuning of parameters, and the accuracy of the ANFIS model [58]-[60]. Testing and simulation would be necessary to evaluate its actual performance in different scenarios. The components and configurations of a FOPDD+I Controller based on ANFIS are presents in Fig. 5, Table 1, and Table 2.

The relationships delineate the functionality of the ANFIS algorithm, specifically tailored for Sugeno-type systems. The ANFIS controller design entails the following procedural steps:

- Pre-processing the dataset intended for training and normalization if necessary.

- Loading the trains datasets by the MATLAB workspace.
- The grids partitions options are used in this study's construction of the (FIS), with the number and types of membership functions that are desired. Triangular membership function types were selected for ten (10) membership numbers.
- After creating the FIS, 50 epochs of hybrid optimization with zero error tolerance are used to train it.
- Until the Root Mean Square Error (RMSE) value is acceptable, the process is repeated with different options.
- The FIS is loaded into the FIS block in the Simulink environment after being saved to the workspace. The evaluation yielded a minimum training RMSE of 0.133646, and an ATE of 0.1336462.



(a) FOPDD+I controller based on ANFIS

(b) ANFIS I/O rules

(c) ANFIS based 10 hybrid input MFs

(d) Training error data for memberships based hybrid controller

Fig. 5. Hybrid intelligent FOPDD+I controller based ANFIS

Table 1. Essential parameters of the FOPDD+I controller based on ANFIS

FOPDD+I Controller based on ANFIS Parameter	Values
KP (Proportional)	0.5
KI (Integral)	0.44
KD^1 (Derivative)	0.20
KD^2 (Derivative)	0.20
λ (Lambda)	-5
μ (Mu)	1.32

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Table 2. ANFIS settings based on the FOPDD+I controller

ANFIS Parameters	Values
No. of linear parameters	10
No. of nonlinear parameters	30
Total no. of parameters	40
No. of training data pairs	5110
No. of checking data pairs	0
No. of fuzzy rules	10
No. of Nodes	44

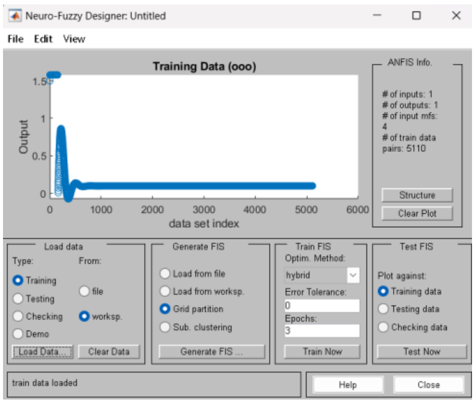
4. Results and Discussion

In this part, the results of (AVR) model and design phases are discussed. The differences between the ANFIS controllers that use PID and the Hybrid Intelligent FOPDD+I-based ANFIS controllers with and without integration are highlighted. It also offers an overview of the outcomes obtained during the hybrid intelligent FOPDD+I-based ANFIS's training, validation, and testing phases.

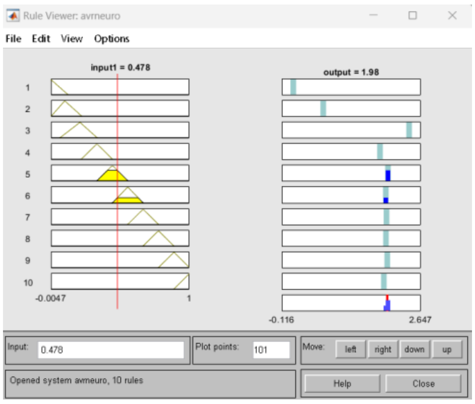
4.1. Hybrid Controller based ANFIS Design and Outcomes

Upon loading the training dataset, a training data pair reaching 5110 with a maximum output recorded at 1.98 is revealed on the graph that plots the index against the output sample. As mentioned earlier, the ANFIS configuration uses a hybrid training optimization technique and triangular membership functions to create 10 membership functions. Furthermore, a surface representation that shows how the input and output of the ANFIS design are mapped has been created.

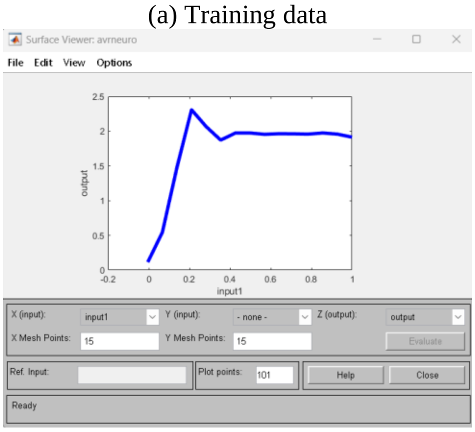
The error chart shows that, following 50 epochs of training, every point clusters around zero point. As seen in Fig. 6, this clustering indicates that the training of (FIS) was successful, satisfying the zero-error tolerance during testing and validation.



