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Automatic Voltage Regulator Betterment Based on a New Fuzzy FOPI+FOPD Tuned by TLBO

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Abstract: This paper presents a novel Fuzzy Logic Controller (FLC) framework aimed at enhancing the performance and stability of Automatic Voltage Regulators (AVRs) in power systems. The proposed system combines fuzzy control theory with the Fractional Order Proportional Integral Derivative (FOPID) technique and employs cascading control theory to significantly improve reliability and robustness. The unique control architecture, termed Fuzzy Fractional Order Proportional Integral (PI) plus Fractional Order Proportional Derivative (PD) plus Integral (Fuzzy FOPI+FOPD+I), integrates advanced control methodologies to achieve superior performance. To optimize the controller parameters, the Teaching–Learning-Based Optimization (TLBO) algorithm is utilized in conjunction with the Integral Time Absolute Error (ITAE) objective function, ensuring precise tuning for optimal control behavior. The methodology is validated through comparative analyses with controllers reported in prior studies, highlighting substantial improvements in performance metrics. Key findings demonstrate significant reductions in peak overshoot, peak undershoot, and settling time, emphasizing the proposed controller's effectiveness. Additionally, the robustness of the controller is extensively evaluated under challenging scenarios, including parameter uncertainties and load disturbances. Results confirm its ability to maintain stability and performance across a wide range of conditions, outperforming existing methods. This study presents a notable contribution by introducing an innovative control structure that addresses critical challenges in AVR systems, paving the way for more resilient and efficient power system operations.

Keywords: AVR; TLBO; fuzzy FOPI+FOPD+I; ITAE; power system stability

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1. Introduction

The Automatic Voltage Regulator (AVR) is a critical component in modern power systems, tasked with maintaining the terminal voltage of synchronous generators at a stable and nominal level [1]. By dynamically adjusting the excitation voltage, the AVR ensures consistent power delivery and enhances overall system reliability. Its role becomes particularly vital in environments characterized by varying load demands and dynamic operational conditions [2].

Voltage regulation is a complex challenge due to the high inductance of generator field windings and the inherent variability of load conditions. These factors can lead to instability, slower response times, and deviations in terminal voltage. Thus, achieving a stable and rapid response from the AVR is crucial for ensuring power system stability and maintaining electrical power quality [3]. In scenarios such as no load, partial load, or full load, the AVR continuously adjusts the excitation current of the synchronous generator's exciter to counteract fluctuations and stabilize the terminal voltage [4].

While AVRs play a fundamental role in power systems, their performance is often constrained by system nonlinearity and the challenges associated with traditional control methods. Load variations, time delays, and the high inductance of alternator windings further exacerbate these challenges, necessitating advanced control strategies. A well-designed control system is essential to achieve the following goals [5,6]:

Improved Stability: Maintain terminal voltage consistency under all operating conditions.

Faster Response: Reduce transient times and ensure quick recovery from disturbances.

Reduced Overshoot: Minimize deviations during voltage adjustments.

From a control engineering perspective, ensuring the stable and reliable operation of modern power systems remains a significant challenge. This complexity arises from the continuous expansion of power system size, which increases structural and operational intricacies. Additionally, power systems are subject to a range of unpredictable internal and external disturbances, further complicating their dynamic behavior [7]. To address these challenges, researchers have extensively explored various control strategies for analyzing and improving the performance of AVR systems, aiming to achieve enhanced dynamic response and system stability.

Notably, the classical Proportional, Integral, and Derivative (PID) controller was the most commonly proposed technique to function as an AVR system [8]. This controller was implemented in the literature based on different techniques. However, there has been considerable consideration for using optimization algorithms to tune its parameters in order to achieve the optimal values of its parameters. In [9], a memory-based smoothed functional algorithm (MSFA) is used to efficiently tune PID controllers in AVR systems, enhancing performance while reducing computational costs. An AVR system based on a PID controller optimized by a sine–cosine algorithm (SCA) is proposed in [10]. This design has outperformed PID tuned by Artificial Bee Colony (ABC) and Differential Evolution (DE). A Symbiotic Organisms Search (SOS) algorithm is utilized in [11] to efficiently determine the optimum values of PID used for the AVR system. AVR based on a PID controller tuned by the Naked Mole Rat Algorithm (NMRA) is proposed in [12]; this controller has bettered the performance of PID tuned by other optimization tools in the literature. Moreover, recent studies have explored more advanced optimization algorithms for enhancing PID controllers in AVR systems, demonstrating significant improvements in performance and reliability. The Tree Seed Algorithm (TSA) [13] was shown to enhance stability and dynamic response, while the Grasshopper Optimization Algorithm (GOA) [14] effectively balances exploration and exploitation to improve transient and steady-state performance. The World Cup Optimization (WCO) algorithm [15], inspired by competitive dynamics, has achieved superior control performance with reduced overshoot and faster response times. Similarly, the Ant Lion Optimizer (ALO) [16] and Particle Swarm Optimization (PSO) [17] have demonstrated their ability to optimize PID parameters efficiently, achieving robust and accurate tuning with improved system stability. The Local Unimodal Sampling (LUS) algorithm [18] has provided efficient local search capabilities, resulting in better transient response. Moreover, the Water Wave Optimization (WWO) algorithm [19] has shown excellent performance in handling complex, nonlinear search spaces for AVR systems. Additionally, the hybrid Equilibrium Optimizer–Evaporation Rate Water Cycle Algorithm (EO–ERWCA) [20] has combined exploration and refinement capabilities to achieve optimal PID parameters, leading to faster settling times, reduced overshoot, and enhanced stability under various conditions. These advancements highlight the effectiveness of modern optimization techniques in addressing the challenges of PID tuning for AVR systems.

Although the aforementioned designs have demonstrated good performance, more advanced designs were proposed to achieve superior results. Consequently, to improve the performance of PID controllers for AVRs, enhanced versions were developed, leveraging various theories and optimization techniques. PID Acceleration (PIDA) is another version of PID but with three more gains; K_a, which is the acceleration gain, in addition to $\propto$ *and* β, which are the filter coefficients to improve stability. This controller was implemented in [21] for an AVR based on the whale optimization algorithm (WOA) and outperformed the traditional PID tuned by the same algorithm. PID and PIDA optimized by a novel hybrid technique between the Harmony Search (HS) and Dwarf Mongoose Optimization (DMO) algorithms was proposed in [22] as an AVR controller; the introduced designs illustrated robust performance under different conditions. A PID controller with filtered derivative action (PID-F) incorporates four independent parameters that are precisely optimized through the application of the Symbiotic Organism Search (SOS) algorithm is presented in [23]. Another unique design of PID is proposed in [24] for AVR applications. This design benefits from double derivative actions; PID plus second-order derivative ($PIDD^2$). The results showed that $PIDD^2$ provided a better dynamic response than the classical PID controller.

Fractional Order PID (FOPID or $PI^{\lambda}D^{\mu}$) was proposed as an effective solution for AVRs. The FOPID controller offers two additional degrees of flexibility compared to the traditional PID controller, enhancing its performance by introducing fractional orders (λ, which is the order of the integration, and μ, which is the order of the differentiator) alongside the standard three parameters [25]. FOPID optimized by an improved version of the Marine Predators Algorithm (MPA) within an AVR system is demonstrated in [26]. A modified smoothed function algorithm (MSFA)-based approach for tuning the FOPID controller of an AVR system is proposed in [27]; the algorithm is approved to minimize the number of function evaluations required per iteration and the controller provided a good performance as it outperformed other controllers in the literature. The study in [28] presents a FOPID controller for AVR systems, tuned with the Dandelion Optimizer (DO), achieving superior robustness and transient response compared to traditional PID controllers. It emphasizes its practical application for reliable voltage regulation. In [29], the Chaotic Yellow Saddle Goatfish Algorithm (CYSGA) is introduced for FOPID tuning, offering enhanced dynamic response and stability margins while effectively handling system uncertainties, making it a robust solution for AVR systems.

Furthermore, extended improvements to the FOPID were proposed in the literature to further enhance the performance of AVRs. The authors in [30] proposed a cascaded Real PID with Double Derivative ($RPIDD^2$) and Fractional Order Proportional Integral (FOPI) controller for AVR systems. This advanced controller enhances precision, stability, and adaptability in voltage regulation. The $RPIDD^2$ controller improves phase margin and stability, while the FOPI controller adds flexibility through fractional order terms. This was fine-tuned using the Quadratic Wavelet-Enhanced Gradient-Based Optimization (QWGBO) algorithm, where the cascaded $RPIDD^2$-FOPI controller outperforms conventional methods by minimizing overshoot, rise time, and settling time. The study in [31] presents a comparative study of AVR control systems, introducing a novel Optimized Proportional Integral Derivative Model Reference Fractional Adaptive (OPIDMR-FA) controller. This controller integrates model reference adaptive control and fractional order design principles to achieve superior dynamic performance. Compared to traditional controllers such as PID, PIDA, and FAOPID, OPIDMR-FA demonstrated smoother transient responses with zero steady-state error. The research in [32] introduces a modified Tilt-Integral-Derivative (TID) controller, named $I^{\lambda}DND^2N^2 - T$, for AVR systems. This fractional order controller integrates advanced tuning flexibility and enhanced robustness through second-order derivative terms and low-pass filters. The proposed $I^{\lambda}DND^2N^2 - T$ tuned using an Equilibrium Optimizer (EO) demonstrated superior performance over traditional PID, PIDD^2, and FOPID controllers, showcasing its efficacy in improving AVR system reliability.

