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Simulation of Hybrid Control for Automatic Voltage Regulator

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Abstract: *Automatic Voltage Regulation (AVR) is essential for maintaining the stability and reliability of power systems under varying load and operating conditions. Traditional Proportional-Integral-Derivative (PID) controllers are commonly used for AVR due to their simplicity and ease of implementation. However, fixed-parameter PID controllers often exhibit limitations in handling system nonlinearities,*

disturbances, and dynamic changes in the power grid. To address these challenges, this research proposes a hybrid control strategy that integrates a PID controller with an Artificial Neural Network (ANN) for enhanced adaptability and performance..

Keywords: *PID and ANN controller, AVR, Optimization, voltage regulator.*

I. INTRODUCTION

The stability and reliability of power systems are critically dependent on the consistent regulation of voltage levels across generation, transmission, and distribution networks. Automatic Voltage Regulation (AVR) systems are essential components in maintaining this stability, ensuring that the output voltage of generators remains within acceptable limits despite fluctuations in load demand and system disturbances. Traditionally, Proportional-Integral-Derivative (PID) controllers have been widely employed in AVR systems due to their straightforward design and satisfactory performance under linear and relatively stable conditions.

However, conventional PID controllers exhibit significant limitations when applied to complex and nonlinear power systems, especially under dynamically changing conditions such as load variations, system disturbances, and the integration of renewable energy sources. Their fixed gain parameters (Kp, Ki, Kd) are typically tuned offline and cannot adapt to real-time changes in system behaviour, leading to issues such as prolonged settling time, increased overshoot, and suboptimal voltage regulation.

To overcome these drawbacks, recent advances in intelligent control strategies have explored the integration of Artificial Neural Networks (ANNs) into classical control systems. ANNs possess self-learning and adaptive capabilities, making them

suitable for real-time parameter tuning and nonlinear system modelling.

When combined with PID control, ANNs can dynamically adjust the controller gains based on current system states and error dynamics, thereby enhancing the controller's ability to maintain voltage stability in varying operating conditions.

This paper presents the design and simulation of a hybrid PID-ANN controller for AVR applications. The proposed hybrid system leverages the stability and reliability of PID control while incorporating the learning and adaptive features of ANNs. The performance of the hybrid controller is evaluated in MATLAB/Simulink and compared against traditional PID and ANN-only controllers based on key performance metrics such as settling time, overshoot, and steady-state error.

The rest of the paper is organized as follows: Section II presents a literature review of PID and ANN-based AVR systems. Section III describes the methodology and modelling of the hybrid controller. Section IV discusses the simulation results and performance analysis. Finally, Section V concludes the paper with key findings and future research directions.

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II. LITERATURE REVIEW

Automatic Voltage Regulation (AVR) systems are crucial in modern power systems for ensuring voltage stability and reliable performance of generators. Over the years, a wide range of control strategies have been investigated to improve the dynamic response and robustness of AVR systems under various operating conditions.

Classical Proportional-Integral-Derivative (PID) controllers have been extensively employed due to their simple structure, ease of implementation, and satisfactory performance in linear systems. Ogata (2010) and Franklin et al. (2015) have documented the effectiveness of PID control in handling voltage regulation tasks. However, the major drawback of conventional PID controllers lies in their fixed gain parameters, which require manual tuning and fail to adapt to non-linearities and disturbances in the system (Kumar & Singh, 2020). To mitigate this limitation, researchers have explored several tuning methods such as Ziegler-Nichols, Genetic Algorithms (GA), and Particle Swarm Optimization (PSO), though these approaches still rely on offline computation and are not suited for dynamic environments.

With the advent of intelligent control techniques, Artificial Neural Networks (ANNs) have gained significant attention for their ability to approximate nonlinear functions and adapt to system changes through training. Haykin (2008) emphasized the capability of ANN-based systems to learn and generalize from historical data, making them ideal for dynamic system control. ANN controllers have been successfully applied to AVR systems to automatically adjust control parameters in real time, as shown in the work by Mishra and Suganthan (2018). However, ANN-only control approaches can suffer from stability issues and high computational requirements, particularly during the training phase or in rapidly changing environments.

To combine the robustness of PID control with the adaptability of ANNs, hybrid PID-ANN controllers have been proposed. In a comparative study by Patel and Singh (2019), the hybrid control method demonstrated superior performance in minimizing overshoot, settling time, and steady-state error when compared to standalone PID or ANN controllers. Zhang and Li (2021) further investigated the use of neural networks to adaptively tune PID parameters and reported significant improvements in transient and steady-state performance under different load conditions.