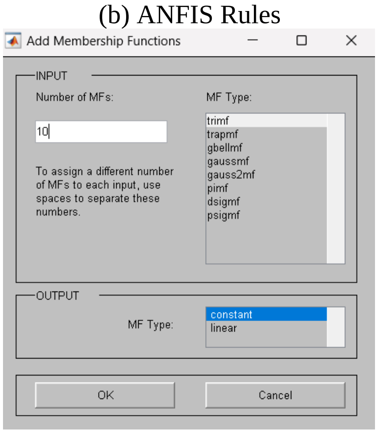
(a) Training data



(b) ANFIS Rules



(c) ANFIS MFs Surface Coordination

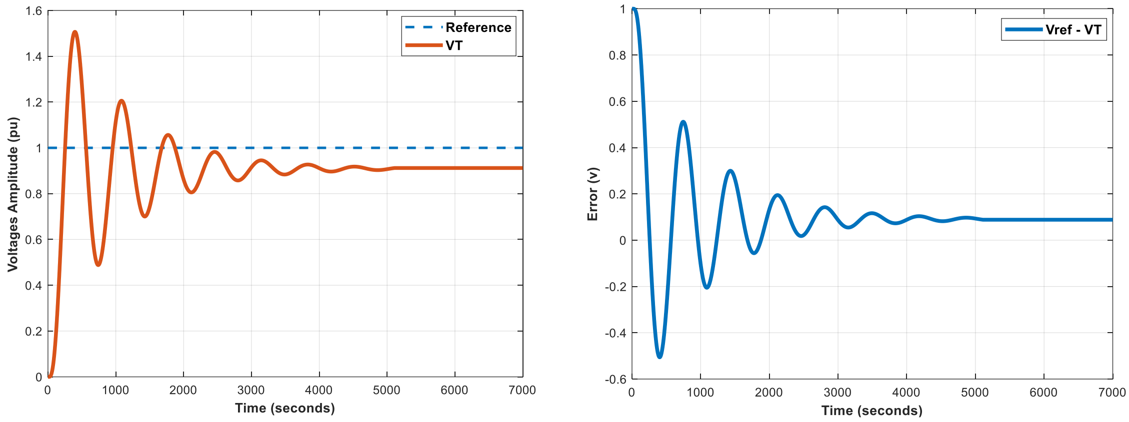


(d) ANFIS MFs Type and Number

Fig. 6. ANFIS Setups on MATLAB

4.2. AVR System Only

The resulting error is shown when the simulation time is set to 7 seconds and the system is subjected to a unit step input as the reference input. The difference between VT, and V ref, is represented by this error, which is presented in the given axes. Additionally assessed is the AVR's capacity to follow or react for the unit-step references entry. The voltage amplitude's quantification in terms of per unit (pu) suggests that the system's performance was not up to par. It showed persistent oscillations and a long settling time. Furthermore, it was judged to be insufficient in terms of tracking or responding appropriately. This suggests that there may be a risk of serious system failure due to the system's inability to respond appropriately to changes in load or other disturbances. Fig. 7 shows an illustration of this scenario.

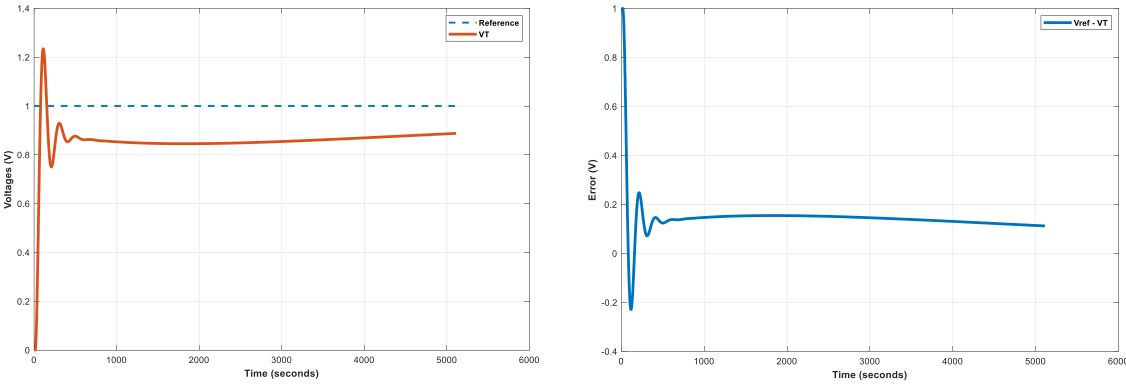


(a) Voltages amplitude for AVR-only (b) Error for AVR-only

Fig. 7. Step response and error for AVR-only in MATLAB

4.3. AVR System with PID Controller

The tracks performance for the proposed system is investigated, as well as its stability in response to a unit reference input. When this response is contrasted with the AVR that does not have a PID controller, the PID controller system was more sensitive to changes or disruptions. As a result, the error signal response produced by the PID controller was more advantageous. Upon closer inspection, the error curve revealed a more favorable curve in comparison to the error seen in the absence of the PID controller, as shown in Fig. 8.