While traditional controllers like PID are prevalent in AVR applications, advanced control strategies such as Sliding Mode Control (SMC), Model Predictive Control (MPC), H-infinity (H_∞) control, adaptive control, and Linear Quadratic Regulator (LQR) have seen comparatively limited implementation. These methodologies offer robust performance in the presence of system uncertainties and disturbances.

SMC is recognized for its robustness against matched uncertainties and was applied in various domains, including power electronics. It ensures system trajectories reach and maintain a sliding manifold, providing insensitivity to certain disturbances. However, its practical application can be hindered by chattering phenomena and implementation complexity [33,34].

MPC handles multi-variable control and constraints by predicting future system behavior and optimizing control actions accordingly. This predictive capability makes it suitable for complex systems, but its reliance on accurate models and computational intensity can limit real-time applications [35–37].

H_∞ control techniques are designed to manage systems with nonlinearities and uncertainties, offering robust performance under varying conditions. They aim to achieve stabilization with guaranteed performance by formulating the control problem as a mathematical optimization problem. The complexity of designing H∞ controllers and the need for precise system models can restrict their practical use [38,39].

Adaptive control adjusts controller parameters in real-time to cope with system changes, enhancing performance in uncertain environments. It was applied in various fields, including aerospace, to handle systems with significant uncertainties. The design and analysis of adaptive controllers can be complex, which may limit their widespread adoption [40].

LQR is an optimal control strategy that minimizes a quadratic cost function, balancing state error and control effort. It provides a systematic approach to designing controllers for linear systems but may not directly address robustness to model uncertainties [41,42].

Despite their theoretical advantages, the practical application of these advanced control strategies in AVR systems remains less common, possibly due to implementation complexity and the need for precise system models.

Recent advancements in AVR systems have explored the integration of Fuzzy Logic Controllers (FLCs) to enhance performance under varying operational conditions. FLCs, known for their ability to handle system nonlinearities and uncertainties, were effectively applied to AVR systems to improve voltage regulation. A robust fuzzy PI and Type-2 Fuzzy PI controllers optimized using metaheuristic algorithms like Artificial Bee Colony (ABC) and PSO, which demonstrate improved robustness and transient response under varying parameters and disturbances, are presented in [43]. The study presented in [44] implements an FLC for AVR systems, showing significant enhancements in dynamic performance and voltage stability; the FLC-based AVR system outperformed traditional methods in mitigating load variations and achieving faster stabilization. Similarly, the integration of a fuzzy PID controller with Programmable Logic Controllers (PLCs), tuned through genetic algorithms and radial-basis function networks, achieves efficient voltage regulation and reduces oscillations, combining the adaptability of fuzzy logic with the reliability of PLCs, as studied in [45]. Additionally, the study in [46] presents an FLC designed with triangular membership functions that outperforms traditional PID controllers, achieving better performance, and ensuring superior transient and steady-state performance. Table 1 provides an overview of the controllers and optimization algorithms utilized for tuning AVR control systems. It highlights the diverse range of controllers and algorithms implemented in the literature.

Table 1. An outline of the control methods and optimization tools of AVR systems in the literature.

Reference	Control Method	Optimization Tool
Ref. [9]	PID	Memory-based smoothed functional algorithm (MSFA)
Ref. [10]	PID	Sine–Cosine Algorithm (SCA)
Ref. [11]	PID	Symbiotic Organisms Search (SOS) algorithm
Ref. [12]	PID	Naked Mole Rat Algorithm (NMRA)
Ref. [13]	PID	Tree Seed Algorithm (TSA)
Ref. [14]	PID	Grasshopper Optimization Algorithm (GOA)
Ref. [15]	PID	World Cup Optimization (WCO) algorithm
Ref. [16]	PID	Ant Lion Optimizer (ALO)
Ref. [17]	PID	Particle Swarm Optimization (PSO)
Ref. [18]	PID	Local Unimodal Sampling (LUS) algorithm
Ref. [19]	PID	Water Wave Optimization (WWO)
Ref. [20]	PID	Equilibrium Optimizer–Evaporation Rate Water Cycle Algorithm (EO–ERWCA)
Ref. [21]	PIDA	Whale optimization algorithm (WOA)
Ref. [22]	PIDA	Hybrid Harmony Search (HS) and Dwarf Mongoose Optimization (DMO) algorithms
Ref. [23]	PIDF	Symbiotic Organism Search (SOS) algorithm
Ref. [24]	$PIDD^2$	Particle Swarm Optimization (PSO)
Ref. [26]	FOPID	Marine Predators Algorithm (MPA)
Ref. [27]	FOPID	A Modified Smoothed Function Algorithm (MSFA)
Ref. [28]	FOPID	Dandelion Optimizer (DO)
Ref. [29]	FOPID	Chaotic Yellow Saddle Goatfish Algorithm (CYSGA)
Ref. [30]	$RPIDD^2$-FOPI	Quadratic Wavelet-Enhanced Gradient-Based Optimization (QWGBO) algorithm
Ref. [31]	FOPID-MRAC	Manually tuned
Ref. [32]	$I^{\lambda}DND^2N^2-T$	Equilibrium Optimizer (EO)
Ref. [33]	SMC	Sine–Cosine Algorithm and Grey Wolf Optimization
Ref. [34]	SMC	Sine–Cosine Algorithm (SCA)
Ref. [35]	MPC	Mathematically calculated
Ref. [36]	MPC	Marine Predators Algorithm (MPA)
Ref. [38]	H_2/H_∞	Fuzzy logic
Ref. [39]	H_∞ and μ-analysis	Mathematically calculated
Ref. [40]	Adaptive	Mathematically calculated
Ref. [41]	LQR	Mathematically calculated
Ref. [42]	LQR	Biogeography-Based Optimization (BBO)
Ref. [43]	Fuzzy PI	Artificial Bee Colony (ABC) and PSO
Ref. [44]	Fuzzy Control	Mathematically tuned
Ref. [45]	Fuzzy and PLC	Genetic algorithm
Ref. [46]	Fuzzy Control	Mathematically tuned
Proposed	Fuzzy FOPI+FOPD + I	Teaching–Learning-Based Optimization (TLBO) algorithm

In AVR systems, achieving an optimal balance between response speed and voltage stability is crucial. A fast response with overshoot enables quick voltage stabilization, which is essential in dynamic environments with frequent load changes. However, this can temporarily exceed safe voltage limits, potentially harming sensitive equipment. Conversely, a slower response without overshoot maintains voltage within desired thresholds, safeguarding equipment, but may result in temporary undervoltage or overvoltage during load transitions. Therefore, the ideal controller design depends on specific application requirements and system constraints, aiming to harmonize rapid response with minimal overshoot to ensure both performance and safety [47].

While the aforementioned techniques demonstrate distinct merits and have substantially addressed the challenges associated with Automatic Voltage Regulator (AVR) systems, their implementation in power systems is not without limitations. Traditional controllers, for instance, often fail to deliver adequate performance under nonlinear operating conditions or high system sensitivity. Despite their low cost being a significant advantage, these controllers lack the adaptability required for modern AVR applications. On the other hand, advanced methods such as adaptive control and SMC provide effective solutions for AVR systems but are hindered by the complexity of their design and the high computational overhead they entail. Similarly, while various fuzzy control approaches were proposed for voltage regulation, most fail to incorporate reliability considerations into their design.

To overcome these challenges, this study proposes an innovative FLC configuration designed to ensure a high degree of reliability for AVR systems. The proposed controller, termed Fuzzy cascade FOPI plus FOPD plus I (Fuzzy FOPI+FOPD + I), integrates a two-input-one-output fuzzy controller with a cascaded FOPI and FOPD controller at its output terminal in addition to an integral controller to further enhance the reliability of the AVR system. To achieve optimal performance, the controller parameters are fine-tuned using the Teaching–Learning-Based Optimization (TLBO) algorithm, a robust and efficient optimization technique. Concisely, the key contributions of the study are as follows:

1. Novel Controller Design: Introduces a unique Fuzzy Logic Controller configuration for AVR systems, featuring a two-input-one-output fuzzy logic design combined with a cascade FOPI-FOPD controller, forming the Fuzzy FOPI-FOPD+I controller.
2. Performance Validation: Demonstrates the superiority of the proposed design through comparative analysis with traditional PID controllers optimized using multiple state-of-the-art tools.
3. Robustness Assessment: Examines the resilience of the proposed controller under parametric uncertainties and load disturbance, validating its robustness and reliability in diverse operating conditions.

The rest of the paper is categorized as follows: Section 2 describes the AVR system and its mathematical model with dynamic response without a controller. Section 3 details the proposed controller and provides a brief idea about the mechanism of the proposed algorithm and the used objective function. Section 4 presents the main results and illustrates a detailed discussion of the findings. Section 5 investigates the robustness of the testbed system with the proposed controller. Finally, Section 6 provides a concise conclusion, mentions the limitations of this study, and proposes different directions for possible future works.

