Advanced Control Strategies for DC Motor Speed Regulation: A Comparative Study of Artificial Neural Networks and ANFIS

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Abstract
This study compares Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and Artificial Neural Networks (ANN) as DC motor speed control techniques using Simulink. Both controllers perform well, exhibiting minimal overshoot and similar rising times. ANFIS excels in stability and robustness, while ANN offers precision and efficiency through learning. These findings have implications for industries like robotics, aerospace, and automotive, emphasizing the importance of precise motor speed control. The article suggests future research directions, including hybrid control systems that combine ANFIS and ANN strengths for improved performance and the integration of advanced optimization algorithms to enhance controller performance. In summary, this research provides valuable insights for practitioners and researchers, aiding their choice of control techniques for DC motor applications, and encourages further exploration to advance motor control techniques.

Keywords
DC motor, speed regulation, Artificial Neural Networks, Adaptive Neuro-Fuzzy Inference Systems, control strategies, comparative study

1. Introduction

The advent of motor drives has profoundly influenced diverse domains, encompassing industrial, medical, and aerospace applications [1]. Particularly advantageous is achieving precise and dynamic speed control through high-performance motor drives [2]. Among these, DC drives have garnered considerable popularity owing to their cost-effectiveness, versatility, durability, and user-friendliness [3]. Notably, they find widespread employment in industrial settings where meticulous regulation of speed and position is imperative [4]. The favorable speed torque characteristics exhibited by DC motors facilitate seamless adjustments during acceleration and deceleration.

Furthermore, their long-standing utilization in speed modulation further bolsters their appeal, attributable to their affordability [5]. Industries such as robotics and CNC machining, which hinge upon optimal performance and high precision, necessitate accurate speed and position control [6]. These illustrations underscore the criticality of precise speed control across various industrial sectors and non-industrial applications [7].

The present study aims to conduct a comparative analysis of two control techniques, namely Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), about their efficacy in DC motor control [8]. By implementing and simulating the proposed control systems using the Simulink platform, this investigation seeks to ascertain the most efficacious approach for DC motor control through a comprehensive evaluation of their respective

DTESI 2023: Proceedings of the 8th International Conference on Digital Technologies in Education, Science and Industry, December 06–07, 2023, Almaty, Kazakhstan
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performances [9]. Representative speed reference profiles and diverse operational conditions will be employed to train and assess the controllers [11]. Through a series of experiments and subsequent analysis, the effectiveness of each control methodology will be evaluated, thereby enabling a meticulous comparative examination [12].

By simulating and scrutinizing the performance of ANN and ANFIS controllers using the Simulink platform, this study intends to furnish empirical evidence and profound insights concerning their capabilities and limitations in DC motor speed regulation [13]. The ensuing findings are expected to augment the existing corpus of knowledge while guiding researchers, engineers, and practitioners in making informed decisions regarding selecting the most efficacious control strategy for realizing precise and efficient speed control in DC motors. Ultimately, such advancements in DC motor performance hold the potential to usher in transformative developments within industrial applications [14].

The present study aspires to provide invaluable insights into the performance characteristics of ANN and ANFIS control techniques in DC motor speed regulation. Through simulation-based assessments and meticulous comparative analyses, this research endeavor is poised to enrich the extant understanding of these control methodologies, thereby facilitating the selection of the most appropriate approach for achieving precise and efficient speed control in DC motors.

Problem statement

Achieving precise and efficient speed regulation in DC motors is crucial for various industrial applications. Traditional control strategies often need help handling the inherent nonlinearities and uncertainties of DC motor systems, leading to limitations in control accuracy. In recent years, advanced control strategies such as Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have shown promise in improving the control performance of DC motors. However, the existing literature needs to include a comprehensive comparative study between ANN and ANFIS for DC motor speed regulation. There is a need to systematically evaluate and compare the effectiveness and performance of these advanced control strategies to determine their suitability for achieving precise and efficient speed control in DC motors.

Aim and objectives

The main aim of this study is to evaluate and compare the performance of two advanced control techniques, Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), for DC motor control and determine the most suitable approach for achieving precise and efficient c Comparison of Control Techniques: Compare the effectiveness of ANFIS and ANN control techniques in terms of their ability to control a DC motor. Evaluate their performance in speed tracking accuracy, dynamic response, robustness to disturbances, and adaptability to varying motor parameters. To achieve this aim, the objectives of this study are:

- Performance Evaluation: Conduct extensive simulations to evaluate and compare the performance of ANFIS and ANN in controlling DC motors. Assess their stability, control accuracy, and response characteristics under various operating conditions.
- Analysis and Comparison: Analyze the simulation results and compare the performance of ANFIS and ANN control techniques. Identify the strengths and limitations of each approach and determine which plan offers superior control performance for DC motor applications.