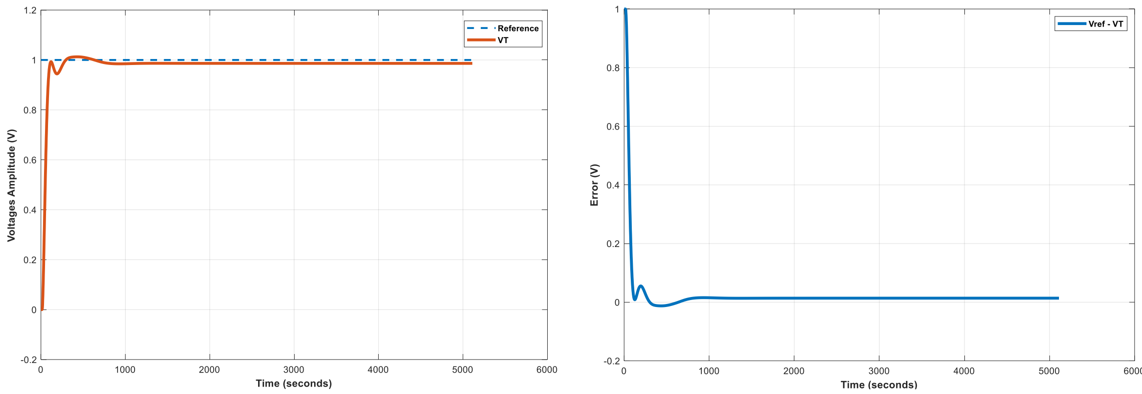


(a) Voltages for PID Controller (b) Error for PID Controller

Fig. 8. Step response and error for AVR-PID in MATLAB

4.4. Hybrid Controller AVR System

The hybrid controller that was specifically designed to replace the PID controller was used, and the error and response curves that resulted were examined. It is noteworthy that these curves demonstrated a significant improvement in the system's response time to disturbances in comparison to the PID controller's use. Furthermore, it should be mentioned that the system using the Hybrid Controller exhibits a slight steady-state error, as shown in Fig. 9.

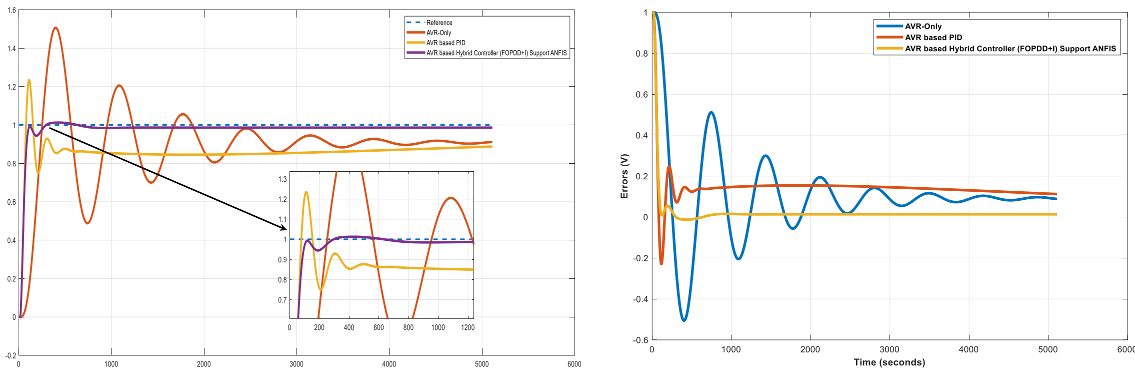


(a) Voltages for hybrid controller (b) Error for hybrid controller

Fig. 9. Step Response and Error for AVR-Hybrid Controller in MATLAB

4.5. Comparative Evaluation of Complete Sets

A comparison of the functionality of several configurations was conducted. These included the AVR system alone with no controllers, as well as setups using the FOPID, PID, FOPD-I, and Hybrid controller with ANFIS. Their respective reactions to a unit step reference input were the focus of this analysis. It is noteworthy that three different curves show how each setup responds to a unit step input. The configuration in which there was no controller connected exhibited chaotic behavior with no apparent stable point, while the PID, FOPID, FOPD-I, and hybrid controller curves using ANFIS stabilized steadily over time. More specifically, the hybrid controller's curve behaved better than the PID controller's, showing less overshoot and a quicker rise time. The comparison between the hybrid controller with and without load (LTI System) is shown in the final set of curves, which are represented by Fig. 10, Fig. 11, Fig. 12, and Fig. 13, respectively.



(a) Comparison over three setups in step response (b) Comparison over three setups in errors

Fig. 10. Comparison over three setups based step response and errors

In a similar vein, all curves' steady-state characteristics, like those in the previous figures, showed behaviour like Fig. 11. The setup curve for the Hybrid controller based on ANFIS, on the other hand, demonstrated superiority over the PID controller configuration, albeit with a slight steady-state error. Additionally, for every setup, using the "step-info" commands on the MATLAB commands screen allowed of this recording and display for relevant characteristics, which are described in Table 3.

Table 3 shows that while the PID controller is less effective than the Hybrid controller, the rise time for the AVR-only setup is roughly 75% faster than that of the PID setup. The hybrid controller setup performs better than both the PID setup and the AVR-only setup in terms of settling time and overshoot performance. Despite this, the hybrid controller outperforms the AVR-only setup, the PID setup, the FOPID controller setup, and the FOPD-I controller setup in terms of steady-state performance. As a result, the hybrid controller setup performs better overall than the other configurations overall.