2. AVR System

Figure 1 illustrates a simplified general model of the AVR system developed for this study, which regulates the generator's output voltage by controlling its excitation through an error signal generated by comparing the sensed terminal voltage of the generator with a predefined reference voltage. During a voltage drop, typically caused by increased loading conditions, the error signal increases positively, prompting the AVR to enhance the generator's excitation until the sensed voltage aligns with the reference value, after which the excitation stabilizes to maintain a constant supply voltage. Conversely, when the load decreases, a voltage rise occurs, generating a negative error signal that causes the AVR to reduce the generator's excitation until equilibrium is achieved, ensuring voltage stability. The transfer function of the AVR system is modeled using Laplace transform. Each component of the AVR—namely the amplifier, exciter, generator, and sensor—is linearized for analytical convenience. This system has been widely used in the literature for AVR applications.

The closed-loop transfer function of the model presented in Figure 2 based on the parameters given in Table 2 is illustrated in Equation (1). This model was an extensively investigated system in the literature to study the dynamic behavior of different control concepts for AVR systems [13]. The step response of the system is demonstrated in Figure 3 with the following characteristics: peak amplitude = 1.5066 pu; peak time = 0.7522 s; settling time = 6.9865 s; rise time = 0.2607 s; and steady-state error = 0.091 pu. The model has one zero at −100, two real poles at −99.9712 + 0i, and −12.4892 + 0i, and two complex poles at −0.5198 + 4.6642i and −0.5198 − 4.6642i, as shown in the root locus plot presented in Figure 4.

$$TF_{AVR} = \frac{0.1s + 10}{0.0004\ s^4 + 0.045\ s^3 + 0.555\ s^2 + 1.51\ s + 11}$$

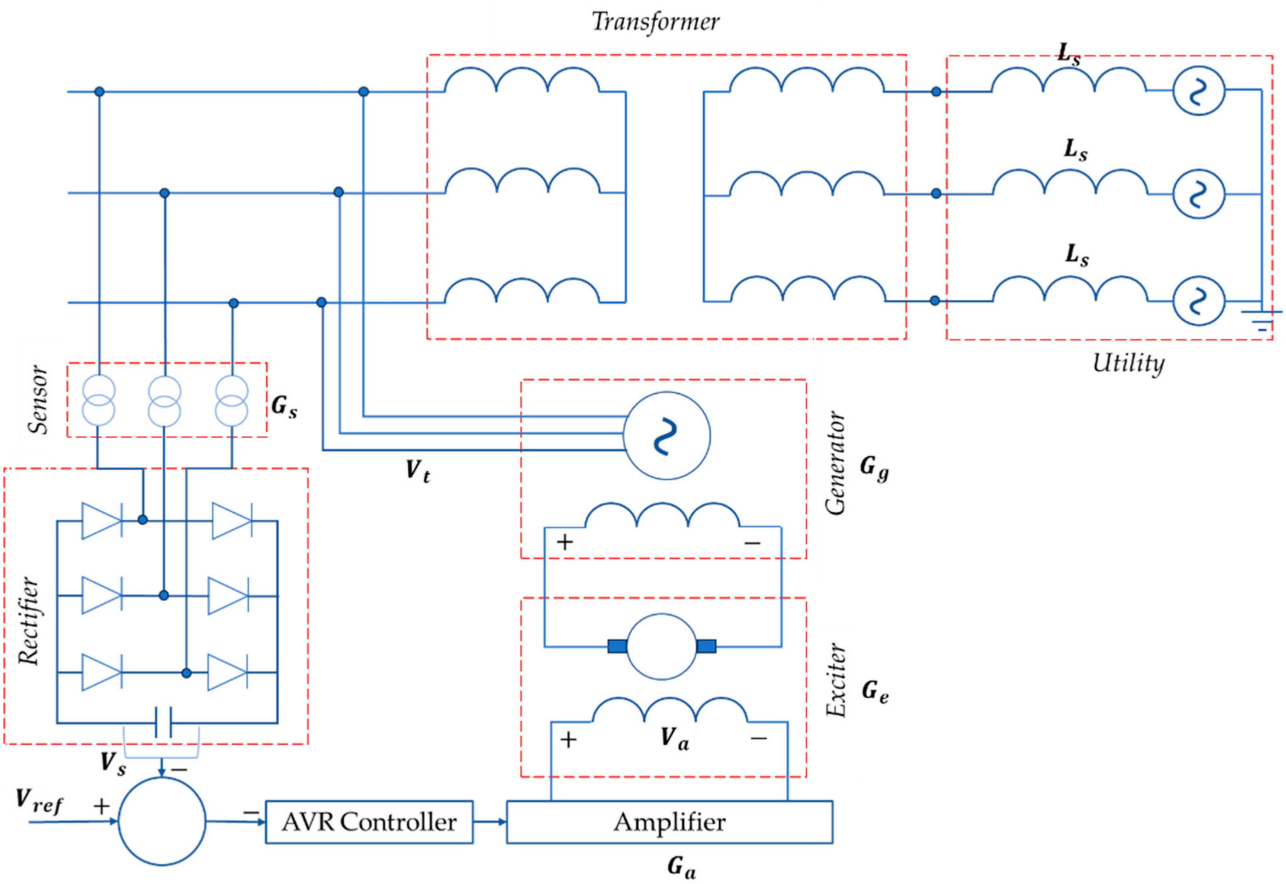

Figure 1. Schematic representation of generalized AVR components.

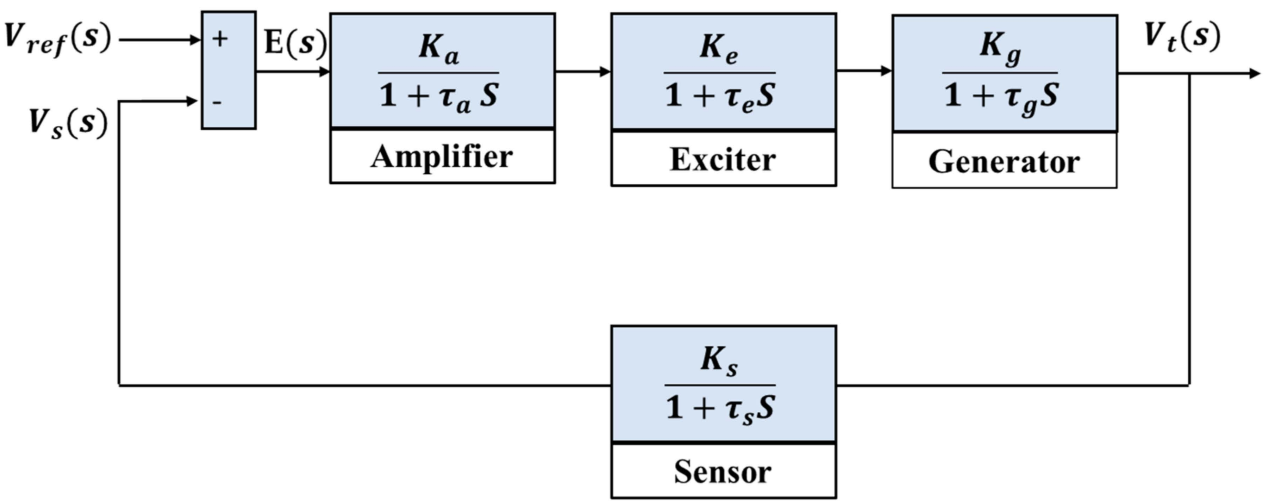

Figure 2. The traditional AVR model without a controller.

Table 2. The range and implemented values of the AVR model.

AVR Component	Transfer Function	Value Range	Implemented Value
Generator	$\frac{K_g}{1+\tau_g}$	$0.7 \leq K_g \leq 1$ $1 \leq \tau_g \leq 2$	$K_g = 1, \tau_g = 1$
Excitor	$\frac{K_e}{1+\tau_e}$	$1 \leq K_e \leq 10$ $0.4 \leq \tau_e \leq 1$	$K_e = 1, \tau_e = 0.4$
Sensor	$\frac{K_s}{1+\tau_s}$	$1 \leq K_s \leq 2$ $0.001 \leq \tau_s \leq 0.06$	$K_s = 1, \tau_s = 0.01$
Amplifier	$\frac{K_a}{1+\tau_a}$	$10 \leq K_a \leq 400$ $0.02 \leq \tau_a \leq 1$	$K_g = 10, \tau_g = 0.1$