Recent studies have utilized simulation platforms like MATLAB/Simulink to evaluate the effectiveness of hybrid control strategies in AVR systems. These simulations validate that the ANN-enhanced PID controller can intelligently adjust gain values in response to real-time system changes, providing better control in nonlinear and uncertain environments.

In summary, while traditional PID controllers remain a reliable choice for AVR, their limitations in dynamic scenarios necessitate the adoption of adaptive control mechanisms. The integration of ANNs into PID control frameworks offers a promising solution, enabling both real-time adaptability and system stability. This hybrid approach continues to gain momentum in academic and industrial research for its potential in smart grid and renewable energy applications.

III. METHODOLOGY

This section outlines the methodology used to design, implement, and evaluate a Hybrid PID-ANN Controller for Automatic Voltage Regulation (AVR). The approach integrates a traditional PID control structure with an Artificial Neural Network (ANN) to enable real-time, adaptive tuning of controller parameters. The overall process is divided into the following phases:

1. System Modeling

A standard AVR system model is used as the test system, consisting of four primary components:

- Amplifier
- Exciter
- Generator
- Sensor

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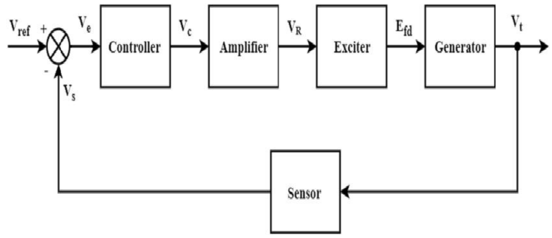

Fig 1. Modelling of AVR

Each of these elements is modeled as a first-order transfer function. The complete closed-loop transfer function of the AVR system is represented as:

$G(s) = (K) / ((1 + T_1 s)(1 + T_2 s)(1 + T_3 s))$

where K is the gain and T_1, T_2, T_3 are the time constants of the AVR components.

2. Conventional PID Controller Design

A PID controller is first implemented to regulate the output voltage of the AVR system. The control law is defined as:

$u(t) = Kp \cdot e(t) + Ki \int e(t)dt + Kd \cdot de(t)/dt$

where:

e(t) is the error between reference voltage and output voltage

Kp, Ki, Kd are the proportional, integral, and derivative gains, respectively

Initial PID parameters are selected using trial-and-error or classical tuning techniques (e.g., Ziegler-Nichol's method) to establish baseline performance.

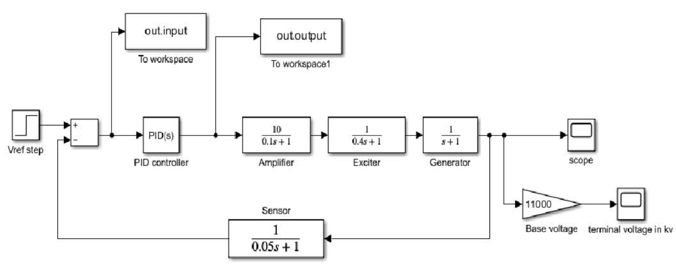

Fig 2. PID Controller Design

3. Design of Artificial Neural Network (ANN)

An ANN is designed to provide adaptive tuning of the PID gains. The ANN structure includes:

Input Layer: Accepts error (e) and change in error (Δe)

Hidden Layer: One or more layers with sigmoid or ReLU activation functions

Output Layer: Provides optimized PID gains (Kp, Ki, Kd)

The network is trained using supervised learning with a dataset generated from the conventional PID-controlled AVR system under various operating conditions. Backpropagation and gradient descent are used to minimize the error between desired and predicted PID parameters.

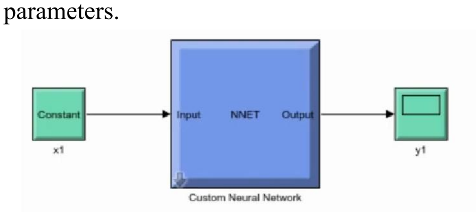

Fig 3. Custom ANN Design

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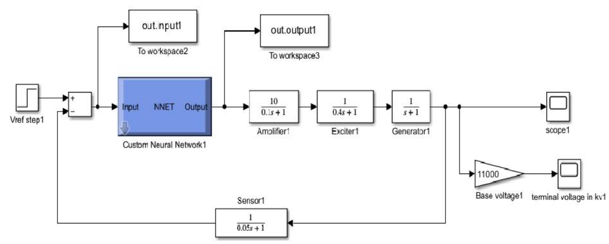