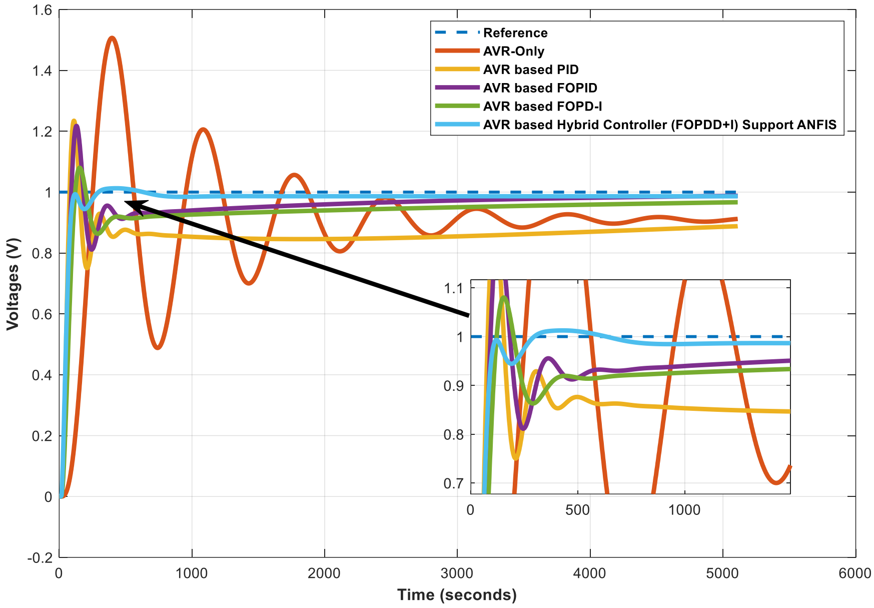


Fig. 11. Comparison between hybrid controller performance and other controllers based step response

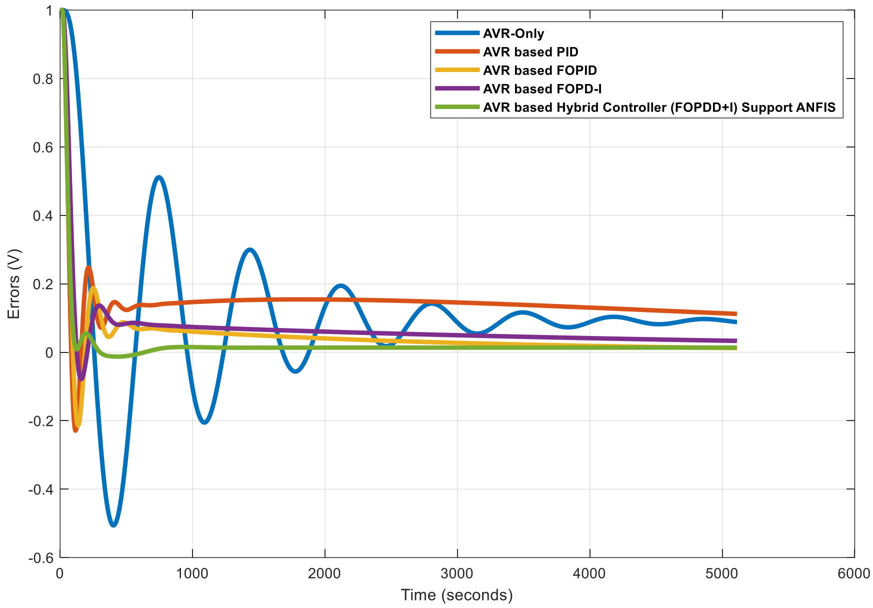


Fig. 12. Comparison between hybrid controller performance and other controllers based errors

Table 3. Criteria of parameters values between AVR-only, AVR with PID, and hybrid controller

Parameters	AVR-only	AVR with PID	AVR with Hybrid Controller (FOPDD+I based ANFIS)
Rise Time (s)	0.40782	0.50367	1.1162
Settling Time (s)	9.97728	3.80925	0.5531
Overshoot (%)	51.066	52.5	0
Undershoot (%)	0.488	0.384	0.345
Steady State Error	0.4468	0.19075	0.00272
Peak	1.50656	1.2345	1.0126
Peak time (s)	0.753	2.19053	0.8

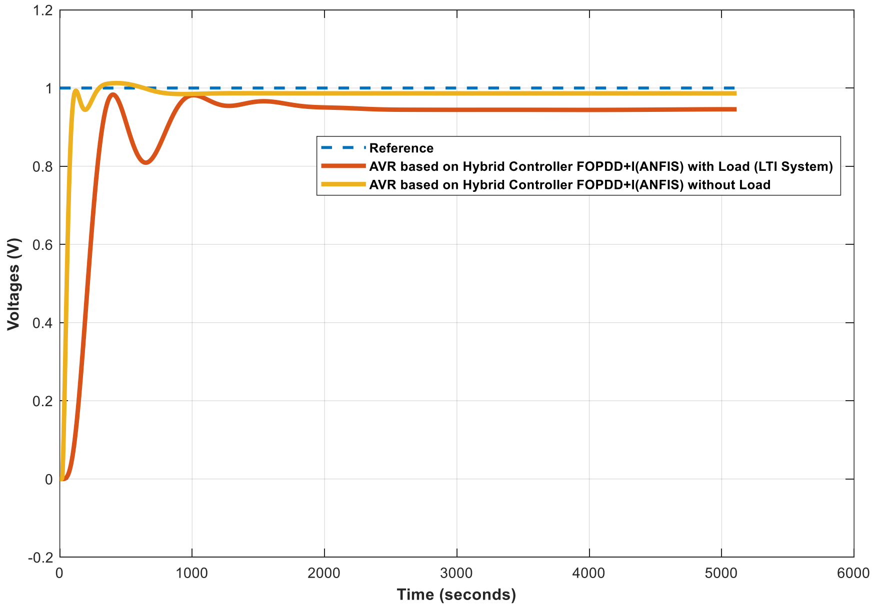


Fig. 13. Comparison between hybrid controller performance with and without load (LTI System)