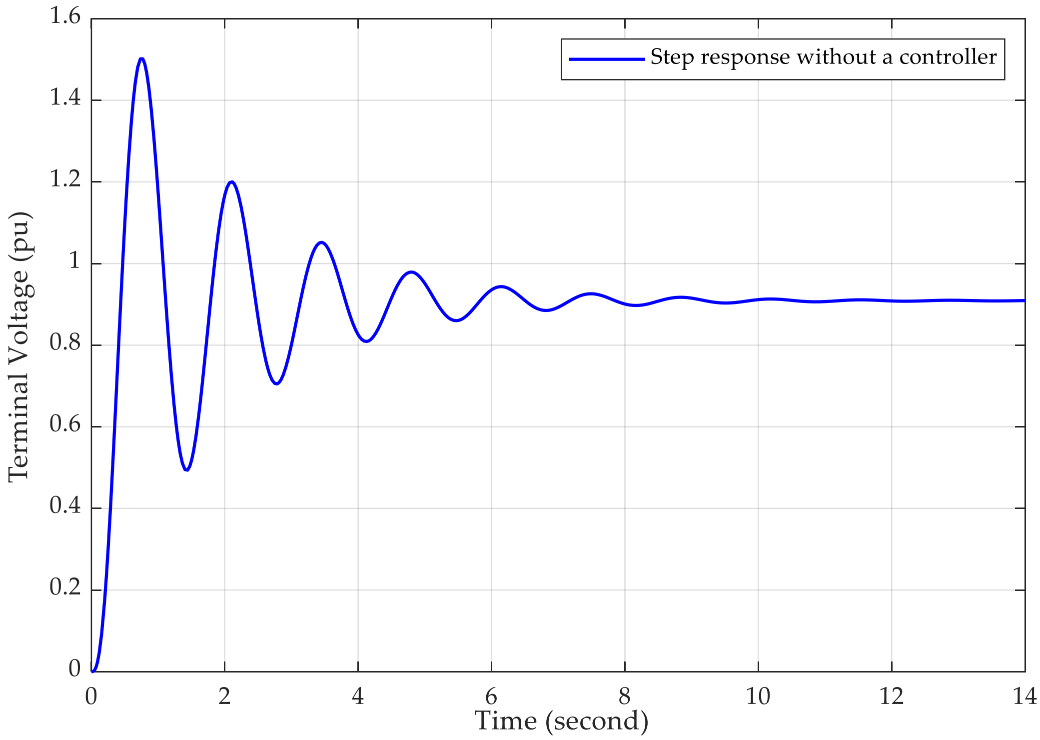

Figure 3. Step response of AVR system without controller.

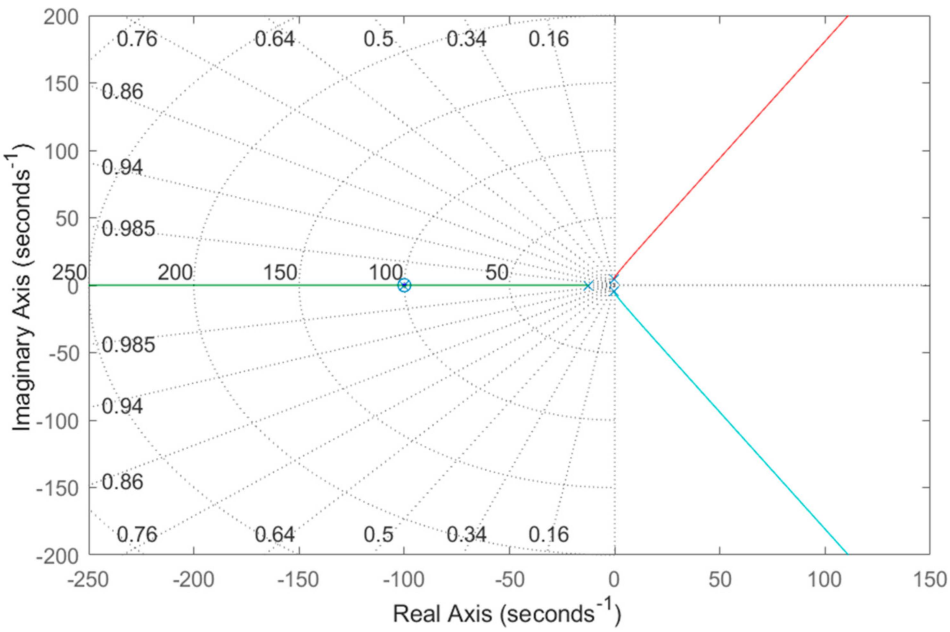

Figure 4. A root locus diagram of the AVR system without a controller.

From the characteristics presented above, it is clear that a proper control design is needed to improve the overall performance of the system in its transient and steady-state responses. The design of the controller is investigated in Section 3.

3. The Proposed Controller and Implemented Optimization Tool and Cost Function

3.1. The Proposed Fuzzy FOPI Plus FOPD Plus I Controller

Figure 5 illustrates the structural diagram of the proposed controller, which integrates two main components: a Fuzzy FOPI plus FOPID controller and a classical I controller. The fuzzy controller is designed with two inputs: the error and the derivative of the error. These inputs are scaled by two input gain factors, denoted as K_1 *and* K_2, respectively. The controller produces a single output, which is subsequently connected to the FOPI controller. To maintain simplicity and minimize computational time, five triangular membership functions are employed for both the input and output variables. These membership functions, as shown in Figure 6, are defined as Negative Big, Negative Small, Zero, Positive Small, and Positive Big.

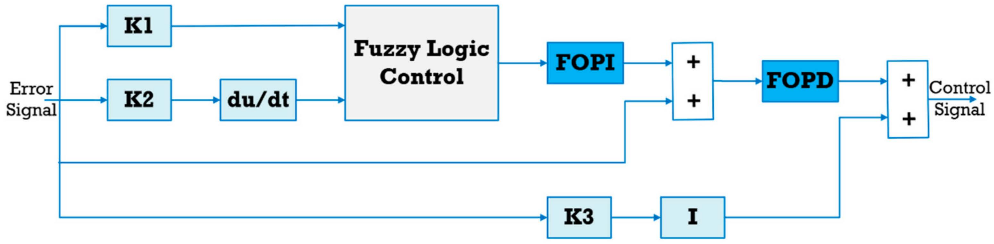

Figure 5. The proposed Fuzzy FOPI+FOPD+I AVR system.

The controller utilizes 25 fuzzy rules to generate its output, with the complete rule base provided in Table 3. These rules were meticulously developed based on a detailed analysis of the dynamic behavior of the testbed system. The Mamdani inference system is used for the fuzzification process, ensuring efficient mapping of crisp inputs to fuzzy values. For the defuzzification stage, the centroid method is applied, converting the fuzzy output into a crisp real-valued control signal. This design ensures an effective and computationally efficient implementation of the controller.

Table 3. The rule base of the fuzzy controller.

Error	Change in Error				
	NB	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	BS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

The output of the fuzzy controller serves as an input of the FOPI controller. The FOPI controller's transfer function is given in Equation (1), where λ is the order of integration, K_{p1} is the proportional gain, and K_i is the integral gain.

$$\text{FOPI Controller}_c(S) = K_{p1} + \frac{K_i}{S^\lambda} \quad (1)$$

The FOPD controller, in turn, receives its input from two signals: the output of the FOPI controller and the error signal. The FOPD controller's transfer function is given in

Equation (2), where μ is the order of differentiator, K_{p2} is the proportional gain, and K_d is the derivative gain.

$$\text{FOPD Controller}_c(S) = K_{p2} + K_d S^{\mu} \tag{2}$$

The final control signal is generated by summing the output of the FOPD controller with the output of the classical I controller with a gain named K_3. This comprehensive approach enhances the performance and robustness of the proposed control strategy.

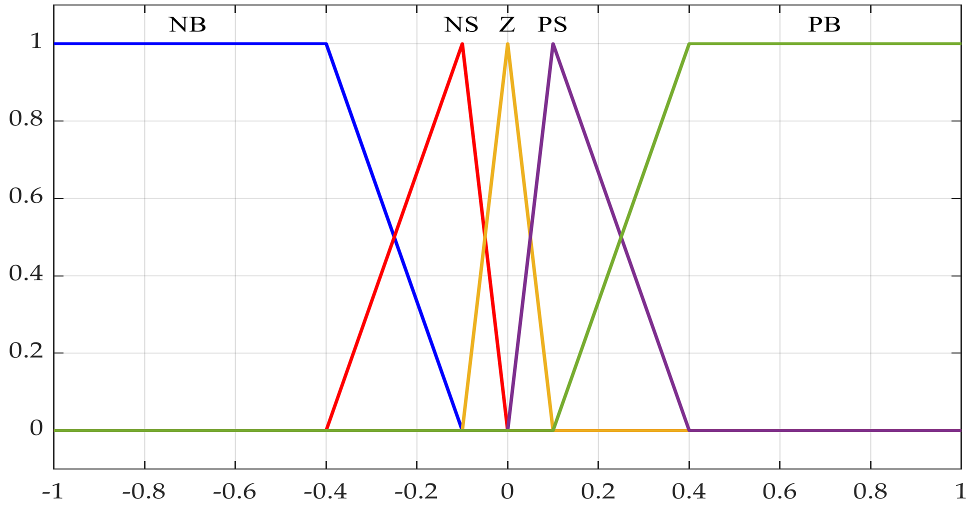

Figure 6. The membership functions of the fuzzy controller.

3.2. The Implemented TLBO Algorithm and the Utilized Cost Function

To enhance the performance of a controller, it is critical to thoroughly understand the behavior of the controlled plant and design the controller to achieve the desired system dynamics. A pivotal step in the control design process is the determination of the optimal parameters for the controller. However, accurately estimating these parameters to ensure optimal performance often proves challenging. To address these limitations, soft computing based on optimization algorithms were introduced, offering a robust solution to this challenge and other complex optimization problems.

Therefore, in order to achieve most of the proposed fuzzy controller for AVR, a powerful and modern heuristic algorithm, the Teaching–Learning-Based Optimization (TLBO) algorithm, is used to find the optimal values of the controller's parameters: K_1, K_2, K_3, K_{P1}, K_I, λ, K_{P2}, K_D, and μ, as explained in Figure 7.