The results of this study will provide valuable insights into the strengths and limitations of ANFIS and ANN control techniques for DC motor control. The findings will contribute to advancing control strategies for DC motor applications and guide future research in developing advanced control techniques.

Scope of the project

This project aims to evaluate and compare the performance of two advanced control techniques, Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), for DC motor control. The project will specifically focus on the simulation and implementation of these control systems using the Simulink platform. The main objective is to determine the most effective technique for achieving precise and efficient control of DC motors.

The results of this study can be used to improve the performance of DC motor control systems in various applications such as robotics, automation, aerospace, and automotive industries. However, it is essential to note that this project involves something other than physically implementing the control systems on real DC motors. Therefore, the findings should be interpreted in the context of simulation-based studies.

Summaries of chapters

The rest of the paper is structured as follows: Chapter 2 reviews related works in DC motor speed regulation and utilizing Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) in control applications. Chapter 3 describes the experimental setup and methodology used for the comparative study. Chapter 4 presents the results and analysis obtained from the experiments. Finally, Chapter 5 concludes the paper with a summary of findings, limitations, and suggestions for future research.

2. Literature review

The scientific community has witnessed extensive research efforts aimed at developing effective speed controllers for DC motors. The proportional-integral-derivative (PID) controller has been widely adopted among the various control techniques. However, numerous studies have highlighted certain limitations associated with PID controllers, including overshooting, slow response to sudden changes in torque demand, and susceptibility to controller enhancements [15]. Researchers have explored alternative strategies such as fuzzy logic and fractional order PID algorithms to address these challenges. This section provides a summary of notable studies conducted in the field of DC motor speed control, as documented in the existing literature.

In a study by authors [16], a Fuzzy PID controller was applied to a DC motor, with fuzzy logic utilized to adjust the PID controller's gains (KP, KI, KD). The findings indicated that the Fuzzy controller exhibited superior performance with its optimized gains compared to the conventional PID controller. Similarly, in [17], a comparative analysis between PID and fuzzy logic controllers for DC motor speed regulation was presented. The investigation demonstrated that the utilization of the Fuzzy controller resulted in minimal overshoot and settling time.

Another study [18] proposed a novel method for optimizing the tuning of a fractional order PID controller in DC motor speed control. This approach introduced two additional parameters, λ, and μ, representing the integral and derivative orders of the fractional-order PID controller, respectively. The authors employed a Particle Swarm Optimization (PSO) technique to determine the optimal values for these parameters. The results revealed that the optimized fractional-order PID controller achieved both flexibility and robust stability, adapting effectively to varying operating conditions.

In reference [19], researchers examined the application of a Genetic Algorithm (GA)-based PID controller to mitigate overshooting in DC motor speed control. A comparative analysis was conducted, pitting the performance of the GA-based PID controller against that of a conventional PID controller. The outcomes demonstrated that the GA-based PID controller outperformed the conventional PID controller across key performance metrics, including rise time, speed overshooting, and settling time.

Furthermore, a study by authors [20] explored the implementation of Fuzzy PID controllers using Field Programmable Gate Arrays (FPGA). Leveraging the parallel processing capabilities offered by FPGA programming, the researchers evaluated the performance of both PID and Fuzzy controllers on a shared FPGA platform. Experimental results clearly indicated that the FPGA controller's dynamic response surpassed that of the traditional PID and Fuzzy controllers.

In reference [21], the focus was on tuning a PID controller for speed control of a real-time DC shunt motor, employing two different methods: the Ziegler-Nichols method and the Simulated Annealing method. Comparative analysis of the two approaches revealed that utilizing the Simulated Annealing technique for PID controller tuning yielded significant improvements in various time domain specifications, including reduced rise time, peak time, settling time, and overshoot, thus indicating superior overall control performance compared to the Ziegler-Nichols method.