5. Conclusion

In this study, we delved into the learning algorithms of a Hybrid Intelligent Controller based on ANFIS. We chose and implemented a hybrid learning optimization method to train the Fuzzy Inference System (FIS), which yielded the results outlined in the preceding sections. With zero tolerance and a fixed epoch count of 50, we trained, tested, and validated the optimized FIS using grid partitioning. The results showed that the Hybrid Controller-based ANFIS AVR setup performed well, demonstrating stable output and an improved response to disturbances such as transient voltage changes or load variations, with a steady-state error of 0.00272. The evaluation metrics also returned an acceptable value, with an average testing error of 0.13365. However, the lower overshoot came with a trade-off: a longer settling time. This means that the system would take more time to reach a steady-state value if a disturbance were introduced. This research contributes to improving the performance of an AVR by ensuring a good transient response, adaptability to changing conditions, and robustness against renewable-based generators. This will aid in providing affordable and clean energy, aligning with the seventh Sustainable Development Goal, and will boost energy penetration in Iraq. In future work, the recommendations can be considered as follows:

- The study found that the lower overshoot came with a trade-off: a longer settling time. Future studies could focus on optimizing the settling time without compromising the system's stability or increasing the overshoot.
- While this study used a hybrid learning optimization method to train the Fuzzy Inference System (FIS), future research could explore the use of other learning algorithms to see if they yield better results.
- This study used a fixed epoch count of 50 for training. Future studies could experiment with variable epoch counts to determine if this improves the system's performance.
- This study tested the system's robustness against renewable-based generators. Future research could test the system's robustness against different types of generators, such as fossil fuel-based generators or nuclear power generators.
- If the studies so far have been conducted in a controlled environment, future research could involve testing the system in real-world conditions to see how it performs.
- As this research aligns with the seventh Sustainable Development Goal, future studies could also consider the impact of these systems on other Sustainable Development Goals.

The research findings underscore the pivotal role of AVR systems in maintaining voltage stability and enhancing the efficiency of power systems. The significance of these findings cannot be overstated, as they provide a foundation for the development of more reliable and efficient power systems. The use of advanced control units in AVR systems, as well as the application of modern simulation tools like MATLAB Simulink, are instrumental in achieving these goals. However, the journey does not end here. The field of power engineering is dynamic and constantly evolving. As such, there is a pressing need for continued research and innovation in this area. This is a call to action for all researchers, engineers, and stakeholders in the field. Can build a future where power systems are not just efficient and reliable, but also sustainable and resilient. The future of our planet depends on it.

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References

[1] N. Kanagaraj, "An Adaptive Neuro-Fuzzy Inference System to Improve Fractional Order Controller Performance," *Intelligent Automation & Soft Computing*, vol. 35, no. 3, pp. 3213-3226, 2023, https://doi.org/10.32604/iasc.2023.029901.

[2] N. B. Mohamadwasel, "Rider Optimization Algorithm implemented on the AVR Control System using MATLAB with FOPID," *IOP Conference Series: Materials Science and Engineering*, vol. 928, no. 3, p. 032017, 2020, https://doi.org/10.1088/1757-899X/928/3/032017.

[3] M. J. Lawal, S. U. Hussein, B. Saka, S. U. Abubakar, and I. S. Attah, "Intelligent fuzzy-based automatic voltage regulator with hybrid optimization learning method," *Scientific African*, vol. 19, p. e01573, 2023, https://doi.org/10.1016/j.sciaf.2023.e01573.

[4] Ö. Can, C. Andiç, S. Ekinci, and D. Izci, "Enhancing transient response performance of automatic voltage regulator system by using a novel control design strategy," *Electrical Engineering*, vol. 105, no. 4, pp. 1993–2005, 2023, https://doi.org/10.1007/s00202-023-01777-8.

[5] A. Jegatheesh, V. Thiyagarajan, N. B. M. Selvan, and M. D. Raj, "Voltage regulation and stability enhancement in AVR system based on SOA-FOPID controller," *Journal of Electrical Engineering & Technology*, vol. 19, no. 1, pp. 31–44, 2024, https://doi.org/10.1007/s42835-023-01507-x.

[6] O. A. M. Omar, M. I. Marei, and M. A. Attia, "Comparative Study of AVR Control Systems Considering a Novel Optimized PID-Based Model Reference Fractional Adaptive Controller," *Energies*, vol. 16, no. 2, p. 830, 2023, https://doi.org/10.3390/en16020830.

[7] A. Ali, D. B. Bantyirga, and D. G. Biru, "A Review on Design and Control of AGC and AVR for Multi-Area Interconnected Power system," *International Journal of Scientific & Engineering Research*, vol. 13, no. 2, pp. 317–325, 2022, https://www.ijser.org/onlineResearchPaperViewer.aspx?A-Review-on-Design-and-Control-of-AGC-and-AVR-for-Multi-Area-Interconnected-Power-system.pdf.

[8] N. Basil and H. M. Marhoon, "Towards evaluation of the PID criteria based UAVs observation and tracking head within resizable selection by COA algorithm," *Results in Control and Optimization*, vol. 12, p. 100279, 2023, https://doi.org/10.1016/j.rico.2023.100279.