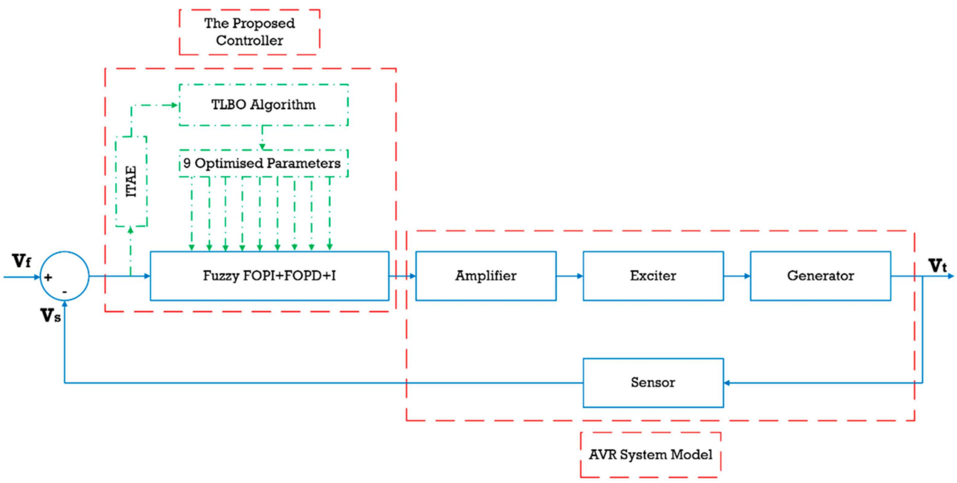

Figure 7. The TLBO-tuned Fuzzy FOPI+FOPD+I for AVR.

TLBO is a heuristic optimization technique introduced in [48]. It is inspired by the teaching and learning processes that occur in a classroom setting, particularly the interactions between a teacher and students. This approach models the influence of a teacher on students' academic performance. In this analogy, the teacher represents the most knowledgeable and skilled individual, providing quality education to enhance students' learning. The improvement in students' performance depends not only on the teacher's effectiveness but also on the students' own efforts and their collaborative knowledge sharing with classmates. The performance of the students is ultimately assessed based on their grades or outcomes in the class.

TLBO is a nature-inspired, parameter-free algorithm that employs a population of solutions to converge toward the optimal result. For TLBO, the population is likened to students in a class, while the control variables represent the subjects they study. The algorithm operates in two main phases, the teaching phase and the learning phase, as detailed below [49]. The flowchart shows the TLBO methodology, as presented in Figure 8

Teaching Phase: This is the first part of the algorithm in which the teacher tries the level best according to their potential to improve the performance of students in a class. The average result of the classroom is improved by the influence of the teacher to some extent, i.e., μ_j^k. If the new average grade of jth subject at kth iteration is μ_{newj}^k, the difference between the existing mean and the new mean of the jth subject at the kth iteration may be given as follows:

$$\mu_{\mathrm{diffj}}^{\mathrm{k}} = \mathrm{rand}\ \left(\mu_{\mathrm{newj}}^{\mathrm{k}} - (\mathrm{TF})\ \mu_{\mathrm{j}}^{\mathrm{k}}\right) \tag{3}$$

where TF is the teaching factor, which is evaluated randomly by the following equation:

$$\mathrm{TF} = \mathrm{round}\ (1{+}\mathrm{rand}(0,1)) \tag{4}$$

The grade of the jth subject of the ith student at $k+1th$ iteration is updated as follows:

$$\mathrm{x}_{\mathrm{ij}}^{\mathrm{k+1}} = \mathrm{x}_{\mathrm{ij}}^{\mathrm{k}} + \mu_{\mathrm{diffj}}^{\mathrm{k}} \tag{5}$$

Learning Phase: It is the last part of the algorithm where students upgrade their results by mutual interactions among themselves. Any two students such as x_i and x_j are randomly selected from the class and their grades are updated based on the better student. The learning process may be expressed mathematically as follows:

$$\mathrm{x}_{\mathrm{ij}}^{\mathrm{k+1}} = \mathrm{x}_{\mathrm{ij}}^{\mathrm{k}} + \mathrm{rand} \times \left(\mathrm{x}_{\mathrm{ij}}^{\mathrm{k}} - \mathrm{x}_{\mathrm{lj}}^{\mathrm{k}}\right)\ \mathrm{if}\ \mathrm{f}(\mathrm{x}_{\mathrm{i}}) < \ \mathrm{f}(\mathrm{x}_{\mathrm{l}}) \tag{6}$$

Otherwise,

$$\mathrm{x}_{\mathrm{ij}}^{\mathrm{k+1}} = \mathrm{x}_{\mathrm{ij}}^{\mathrm{k}} + \mathrm{rand} \times \left(\mathrm{x}_{\mathrm{lj}}^{\mathrm{k}} - \mathrm{x}_{\mathrm{ij}}^{\mathrm{k}}\right)\ \mathrm{if}\ \mathrm{f}(\mathrm{x}_{\mathrm{l}}) < \ \mathrm{f}(\mathrm{x}_{\mathrm{i}}) \tag{7}$$

where x_{ij}^{k+1} and x_{ij}^{k} are the grade point of the jth subject of the ith student at the kth and $k+1th$ iteration; x_{ij}^{k} is the grade point of the jth subject of the lth student (randomly selected) at kth iteration; and $f(x_i)$ is the overall grade point of the ith student.

$$\mathrm{X}_{\mathrm{i}} = \left[\mathrm{x}_{\mathrm{i1}}\mathrm{x}_{\mathrm{i2}}\ldots,\ \ \mathrm{x}_{\mathrm{ij}}\ldots,\mathrm{x}_{\mathrm{iND}}\right] \tag{8}$$

In control theory, achieving both fast response and stability for a controlled system is highly desirable but often presents a significant challenge. Balancing these two requirements necessitates a careful design, as optimizing one typically impacts the other. A proper control design aims to find an equilibrium between quick response and adequate stability by carefully selecting an appropriate controller and designing it to minimize a well-defined objective function and using optimization techniques.

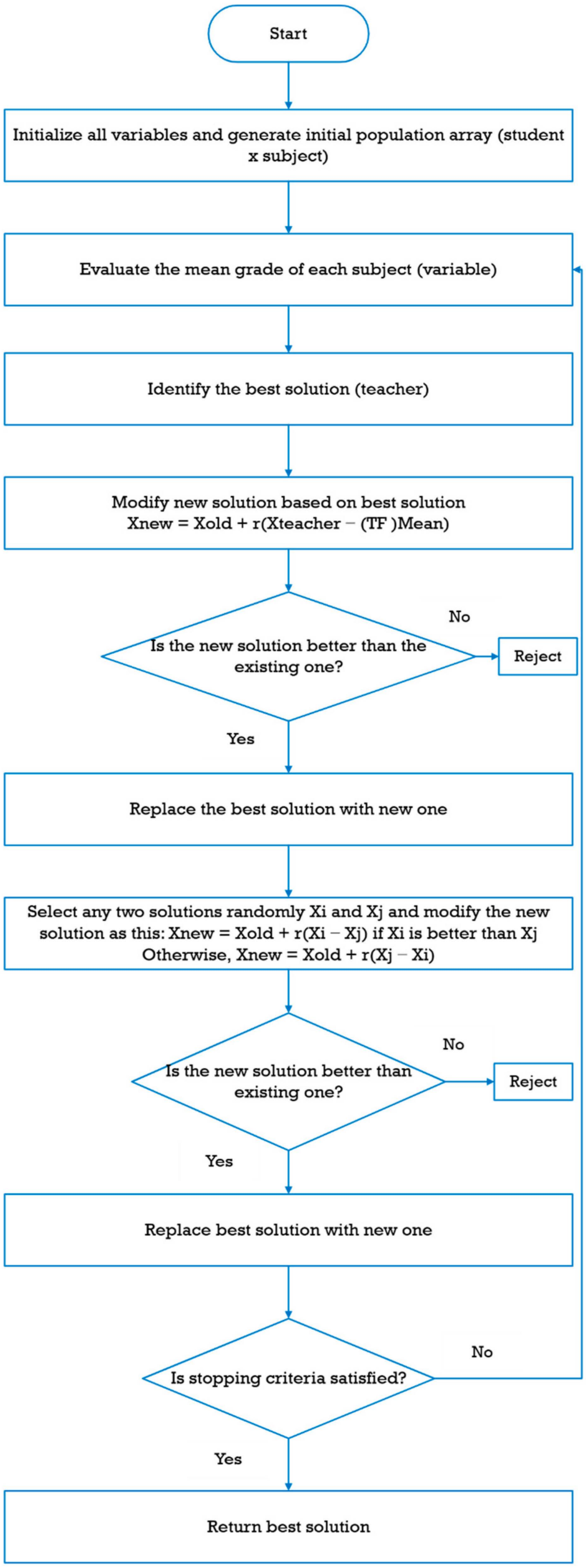

Figure 8. The flowchart of the TLBO algorithm.

In control system design, four commonly considered performance criteria include the Integral of Time-Weighted Absolute Error (ITAE), Integral of Squared Error (ISE), Integral of Time-Weighted Squared Error (ITSE), and Integral of Absolute Error (IAE). Among these, the ISE and ITAE criteria are frequently utilized in the literature due to their superior performance compared to the IAE and ITSE criteria.