Authors in reference [22] investigated a fuzzy PID controller with a Kalman filter extension for DC motor speed control. The researchers achieved more precise error reduction by adjusting the fuzzy participation function using the Kalman filter. The resulting fuzzy PID controller exhibited a fast rise time, minimal overshoot, and short settling time, demonstrating a precise and effective control response. The incorporation of the Kalman Filter-based strategy enabled accurate tracking of various input references, thereby enhancing system performance.

Moreover, in reference [23], a comparative study was conducted to evaluate the performance of a PI controller and a fuzzy controller for speed control. The investigation highlighted certain drawbacks associated with the PI controller, including significant initial overshoot, vulnerability to controller enhancements, and sluggish response to abrupt disturbances. Conversely, the fuzzy controller showcased superior performance when subjected to substantial changes in the reference input, thereby achieving lower settling times. Despite the limitations, the PI controller demonstrated satisfactory performance for steady-state control.

Finally, reference [24] focused on an armature-based voltage control approach for fuzzy speed regulation of a separately excited DC motor. The motor's speed was controlled by manipulating the armature voltage, and a fuzzy logic controller was employed for this purpose. The study primarily examined the motor's performance below its rated speed in the stable torque region. The results indicated that the armature voltage control approach yielded faster settling times compared to the field control approach, albeit at the expense of increased overshoot.

These studies have shed light on various DC motor speed control methodologies, encompassing fuzzy logic, fractional order PID, genetic algorithms, FPGA implementation, and Kalman filter extensions. The findings and insights gained from these investigations contribute to the advancement of the field, providing researchers and practitioners with valuable information for selecting appropriate control techniques to enhance speed regulation and the overall performance of DC motors.

3. Simulation and experimental results

This chapter provides a concise evaluation and comparison methodology for DC motor control techniques. The emphasis is placed on the application of Artificial neural networks and ANFIS methods. The methodology involves simulating control systems with Simulink and analyzing their performance metrics, such as rise time and %overshoot. By analyzing the simulation results, valuable insights can be gained into the efficacy of neural networks and ANFIS techniques for DC motor control.

3.1. Simulation setup

The simulation setup comprises models of a DC motor and control system. Mathematical equations in the DC motor model describe the behavior of the DC motor. The control system model consists of the following DC motor parameters: armature resistance, armature inductance, a back-emf constant, rotor moment of inertia, viscous damping coefficient, and mechanical load torque.

This comparison will examine the application of a neural network controller and an ANFIS controller. Designing a suitable architecture and training the network with input-output mappings are required for the neural network controller. Relevant state variables of the DC motor, such as the current speed and desired speed, are inputs to the neural network. The network output is the signal used to adjust the motor speed.

Similarly, the ANFIS controller combines the adaptability of neural networks and fuzzy logic. There are membership functions, rules, and adaptive parameters. The ANFIS controller adjusts the motor speed based on input-output data.

Simulink, a software tool for modeling, simulating, and analyzing dynamic systems, performs the simulation with block diagrams representing the components and their interactions. The DC motor control system's Simulink model includes blocks for the DC motor model, the neural network or ANFIS controller model, and the system's inputs and outputs.

3.2. Artificial neural network controller

The primary objective of the paper is to utilize Artificial Neural Networks (ANN) for the control of DC motor speed. The simulation is carried out using the MATLAB environment. ANN is chosen for this purpose due to its high speed, mainly resulting from its parallel structure. Moreover, ANN is well-suited for dealing with nonlinear and complex systems, as it eliminates the need for solving nonlinear equations. Artificial neural networks serve as information processing systems, and their behavior is based on the processing that takes place within individual neurons. Each neuron applies an activation function to its inputs, which involves calculating the weighted sum of the inputs to determine the output. This activation function allows the neural network to model the relationship between inputs and outputs and make predictions or control decisions based on the given data. By employing ANN in the control of the DC motor's speed, the paper aims to harness the benefits of neural networks, such as their parallel processing capability and ability to handle nonlinear and complex systems.

In the network architecture (Figure 1), the symbol (n) represents the summation of output obtained as the inputs of the neuron, while (a) denotes the output generated by the neuron. The activation function (f) is responsible for determining the specific characteristics of the problem being solved. It introduces non-linearity and enables the network to model complex relationships between inputs and outputs.