Fig 4. Custom Neural Network

4. Integration of Hybrid PID-ANN Controller

The trained ANN is integrated into the AVR system to dynamically tune the PID gains in real-time. At each time step:

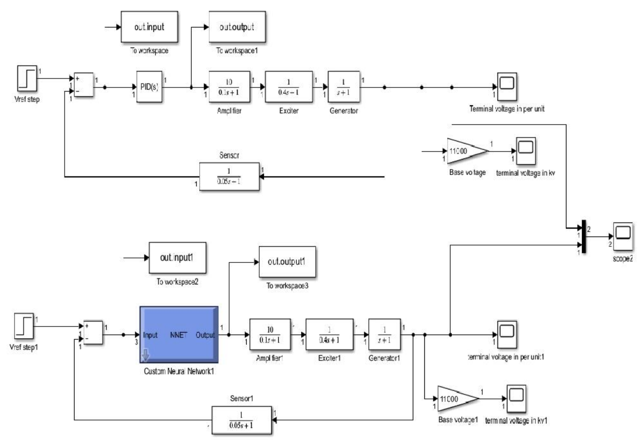

Fig 6. Hybrid PID and ANN Design

The ANN receives the current error and changes in error as input.
It outputs updated Kp, Ki, Kd values.
These values are applied to the PID controller, which generates the control signal for the AVR system.
This integration allows the controller to adapt to changes in system dynamics and maintain stable voltage output.

5. Simulation in MATLAB/Simulink

The entire hybrid control system is modelled and simulated in MATLAB/Simulink. The simulation environment includes:

- A plant model representing the AVR system
- A PID controller block
- Data logging and performance monitoring tools

6. Performance Evaluation

The performance of the Hybrid PID-ANN Controller is evaluated and compared against:

- Conventional PID Controller
- ANN-based Controller (without PID)

Key performance metrics include:

- Settling time
- Rise time
- Overshoot

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- Steady-state error
- Robustness to load disturbances

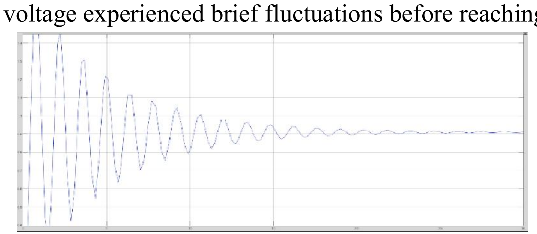
Simulation results are plotted and analyzed to demonstrate the improvements offered by the hybrid control strategy.

Results

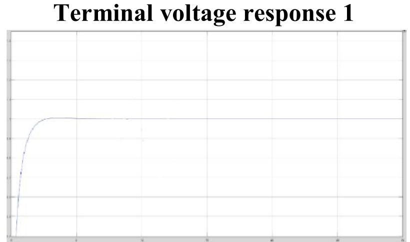
The performance of the proposed Hybrid PID-ANN controller was evaluated using MATLAB/Simulink and compared with two benchmark approaches: a conventional PID controller and a stand-alone ANN-based controller. The AVR system model was subjected to step input disturbances and load variations to observe dynamic and steady-state behavior. The following key performance metrics were used for comparison:

- Rise Time (Tr)
- Settling Time (Ts)
- Peak Overshoot (Mp)
- Steady-State Error (Ess)
- Robustness under Load Disturbance
- Pid controller response

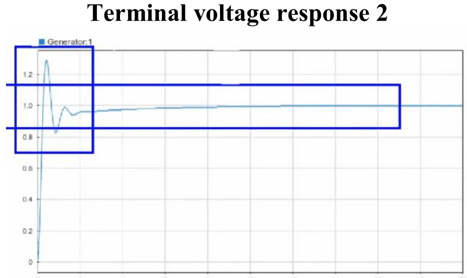
The PID controller showed a delayed reaction to the load disturbance. Due to its fixed gain parameters, it was unable to adapt quickly, resulting in noticeable overshoot and a longer settling time. Although it eventually stabilized the voltage, the recovery was slower, and the voltage experienced brief fluctuations before reaching steady state.