[9] M. M. Hoque, "Design, implementation and performance study of programmable automatic voltage regulator," *Journal of Electrical Systems*, vol. 10, no. 4, pp. 472–483, 2014, https://www.proquest.com/docview/2274273042?pq-origsite=gscholar&fromopenview=true&sourcetype=Scholarly%20Journals.

[10] N. B. Mohamadwasel and S. Kurnaz, "Implementation of the parallel robot using FOPID with fuzzy type-2 in use social spider optimization algorithm," *Applied Nanoscience*, pp. 1–11, 2021, https://doi.org/10.1007/s13204-021-02034-9.

[11] R. J. Widlar, "New developments in IC voltage regulators," *IEEE Journal of Solid-State Circuits*, vol. 6, no. 1, pp. 2-7, 1971, https://doi.org/10.1109/JSSC.1971.1050151.

[12] N. Basil, H. M. Marhoon, M. R. Hayal, E. E. Elsayed, I. Nurhidayat, and M. A. Shah, "Black-hole optimisation algorithm with FOPID-based automation intelligence photovoltaic system for voltage and power issues," *Australian Journal of Electrical and Electronics Engineering*, pp. 1-13, 2024, https://doi.org/10.1080/1448837X.2024.2308415.

[13] M. J. Blondin, P. Sicard, and P. M. Pardalos, "Controller Tuning Approach with robustness, stability and dynamic criteria for the original AVR System," *Mathematics and Computers in Simulation*, vol. 163, pp. 168–182, 2019, https://doi.org/10.1016/j.matcom.2019.02.019.

[14] D. Al-Fraihat, M. Joy, J. Sinclair, "Evaluating E-learning systems success: An empirical study," *Computers in human behavior*, vol. 102, pp. 67-86, 2020, https://doi.org/10.1016/j.chb.2019.08.004.

[15] N. Basil, M. E. Alqaysi, M. Deveci, A. S. Albahri, O. S. Albahri, and A. H. Alamoodi, "Evaluation of autonomous underwater vehicle motion trajectory optimization algorithms," *Knowledge-Based Systems*, vol. 276, p. 110722, 2023, https://doi.org/10.1016/j.knosys.2023.110722.

[16] K. Hirayama *et al.*, "Digital AVR application to power plants," *IEEE Transactions on Energy Conversion*, vol. 8, no. 4, pp. 602-609, 1993, https://doi.org/10.1109/60.260970.

[17] N. Basil, H. M. Marhoon, and A. R. Ibrahim, "A new thrust vector-controlled rocket based on JOA using MCDA," *Measurement: Sensors*, vol. 26, p. 100672, 2023, https://doi.org/10.1016/j.measen.2023.100672.

[18] F. S. Raheem and N. Basil, "Automation intelligence photovoltaic system for power and voltage issues based on Black Hole Optimization algorithm with FOPID," *Measurement: Sensors*, vol. 25, p. 100640, 2023, https://doi.org/10.1016/j.measen.2022.100640.

[19] H. M. Marhoon, A. I. Alanssari, and N. Basil, "Design and Implementation of an Intelligent Safety and Security System for Vehicles Based on GSM Communication and IoT Network for Real-Time Tracking," *Journal of Robotics and Control*, vol. 4, no. 5, pp. 708-718, 2023, https://doi.org/10.18196/jrc.v4i5.19652.

[20] N. Basil and A. Ma'arif, "NB Theory with Bargaining Problem: A New Theory," *International Journal of Robotics and Control Systems*, vol. 2, no. 3, pp. 606-609, 2022, https://doi.org/10.31763/ijrcs.v2i3.798.

[21] N. Basil, H. M. Marhoon, S. Gokulakrishnan, and D. Buddhi, "Jaya optimization algorithm implemented on a new novel design of 6-DOF AUV body: a case study," *Multimedia Tools and Applications*, pp. 1–26, 2022, https://doi.org/10.1007/s11042-022-14293-x.

[22] H. M. Marhoon, A. R. Ibrahim, and N. Basil, "Enhancement of Electro Hydraulic Position Servo Control System Utilising Ant Lion Optimiser," *International Journal of Nonlinear Analysis and Applications*, vol. 12, no. 2, pp. 2453–2461, 2021, https://doi.org/10.22075/ijnaa.2021.5387.

[23] A. R. Ibrahim, N. Basil, and M. I. Mahdi, "Implementation enhancement of AVR control system within optimization techniques," *International Journal of Nonlinear Analysis and Applications*, vol. 12, no. 2, pp. 2021–2027, 2021, https://doi.org/10.22075/ijnaa.2021.5339.

[24] H. M. Marhoon, N. Basil, and A. Ma'arif, "Exploring Blockchain Data Analysis and Its Communications Architecture: Achievements, Challenges, and Future Directions: A Review Article," *International Journal of Robotics and Control Systems*, vol. 3, no. 3, pp. 609-626, 2023, https://doi.org/10.31763/ijrcs.v3i3.1100.

[25] N. Basil and H. M. Marhoon, "Selection and evaluation of FOPID criteria for the X-15 adaptive flight control system (AFCS) via Lyapunov candidates: Optimizing trade-offs and critical values using optimization algorithms," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 6, p. 100305, 2023, https://doi.org/10.1016/j.prime.2023.100305.