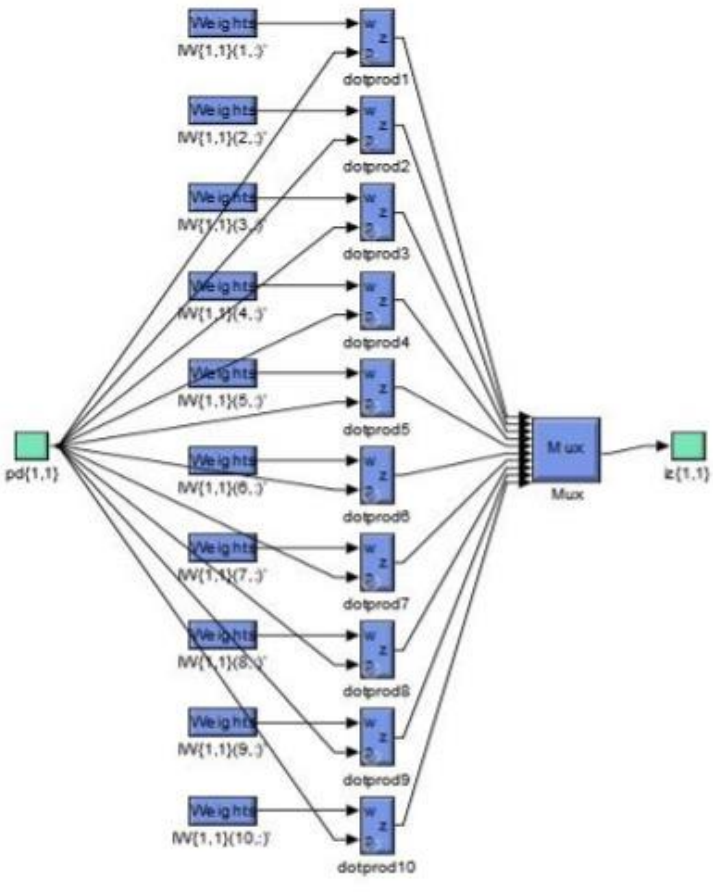

Figure 1: Architecture of ANN

3.3 Artificial adaptive neuro-fuzzy interference system

ANFIS (Adaptive Neuro-Fuzzy Inference System) is a powerful hybrid computational model that combines the advantages of both neural networks and fuzzy logic. It was first introduced by

Jang in 1993 as a method for constructing adaptive fuzzy systems using a combination of neural network and fuzzy logic techniques.

ANFIS is particularly useful in solving problems that involve uncertainty and imprecise information. It combines the ability of neural networks to learn from data and make predictions with the interpretability and linguistic representation of fuzzy logic. The system consists of a set of fuzzy if-then rules that are automatically generated and tuned using a learning algorithm.

A typical ANFIS design is shown in Figure 2, where static nodes are symbolized by circles and adaptable nodes by squares. We concentrate on the two inputs, x and y, combined with one output, z, to keep things simple. Among other FIS models, the Sugeno fuzzy model stands out for its superior interpretability, computational effectiveness, and inclusion of adaptive and optimum strategies. A typical rule set made up of two fuzzy if-then rules may be expressed as follows for a first-order Sugeno fuzzy model:

Rule 1:if x is A_1 and y is B_1,then z_1=p_1 x+q_1 y+r_1

Rule 2:if x is A_2 and y is B_2,then z_2=p_2 x+q_2 y+r_2

Fuzzy sets of Ai and Bi make up the initial state of the fuzzy model, and the training procedure determines the design variables pi, qi, and ri. The ANFIS architecture has five layers, similar to that seen in Figure 2:

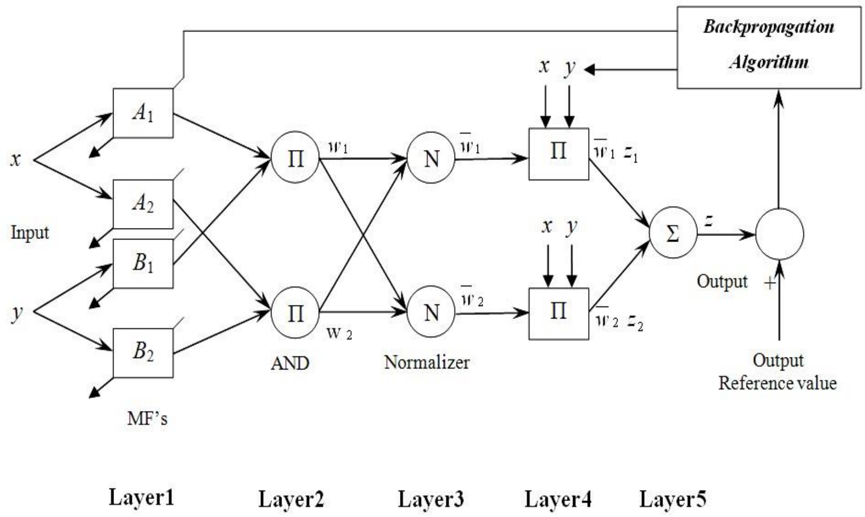

Figure 2: ANFIS architecture

3.4 DC motor control using artificial neural network

The Simulink model (Figure 3) "DC Motor Control Using Artificial Neural Network" is a representation of a control system for a DC motor using an artificial neural network (ANN). The model aims to regulate and control the speed of the DC motor based on the input reference speed. The Simulink model consists of several blocks that perform different functions:

- Input Signal: This block represents the reference speed signal that is provided as an input to the control system. It defines the desired speed at which the DC motor should operate.
- DC Motor Plant: This block represents the physical model of the DC motor. It takes the control input from the neural network and simulates the behaviour of the motor. The model includes the motor's dynamics, such as its electrical and mechanical characteristics.
- Artificial Neural Network (ANN): This block represents the neural network that acts as the controller for the DC motor. The ANN takes the reference speed signal as its input and generates the control signal to regulate the motor's speed. The neural network has been trained using appropriate algorithms to learn the mapping between the input reference speed and the desired control signal.
- Output: This block represents the actual speed output of the DC motor. It provides a visual representation of the motor's speed response to the control signal.

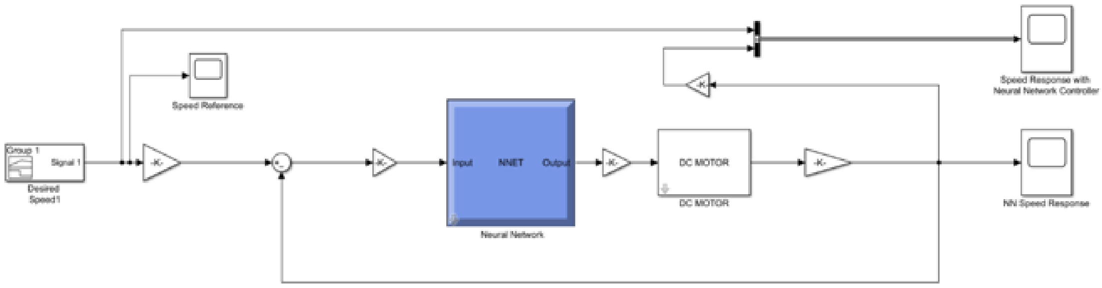

Figure 3: Simulink model of Neural Network Controller for DC Motor

3.5 Results

The graph (Figure 4) depicts two lines: a blue line representing the reference speed generated by the signal builder and a red line representing the actual speed of the DC motor. An Artificial Neural Network (ANN) controls the motor's speed. The graph demonstrates that the actual speed closely tracks the reference speed, indicating the success of the ANN in controlling the DC motor speed. The results reveal that the ANN effectively regulates the DC motor's speed. The low overshoot of 0.847 % indicates that the ANN accurately controls the motor speed without introducing significant deviations from the desired setpoint. This suggests that the ANN precisely estimates the state of the DC motor and generates control inputs that minimize the error between the reference speed and the actual speed. Moreover, the rise time of the ANN in controlling the DC motor speed is 26.868 seconds, which is relatively short compared to the reference speed's rise time of 27 seconds. This signifies that the ANN closely tracks the reference speed with minimal delay. Therefore, the ANN is suitable for applications that demand accurate DC motor speed control with a short delay.