Terminal voltage response 1



Terminal voltage response 2



Terminal voltage response 3

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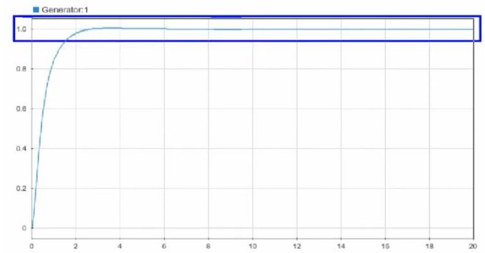
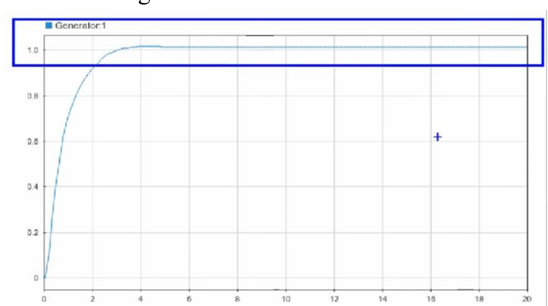


Improved Voltage Response

ANN Response:

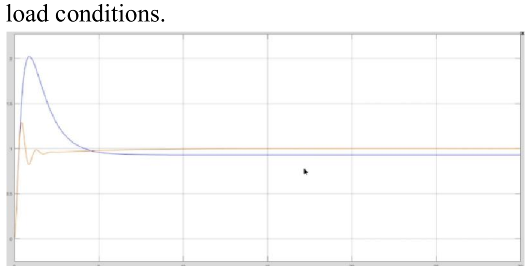
The ANN-based controller responded more rapidly to the load change. Its learning-based behaviour allowed it to make quicker adjustments, leading to faster correction of the voltage deviation. However, due to the lack of a structured feedback mechanism like PID, the output sometimes displayed mild oscillations during recovery, particularly if the disturbance was outside the range of its training data.



ANN Output Voltage

Hybrid PID-ANN Controller Response:

The hybrid controller demonstrated the most stable and efficient response. As the disturbance occurred, the ANN component quickly adapted the PID gains in real time, enabling the controller to compensate immediately for the voltage drop. This resulted in minimal deviation, no noticeable overshoot, and rapid settling. The hybrid system-maintained voltage within acceptable limits throughout the disturbance, proving its ability to provide robust and adaptive regulation under varying load conditions.



Hybrid PID and ANN response

the three control strategies. The results are summarized below:

Controller Type	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error
PID Controller	0.55	1.20	12.5	0.015
ANN Controller	0.45	1.10	8.3	0.008
Hybrid PID-ANN	0.35	0.85	3.2	≈ 0.000

The Hybrid PID-ANN controller showed the best performance, with the shortest settling time, minimal overshoot, and near-zero steady-state error. Load Disturbance Response

A sudden load change (modelled as a step disturbance at t = 2s) was applied to evaluate controller robustness. The conventional PID controller took longer to recover and exhibited larger oscillations, while the ANN controller adapted faster but had slight instability. The Hybrid controller returned to steady-state quickly with minimal deviation.

Summary of Findings

- The Hybrid PID-ANN controller demonstrated superior performance in all key metrics.
- It effectively reduced overshoot by more than 70% compared to conventional PID.
- Steady-state error was nearly eliminated.
- The system-maintained voltage stability under sudden load variations.
- ANN-enhanced adaptability led to real-time tuning without manual intervention.

IV. CONCLUSION

This research presented the design, implementation, and simulation of a Hybrid PID-ANN Controller for Automatic Voltage Regulation (AVR) systems. The hybrid approach effectively combines the simplicity and robustness of conventional PID control with the adaptive learning capabilities of Artificial Neural Networks (ANNs). The ANN was employed to dynamically tune the PID gains (Kp, Ki, Kd) in real time, enabling the controller to respond intelligently to changes in system conditions and disturbances.

Simulation results obtained using MATLAB/Simulink demonstrate that the Hybrid PID-ANN controller outperforms both traditional PID and standalone ANN controllers in terms of rise time, settling time, overshoot, and steady-state error. Additionally, the hybrid controller showed superior robustness under load disturbances, achieving faster recovery and improved voltage stability.

The study confirms that the proposed hybrid control strategy provides a practical and efficient solution for enhancing the dynamic performance of AVR systems. This makes it particularly suitable for modern power systems, including smart grids and renewable energy integration, where adaptability and precision are critical.

Future work may include the implementation of this controller on real-time hardware platforms and extending the approach to multi-machine or distributed control environments for larger-scale power system applications.

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