The ISE criterion evaluates the integral of the squared error over time, giving greater emphasis to larger errors since the square of a large error significantly outweighs smaller ones. Consequently, control systems designed to minimize ISE tend to eliminate substantial errors rapidly but may allow smaller errors to persist over extended periods. This often results in systems with fast response times accompanied by low-amplitude oscillations.

On the other hand, the ITAE criterion integrates the absolute error multiplied by time over the response duration, placing greater weight on errors that persist over longer periods compared to those occurring at the beginning. As a result, ITAE tuning methods generally produce systems that settle more quickly than those tuned using ISE [50]. Accordingly, in this study, the parameters of the Fuzzy FOPI+FOPD+I proposed for AVR applications are optimized using the TLBO algorithm by minimizing the ITAE objective function, which is mathematically expressed as follows:

$$\text{Objective function} = \text{ITAE} = \int_0^t |e|.t.dt \tag{9}$$

For a reasonable computational time needed by the algorithm to tune the parameters, the number of population and number of iterations are set to 50. The convergence curve of the TLBO is presented in Figure 9. The tuning process is performed only prior to the deployment of the actual controller, making it a one-time procedure for each specific application. The process can be further improved by employing alternative optimization techniques with less computational time needed for tuning. However, it is common to encounter extended computational times when tuning controllers that involve fuzzy logic and a relatively large number of parameters. The optimum values of the proposed AVR controller obtained by TLBO by minimizing ITAE are presented in Table 4.

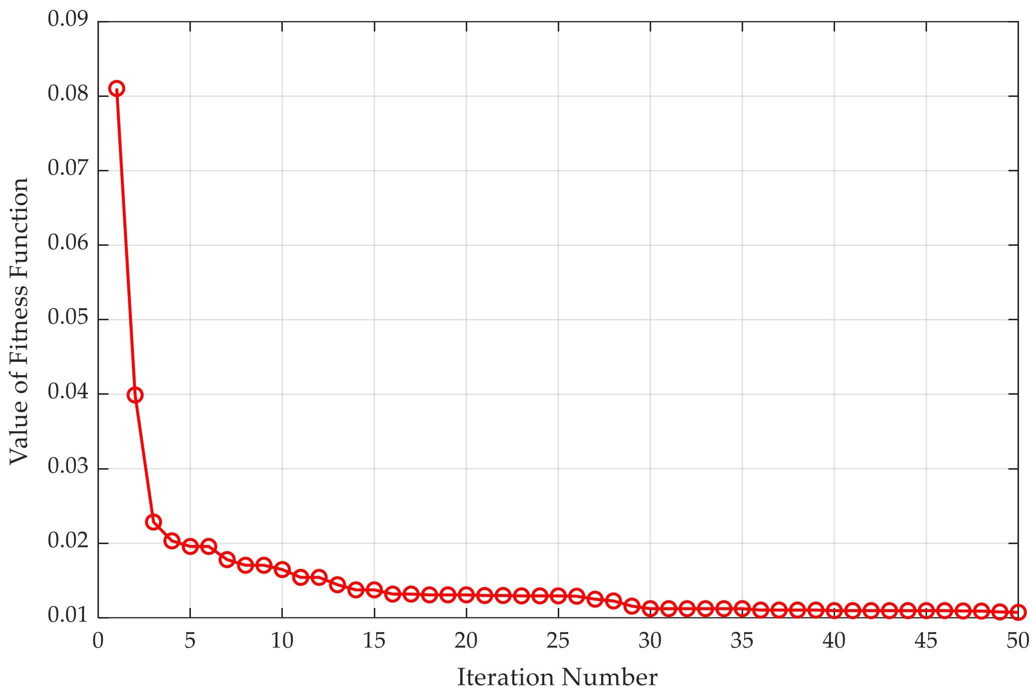

Figure 9. The convergence curve of TLBO.

Table 4. The optimum values of the Fuzzy FOPI+FOPD+I.

Controller	Parameters								
	K_1	K_2	K_3	K_{P1}	K_I	λ	K_{P2}	K_D	μ
Fuzzy FOPI+FOPD + I	0.284	0.7304	1.9193	0.5200	0.4816	0.6971	1.6179	0.7885	0.1499

4. Results and Discussion

This study was implemented on MATLAB 2022a; the TLBO code was programmed in .m file while the AVR model and the controller were implemented in MATLAB Simulink environment. A step response of 1 pu amplitude was set as a reference point. To investigate the supremacy of the proposed technique, the obtained results are compared with other studies presented in the literature based on PID tuned by IWOA [51] ($K_P = 0.8167$; $K_I = 0.6898$; $K_D = 0.2799$), ABC [52] ($K_P = 0.6352$; $K_I = 0.4235$; $K_D = 0.2241$), Many Optimizing Liaisons (MOL) [53] ($K_P = 0.5857$; $K_I = 0.4189$; $K_D = 0.1772$), and TSA [13] ($K_P = 1.1281$; $K_I = 0.9567$; $K_D = 0.5671$). The characteristics of the response represented by the peak overshoot (POs) in pu, peak undershoot (PUs) in pu, settling time (Ts) in seconds, rise time (Tr) in seconds, and the value of the ITAE are presented in Table 5. Figure 10 illustrates the response of the AVR system based on the proposed fuzzy configuration and other PID controllers tuned by different optimization tools previously presented in the literature.

Table 5. The characteristics of the AVR system based on different techniques.

Controller	Characteristics				
	OS (pu)	**US (pu)**	**Ts**	**Tr**	**ITAE**
Proposed Fuzzy	0.055239	**0.9915**	**0.1612**	**0.1094**	**0.01092**
PID IWOA	0.069178	0.9912	0.3276	0.2258	0.07078
PID ABC	**0.0002**	0.9689	0.4559	0.2951	0.06165
PID MOL	**0.019606**	**0.9967**	0.5153	0.3429	**0.05131**
PID TSA	0.15593	0.90455	**0.1897**	**0.1311**	0.08791

Figures in **black bold** represent the **best results** and in **blue bold** represent the **second-best.**

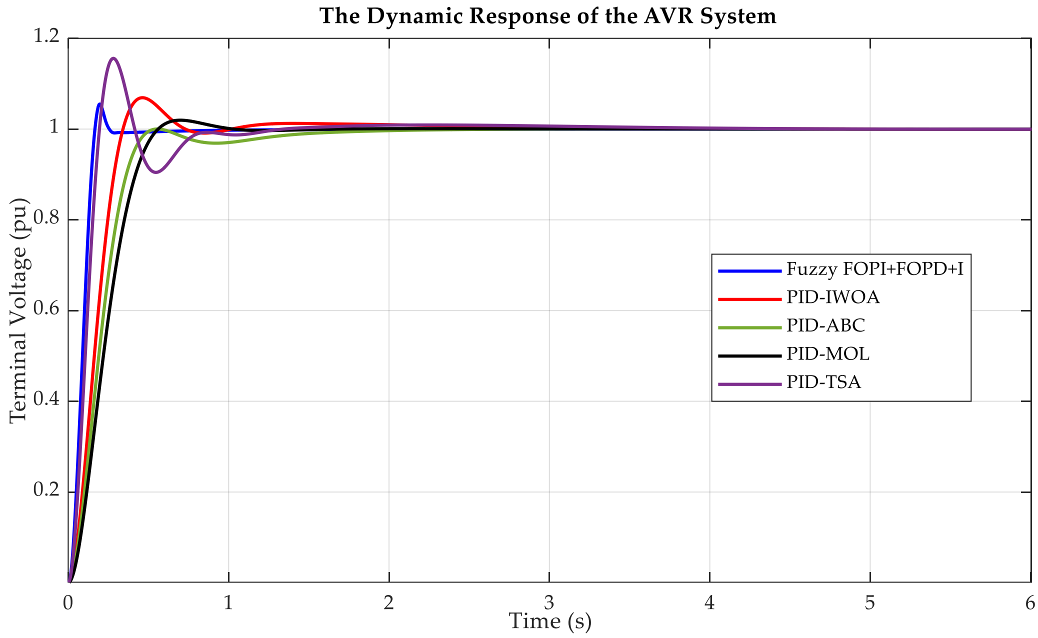

Figure 10. The dynamic response of the AVR system based on different controllers.

As mentioned above the proposed controller is designed to compromise between quick response and robust stability. From the presented findings of Figure 10 and Table 5, it is obvious that the proposed fuzzy structure provides the best overall response. It secured the best settling time, rise time, and objective function with values of 0.1612 s, 0.1094 s, and 0.01092, respectively. Furthermore, it offers the second-best peak overshoot and undershoot. Also, it is clear that the PID-TSA offers the worst overall response.

For unit suitability, Figures 11–13 present a comparative analysis of the characteristics of AVR control systems designed using various approaches, including the proposed Fuzzy

FOPI+FOPD+I method. Specifically, Figure 11 illustrates the settling time and rise time, while Figure 12 provides bar chart comparisons of the ITAE cost function. Figure 13 highlights the maximum overshoot (in pu) and maximum undershoot (in pu).