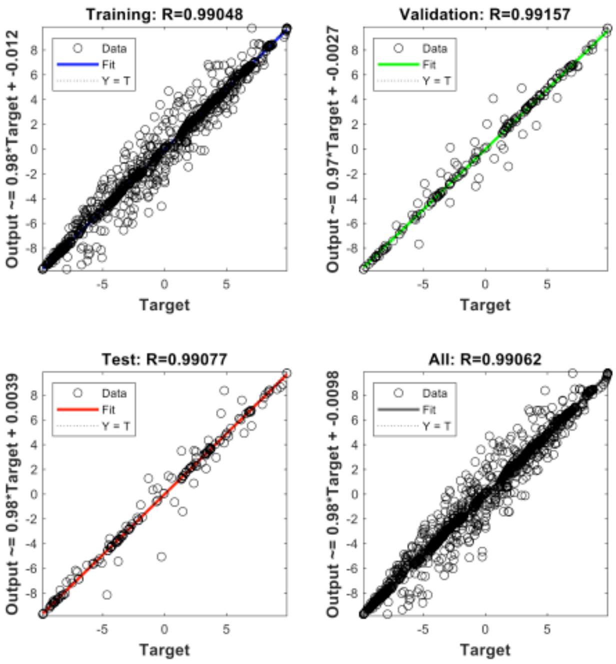

Figure 4: DC Motor speed control using ANN: Graphical Representation

However, it is essential to acknowledge that the rise time requirement may vary depending on the specific application. Further optimization of the ANN's parameters may be necessary for applications requiring faster response times. Additionally, external disturbances or system uncertainties can impact the performance of the ANN. Hence, it is crucial to evaluate the controller's performance within the specific application context and optimize its parameters.

In conclusion, based on these findings, the ANN is effective in controlling the DC motor speed and is well-suited for applications requiring accurate control with minimal delay. However, its performance should be evaluated and optimized considering the application's specific requirements.

3.6 DC Motor Control using ANFIS

The Simulink model for DC motor speed control using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller (Figure 5) is designed to showcase the application of ANFIS control in practical scenarios. The model consists of four main components: the reference speed signal, the DC motor, the ANFIS controller, and the scope.

The reference speed signal is generated using the Signal Builder block, which allows the user to define a custom signal profile representing the desired speed for the DC motor. This reference signal is then fed into the ANFIS controller.

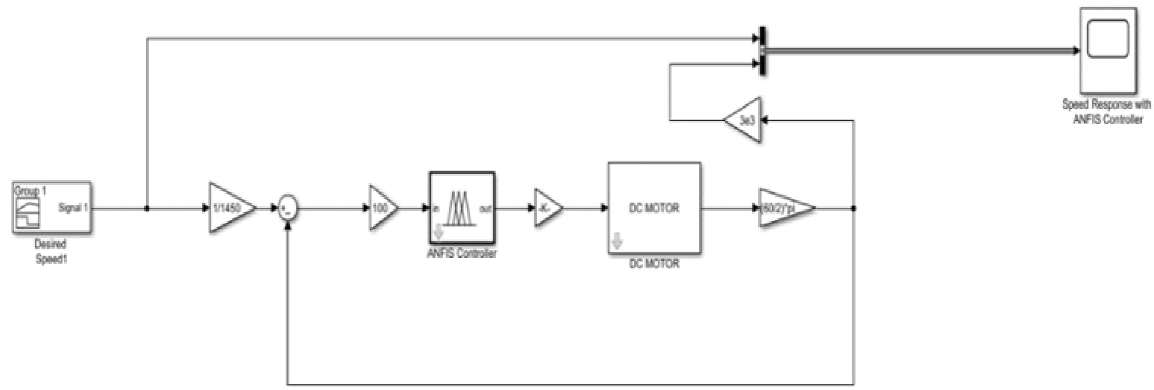

Figure 5: Simulink model of ANFIS Controller for DC Motor

The graph (Figure 6) illustrates the performance of an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller in controlling the speed of a DC motor. The graph consists of two lines: the blue line represents the reference speed generated by the signal builder, and the yellow line represents the actual speed of the DC motor after being controlled by the ANFIS controller.

Based on the results, the ANFIS controller exhibits a small overshoot of 0.820% and a relatively long rise time of 26.955 seconds. The overshoot percentage indicates the deviation of the controlled variable (DC motor speed) from its steady-state value before stabilizing. In this case, the small overshoot of 0.820% suggests that the ANFIS controller effectively minimizes deviations from the desired speed.

However, the relatively long rise time of 26.955 seconds indicates that the ANFIS controller takes a relatively long time to stabilize the DC motor speed. This may not be desirable in applications that require fast response times.

Overall, the results demonstrate that the ANFIS controller is effective in controlling the DC motor speed. The small overshoot suggests that the controller can maintain the motor speed close to its desired value. However, the long rise time indicates a slower response, which may not be suitable for applications requiring fast control.