[26] A. H. Mukalaf, H. M. Marhoon, I. Suwarno, and A. Ma'arif, "Design and Manufacturing of Smart Car Security System with IoT-Based Real-Time Tracking," *International Journal of Intelligent Systems and*

Applications in Engineering, vol. 11, no. 6s, pp. 745–752, 2023, https://www.ijisae.org/index.php/IJISAE/article/view/2909.

[27] T. M. Salman, H. N. Abdullah, H. M. Marhoon, and Z. A. Karam, "Design and Fabrication of a Smart Monitoring System for Liquefied Petroleum Gas-Operated Cars Based on Global System Mobile," *International Journal of Online and Biomedical Engineering*, vol. 19, no. 11, pp. 96-111, 2023, https://doi.org/10.3991/ijoe.v19i11.41937.

[28] M. Murad, O. Bayat, and H. M. Marhoon, "Design and implementation of a smart home system with two levels of security based on IoT technology," *The Indonesian Journal of Electrical Engineering and Computer Science*, vol. 21, no. 1, pp. 546-557, 2021, http://doi.org/10.11591/ijeecs.v21.i1.pp546-557.

[29] I. A. Taha and H. M. Marhoon, "Implementation of controlled robot for fire detection and extinguish to closed areas based on Arduino," *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 16, no. 2, pp. 654-664, 2018, http://doi.org/10.12928/telkomnika.v16i2.8197.

[30] H. M. Marhoon, N. Basil, and A. F. Mohammed, "Medical Defense Nanorobots (MDNRs): a new evaluation and selection of controller criteria for improved disease diagnosis and patient safety using NARMA(L2)-FOP + D(ANFIS)μ–Iλ-based Archimedes Optimization Algorithm," *International Journal of Information Technology*, pp. 1-14, 2024, https://doi.org/10.1007/s41870-023-01724-7.

[31] M. N. Hussain, M. R. Zaman, M. A. Halim, M. S. Ali, and M. Y. A. K. Khan, "A Comprehensive Review of Renewable and Sustainable Energy Sources with Solar Photovoltaic Electricity Advancement in Bangladesh," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 1–7, 2024, https://doi.org/10.59247/csol.v2i1.59.

[32] N. Ramadhani, A. Ma'arif, and A. Çakan, "Implementation of PID Control for Angular Position Control of Dynamixel Servo Motor," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 8–14, 2024, https://doi.org/10.59247/csol.v2i1.40.

[33] M. N. Hussain, M. A. Halim, M. Y. A. Khan, S. Ibrahim, and A. Haque, "A Comprehensive Review on Techniques and Challenges of Energy Harvesting from Distributed Renewable Energy Sources for Wireless Sensor Networks," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 15–22, 2024, https://doi.org/10.59247/csol.v2i1.60.

[34] M. S. Ali, A. Sharma, T. A. Joy, and M. A. Halim, "A Comprehensive Review of Integrated Energy Management for Future Smart Energy System," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 43–51, 2024, https://doi.org/10.59247/csol.v2i1.77.

[35] M. R. Zaman, M. R. Hoque, and M. S. Ali, "An Intensive Analysis of the Energy Management System for Hybrid Electric Vehicles and Electric Drive System Powered by Renewable Energy Sources," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 60–67, 2024, https://doi.org/10.59247/csol.v2i1.75.

[36] M. R. Zaman, M. A. Halim, M. Y. A. Khan, S. Ibrahim, and A. Haque, "Integrating Micro and Smart Grid-Based Renewable Energy Sources with the National Grid in Bangladesh-A Case Study," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 75–81, 2024, https://doi.org/10.59247/csol.v2i1.76.

[37] M. Y. A. Khan, "A Review on Nanotechnology and Its Impact with Challenges on Electrical Engineering," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 82-89, 2024, https://doi.org/10.59247/csol.v2i1.78.

[38] E. Alfian, A. Ma'arif, P. Chotikunnan, and A. J. Abougarair, "Optimizing Light Intensity with PID Control," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 124-131, 2023, https://doi.org/10.59247/csol.v1i3.38.

[39] F. Furizal, S. A. Akbar, A. Yudhana, and M. Kusno, "Analysis of the Influence of Number of Segments on Similarity Level in Wound Image Segmentation Using K-Means Clustering Algorithm," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 132–138, 2023, https://doi.org/10.59247/csol.v1i3.33.

[40] M. A. Yulianto and A. Fadlil, "Wood Type Identification System using Naive Bayes Classification," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 139-143, 2023, https://doi.org/10.59247/csol.v1i3.52.

[41] Z. Salsabila and N. S. Widodo, "Implementation of Behavior Based Robotics on Hexapod Legged Robot Based on Room Mapping," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 144–150, 2023, https://doi.org/10.59247/csol.v1i3.55.

[42] A. Adnan and E. H. Karam, "Optimal Improved PID Controller with GOA Algorithm for Single Link Human Leg Robot," *Journal of Engineering and Sustainable Development*, vol. 26, no. 2, pp. 103–110, 2022, https://doi.org/10.31272/jeasd.26.2.10.

[43] S. C. Ariadita and A. Ma'arif, "Development of an IoT-Monitoring and Control System for Solar Panel Surface Temperature Regulation Utilizing Water-Cooling Techniques," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 174–180, 2023, https://doi.org/10.59247/csol.v1i3.44.