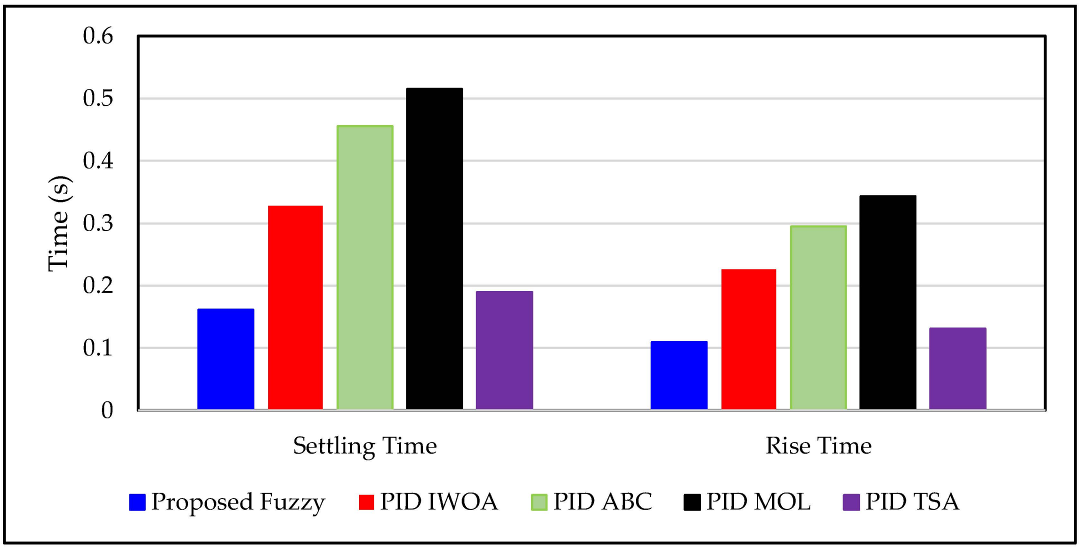

Figure 11. Settling and rise times of different controllers.

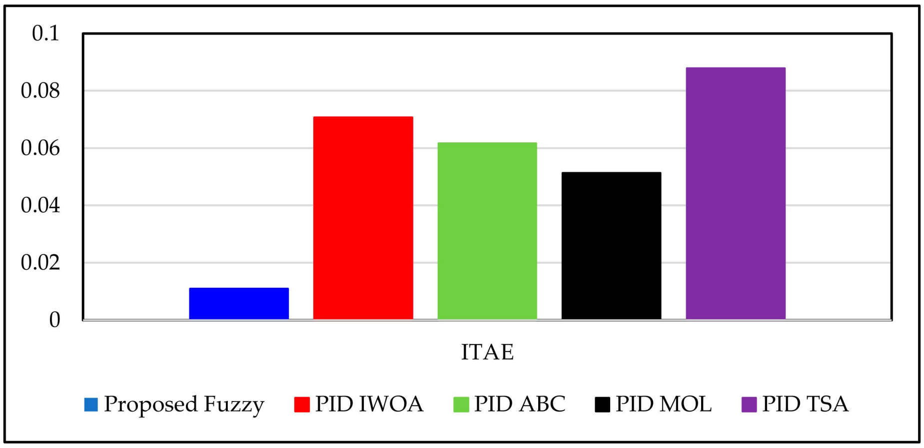

Figure 12. ITAE of different controllers.

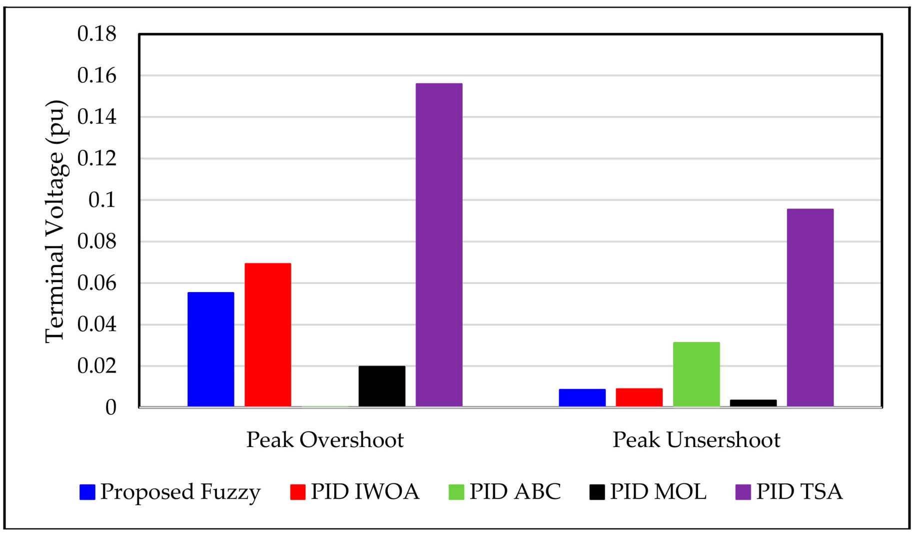

Figure 13. Peak overshoot and undershoot of different controllers.

From Figures 10–13 and Table 5, it is evidenced that the proposed Fuzzy FOPI+FOPD+I demonstrated excellent performance as an AVR controller and has outperformed several techniques proposed in the literature. This controller offered a stable and quick response, which gives clear evidence that this controller can be implemented in real-time applications.

5. Robustness Analysis

The system parameters such as the gains and time constants are inherently prone to constant fluctuations. These variations can significantly deteriorate the performance of closed-loop control systems. Despite their critical impact, this issue has received comparatively less attention in the context of AVR systems within existing research. The influence of parameter variations on the overall performance of the AVR system is thoroughly analyzed. To this end, a detailed investigation is conducted to assess the effects of parametric uncertainties within the system. Each parameter varies by ±50% from its nominal value to examine the impact of this variation on the system's stability, as shown in Table 6. Figure 14 illustrates the parametric uncertainty impact on the AVR system without a controller.

Table 6. Different considered scenarios for parametric uncertainty analysis.

Case	Nominal Value	Variation Range	New Value
Case 1: Generator Coefficient	$K_g = 1$	+50% and − 50%	1.5 and 0.5
Case 2: Generator Time Constant	$\tau_g = 1$	+50% and − 50%	1.5 and 0.5
Case 3: Excitor Coefficient	$K_e = 1$	+50% and − 50%	1.5 and 0.5
Case 4: Exciter Time Constant	$\tau_e = 0.4$	+50% and − 50%	0.6 and 0.2
Case 5: Sensor Coefficient	$K_s = 1$	+50% and − 50%	1.5 and 0.5
Case 6: Sensor Time Constant	$\tau_s = 0.01$	+50% and − 50%	0.015 and 0.005
Case 7: Amplifier Coefficient	$K_a = 10$	+50% and − 50%	15 and 5
Case 8: Amplifier Time Constant	$\tau_a = 0.1$	+50% and − 50%	0.15 and 0.05
Random scenario	$K_g = 1$	−25%	0.75
	$\tau_g = 1$	−50%	0.5
	$K_e = 1$	−50%	0.5
	$\tau_e = 0.4$	+50%	0.6
	$K_a = 10$	+50%	15
	$\tau_a = 0.1$	−50%	0.05
	$\tau_s = 0.01$	−50%	0.005

It is obvious from the subfigures shown in Figure 14 that the variation in the parameters leads to a significant deterioration of the overall performance of the model. Moreover, in some scenarios, the system was slightly oscillated. Accordingly, a random severe scenario of parametric uncertainty of the AVR with six parameters deviated by +50% or −50% from their nominal values is assumed, as shown in Table 6. The proposed Fuzzy FOPI+FOPD+I will be equipped in the investigated system to examine its robustness against a critical scenario of parametric uncertainty and evaluate the overall response and the controller performance. Importantly, the optimal gains determined under nominal conditions remain unchanged when the model is subjected to these parameter variations, highlighting the controller's ability to adapt to dynamic system changes without re-tuning.

Figure 15 illustrates the step response of the testbed system under conditions of parametric uncertainty. Despite the significant parametric variations imposed on the system, it continues to operate within acceptable performance limits. The response under uncertainty is slightly slower compared to nominal conditions and exhibits a minimal steady-state error, which is negligible. This is attributed to the cumulative impact of the deviations across all parameters. The obtained result from the robustness test demonstrates the remarkable robustness and reliability of the proposed AVR fuzzy control system.