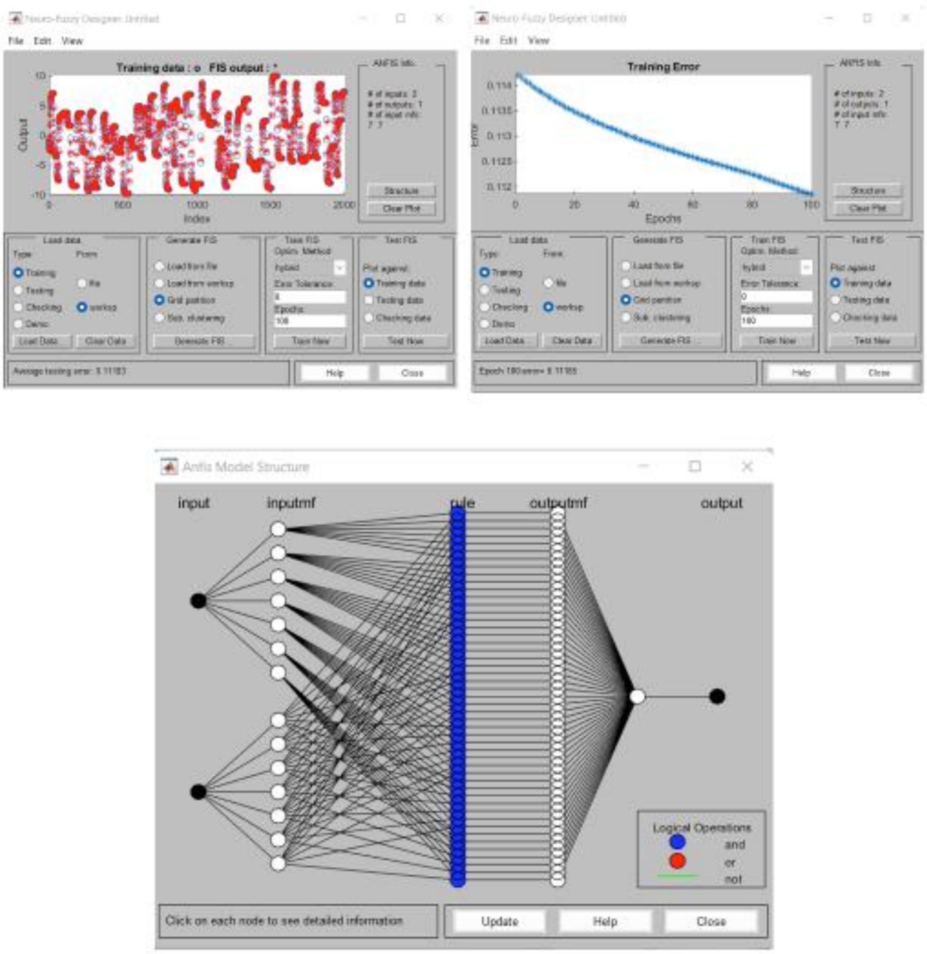

Figure 6: DC Motor speed control using ANFIS: Graphical Representation

4. Discussion

This study comprehensively evaluated and compared two advanced control techniques, ANN (Artificial Neural Networks) and ANFIS (Adaptive Neuro-Fuzzy Inference Systems), for DC motor speed control. Our aim was to determine the most effective controller among these two approaches.

The ANFIS controller combines the strengths of neural networks and fuzzy logic, allowing it to model and adapt to the nonlinear dynamics of the DC motor system. On the other hand, ANN utilizes a network of interconnected artificial neurons to learn and approximate the system's behavior. Both approaches offer promising capabilities for precise and efficient control of DC motors.

Our findings demonstrate that ANN and ANFIS controllers exhibit favorable overshoot and rise time performance, indicating their effectiveness in regulating DC motor speed. However, a more detailed analysis reveals some noteworthy differences. The ANFIS controller shows superior performance in terms of stability and robustness thanks to its ability to interpret and utilize fuzzy rules for system control. It can handle uncertainties and disturbances effectively, making it a reliable choice for DC motor speed control applications.

Moreover, ANFIS provides interpretability, which allows engineers to comprehend the decision-making process and fine-tune the control system based on domain knowledge. On the other hand, ANN offers flexibility and the potential for improved performance through its learning capability and adaptive nature.

Although both ANN and ANFIS controllers demonstrate promising results, it is crucial to consider certain limitations and future research directions. Our study focused primarily on overshoot and rise time as performance metrics, while other important aspects, such as steady-state error and settling time, should also be considered for a comprehensive evaluation.