[44] O. R. Khalaf and A. A. Almukhtar, "Design and Implementation of Arduino-Based Sterilization Robot," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 181–185, 2023, https://doi.org/10.59247/csol.v1i3.62.

[45] A. Haque, M. N. Hussain, M. S. Ali, M. Y. A. Khan, and M. A. Halim, "Technical and Economic Challenges and Future Prospects of a Smart Grid-A Case Study," *Control Systems and Optimization Letters*, vol. 1, no. 3, pp. 186–193, 2023, https://doi.org/10.59247/csol.v1i3.57.

[46] A. A. Cahya and R. D. Puriyanto, "The Design of Rice Milling and Screening Systems Uses the DC Motor PID Method," *Control Systems and Optimization Letters*, vol. 1, no. 1, pp. 1–6, 2023, https://doi.org/10.59247/csol.v1i1.2.

[47] A. F. Mohammed *et al.*, "Selection and Evaluation of Robotic Arm based Conveyor Belts (RACBs) Motions: NARMA (L2)-FO (ANFIS) PD-I based Jaya Optimization Algorithm," *International Journal of Robotics and Control Systems*, vol. 4, no. 1, pp. 262–290, 2024, https://doi.org/10.31763/ijrcs.v4i1.1243.

[48] R. Rikwan and A. Ma'arif, "DC Motor Rotary Speed Control with Arduino UNO Based PID Control," *Control Systems and Optimization Letters*, vol. 1, no. 1, pp. 27–31, 2023, https://doi.org/10.59247/csol.v1i1.6.

[49] M. A. Ali, A. H. Miry, and T. M. Salman, "Implementation of Artificial Intelligence in Controlling the Temperature of Industrial Panel," *Journal of Engineering and Sustainable Development*, vol. 25, no. 1, pp. 92–99, 2021, https://doi.org/10.31272/jeasd.25.1.8.

[50] G. D. Eddine, N. Abdellatif, and S. Abdelkader, "Power System Stabilizer Design using Genetic Algorithms and Particle Swarm Optimization," *Control Systems and Optimization Letters*, vol. 1, no. 1, pp. 52–57, 2023, https://doi.org/10.59247/csol.v1i1.15.

[51] M. S. Amin *et al.*, "Development of AVR controller performance using exponential distribution and transit search optimization techniques," *Frontiers in Energy Research*, vol. 12, p. 1356978, 2024, https://doi.org/10.3389/fenrg.2024.1356978.

[52] P. Gopi, S. V. Reddy, M. Bajaj, I. Zaitsev, and L. Prokop, "Performance and robustness analysis of V-Tiger PID controller for automatic voltage regulator," *Scientific Reports*, vol. 14, no. 1, p. 7867, 2024, https://doi.org/10.1038/s41598-024-58481-1.

[53] G. Saravanan, K. P. Suresh, and C. Pazhanimuthu, "Artificial Rabbits Optimization Algorithm based Tuning of PID Controller Parameters for Improving Voltage Profile in AVR System Using IoT," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 8, p. 100523, 2024, https://doi.org/10.1016/j.prime.2024.100523.

[54] A. K. Sahoo, A. K. Sahoo, S. Nayak, and S. K. Kar, "Load Frequency and Voltage Control of Two Area Interconnected Power System using Covariance Matrix Adaptation Evolution Strategy based Aquila Optimization optimized Fast Fuzzy-Fractional Order Tilt Integral Derivative Controller," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 8, p. 100488, 2024, https://doi.org/10.1016/j.prime.2024.100488.

[55] D. Izci *et al.*, "Refined sinh cosh optimizer tuned controller design for enhanced stability of automatic voltage regulation," *Electrical Engineering*, pp. 1-14, 2024, https://doi.org/10.1007/s00202-024-02344-5.

[56] B. Çavdar, E. Şahin, and E. Sesli, “On the assessment of meta-heuristic algorithms for automatic voltage regulator system controller design: a standardization process,” *Electrical Engineering*, pp. 1-39, 2024, https://doi.org/10.1007/s00202-024-02314-x.

[57] P. K. Pathak, M. Jain, and A. K. Yadav, “Metaheuristic-assisted advanced control approach for time delayed unstable automatic voltage regulator,” *Electric Power Components and Systems*, vol. 52, no. 2, pp. 173-188, 2024, https://doi.org/10.1080/15325008.2023.2215793.

[58] M. Č. Bošković, T. B. Šekara, D. M. Stojić, and M. R. Rapaić, “Novel tuning rules for PIDC controllers in automatic voltage regulation systems under constraints on robustness and sensitivity to measurement noise,” *International Journal of Electrical Power & Energy Systems*, vol. 157, p. 109791, 2024, https://doi.org/10.1016/j.ijepes.2024.109791.

[59] N. D. Chetty, G. Sharma, R. Gandhi and E. Çelik, “A Novel Salp Swarm Optimization Oriented 3-DOF-PIDA Controller Design for Automatic Voltage Regulator System,” *IEEE Access*, vol. 12, pp. 20181-20196, 2024, https://doi.org/10.1109/ACCESS.2024.3360300.

[60] H. Shukla and M. Raju, “Combined frequency and voltage regulation in an interconnected power system using fractional order cascade controller considering renewable energy sources, electric vehicles and ultra capacitor,” *Journal of Energy Storage*, vol. 84, p. 110875, 2024, https://doi.org/10.1016/j.est.2024.110875.