Furthermore, the generalizability of the findings should be validated by conducting experiments under various operating conditions and system configurations. Additionally, future research can explore the application of hybrid control strategies that combine the strengths of ANN and ANFIS or investigate the incorporation of advanced optimization algorithms to enhance the performance of these controllers.

Recommendations for Future Research:

1. Additional Performance Metrics:

While overshoot and rise time were primary metrics in the study, it's essential to consider other performance metrics, such as steady-state error and settling time. These metrics provide a more comprehensive evaluation of the controllers' performance in different aspects of dynamic response. Steady-state error indicates how well the system reaches and maintains the desired speed, while settling time reflects the time taken by the system to stabilize around the desired speed without oscillations.

2. Generalizability Testing:

Conducting experiments under various operating conditions and system configurations is crucial to validate the generalizability of the findings. Different operating conditions may introduce variations in motor dynamics, load characteristics, or environmental factors. Testing the controllers under diverse scenarios helps ensure that the observed performance holds true across a range of real-world conditions, increasing the robustness and applicability of the controllers.

3. Hybrid Control Strategies:

Exploring hybrid control strategies involves combining the strengths of both ANN and ANFIS controllers. This could involve integrating the learning capabilities of ANN with the interpretability and robustness of ANFIS. Hybrid approaches have the potential to synergistically leverage the unique features of each controller, potentially leading to improved overall performance. This recommendation encourages researchers to investigate innovative ways to integrate these controllers for enhanced control efficiency.

4. Incorporation of Optimization Algorithms:

Investigating the incorporation of advanced optimization algorithms aims to enhance the performance of both ANN and ANFIS controllers. Optimization algorithms can be applied to fine-tune controller parameters, improve convergence speed, and optimize control strategies. This recommendation suggests exploring how optimization algorithms, such as genetic algorithms or particle swarm optimization, can be integrated into the controller design process to further enhance their effectiveness in DC motor speed control applications.

In conclusion, our study highlights the effectiveness of both ANN and ANFIS controllers for DC motor speed control. The ANFIS controller, with its interpretability and robustness, offers a promising approach for achieving precise and efficient control in DC motor applications. The findings contribute to the field of control engineering and provide valuable insights for practitioners and researchers in selecting the most suitable control strategy for their specific DC motor control requirements.

5. Conclusion

This study thoroughly evaluated and compared two advanced control techniques, Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), for DC motor speed control. Our objective was to determine the most effective controller for this application.

Quantitative performance metrics, specifically overshoot percentage and rise time, were analyzed to compare the performance of ANN and ANFIS controllers. The results demonstrated that both controllers exhibited excellent performance in regulating the speed of the DC motor. However, a detailed analysis revealed some notable differences between the two approaches.

Based on our analysis, we found that the ANN controller demonstrated exceptional precision and efficiency in controlling the speed of the DC motor. The ANN controller's ability to learn from data and adapt its control actions contributed to its superior performance. The neural network's nonlinear mapping capabilities and inherent parallel processing provided the controller with the flexibility to model complex relationships and adapt to varying operating conditions.

Table 1 presents the quantitative comparison of the performance metrics for the ANN and ANFIS controllers, namely overshoot percentage and rise time. Both controllers demonstrated impressive performance, with minimal overshoot and similar rise times. The ANN controller achieved an overshoot of 0.847% and a rise time of 26.868 seconds, while the ANFIS controller exhibited an overshoot of 0.820% and a rise time of 26.955 seconds.

Table 1
Performance comparison of Artificial Neural Network and ANFIS

Controllers	Overshoot (%)	Rise Time (sec)
Neural Network	0.847	26.868
ANFIS	0.820	26.955

Acknowledging certain limitations and identifying potential areas for future research is important. Our study primarily focused on overshoot percentage and rise time as performance metrics, while other important criteria, such as steady-state error and settling time, were not considered. Additionally, the generalizability of the findings should be validated by conducting experiments under various operating conditions and system configurations.

Future research directions could include exploring hybrid control strategies that combine the strengths of ANN and ANFIS, as well as incorporating advanced optimization algorithms to enhance the performance of these controllers further. Comparative studies with other control strategies, such as model predictive control or adaptive control, could provide further insights into their relative effectiveness in specific operating conditions.

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