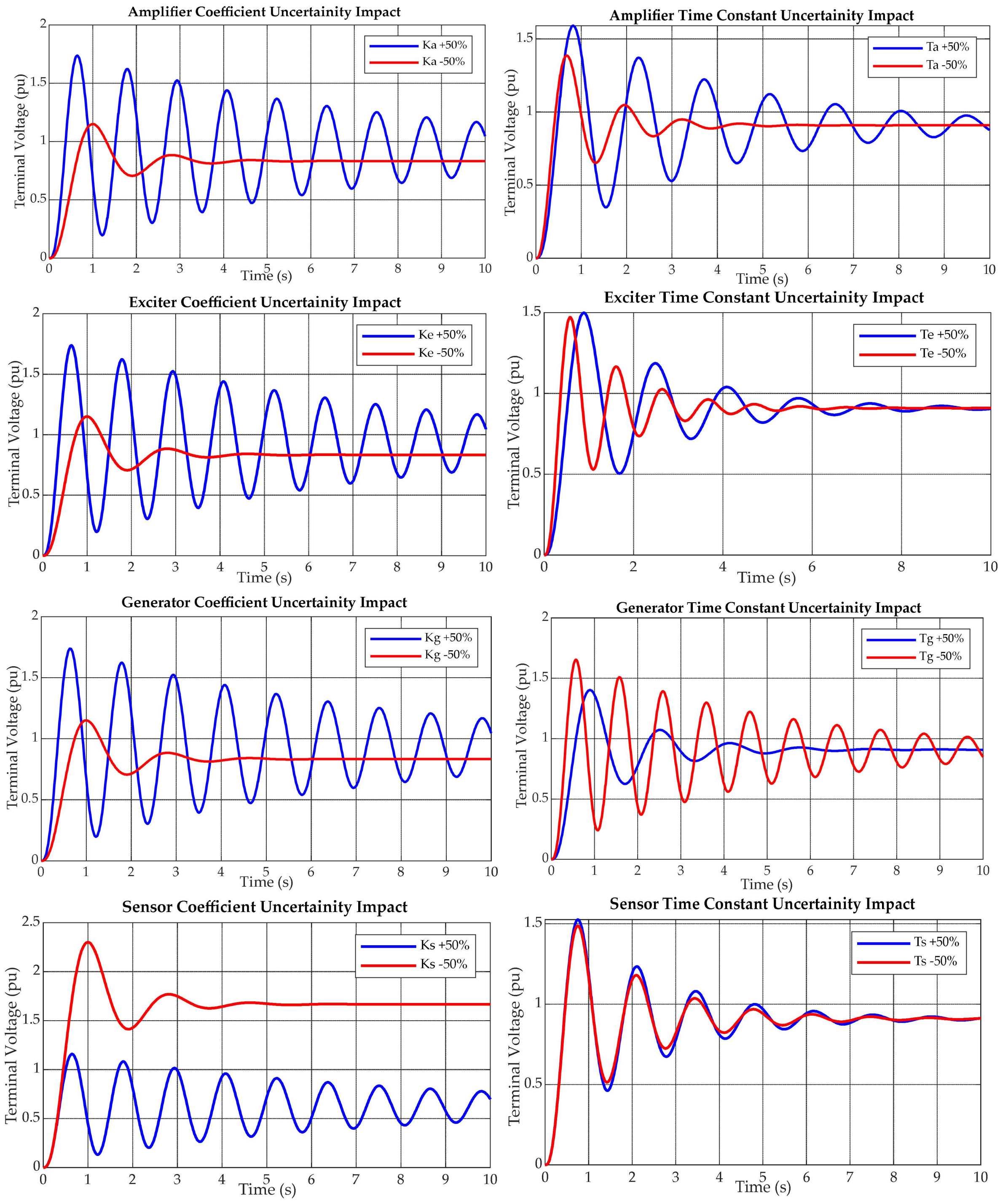

Figure 14. Step responses of AVR systems without controller under different parametric uncertainty conditions.

To thoroughly evaluate the overall performance of the proposed controller, the system will be tested under varying load conditions while being subjected to parametric uncertainty. This scenario represents the most challenging situation the system may encounter during real-time operation.

The rejection of load disturbance effects on AVR output is another critical capability of the controller, demonstrating its robustness. According to [54], disturbances of up to 5% of the generator output voltage are permissible; however, controllers are expected to suppress disturbances exceeding this threshold. In alignment with prior studies, this investigation subjected the system to disturbances rated at 10% of the reference voltage, which were injected into the generator output.

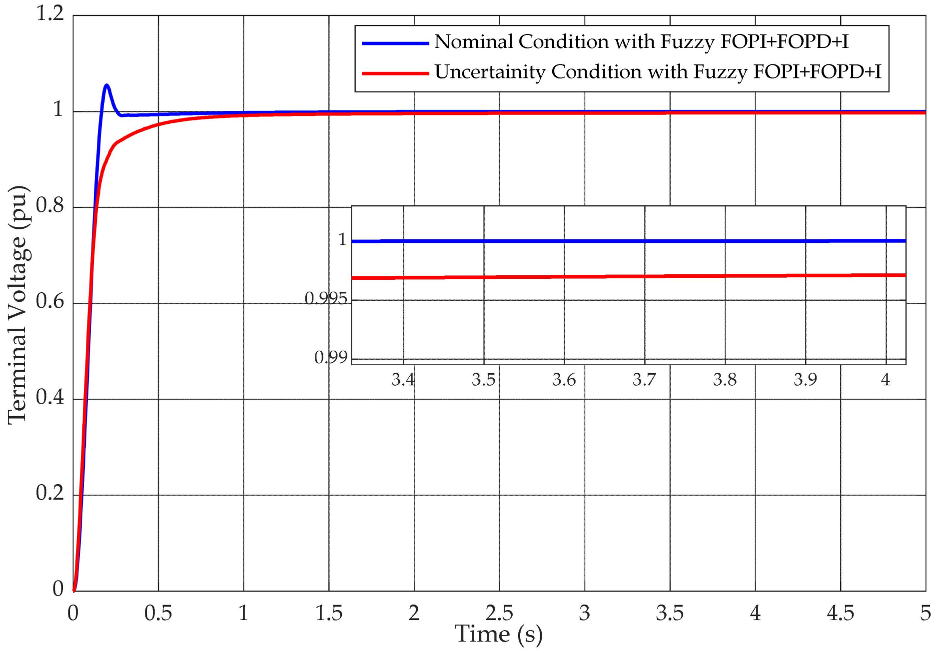

Figure 15. Step responses of AVR systems when system is subjected to parametric uncertainties.

Figure 16 illustrates the injected disturbances, AVR outputs, and corresponding time-domain specifications. The proposed controller effectively suppressed these disturbances, delivering a stable and reliable response across various operating conditions. This highlights the controller's strong ability to maintain performance and robustness under challenging scenarios.

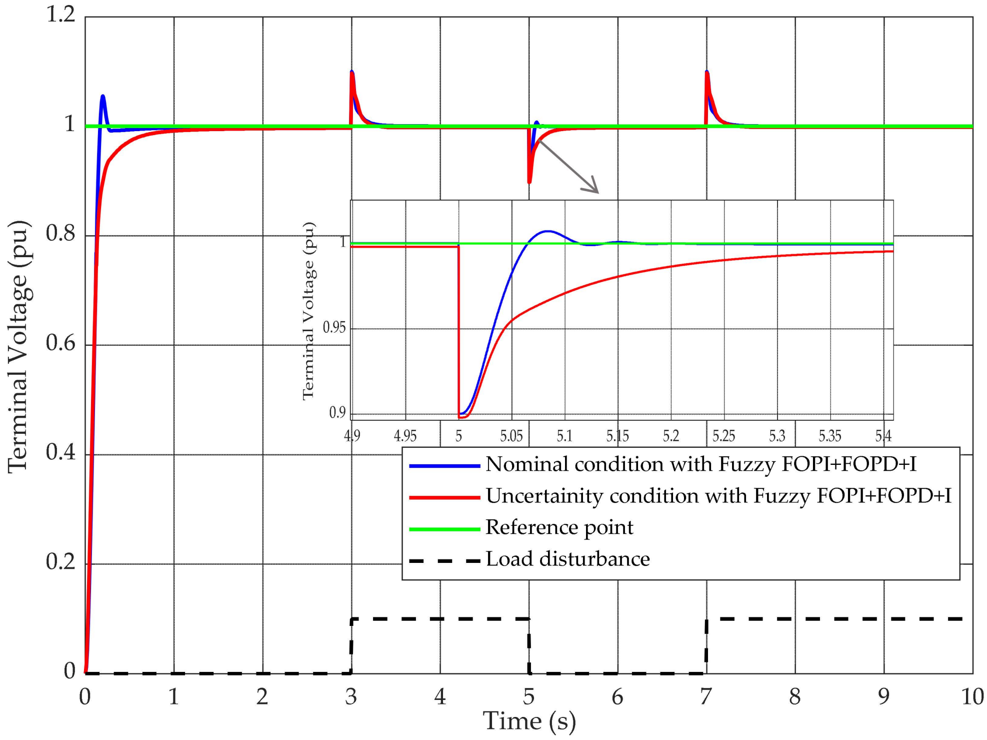

Figure 16. Step responses of AVR systems when system is subjected to parametric uncertainties with load disturbance.

6. Conclusions

This study successfully introduced and implemented a novel fuzzy configuration for AVR systems. The proposed Fuzzy FOPI+FOPD+I controller was optimized using the TLBO algorithm by minimizing the ITAE cost function. This controller was designed to benefit from different control theory advantages such as fuzzy control theory, cascading control, and fractional calculus. The proposed AVR control system demonstrated exceptional performance and outperformed other controllers reported in the literature. These results highlight the controller's readiness for real-time application. The simulation results demonstrate that the Fuzzy FOPI+FOPD+I controller, tuned using the TLBO algorithm, outperforms the other reported methods. Specifically, the peak overshoot was reduced from 0.15593 pu to 0.055239 pu, the peak undershoot was enhanced from 0.90455 pu to 0.9915 pu, and the settling time was significantly improved from 0.5153 s to 0.1612 s. Additionally, the robustness of the proposed controller was thoroughly evaluated under parametric uncertainties, where it exhibited excellent resilience. The controller also maintained superior performance under varying load conditions, further confirming its reliability and effectiveness.

One minor limitation of this study is the computational time required by the TLBO algorithm to tune the controller parameters, which could be improved by adopting a more computationally efficient optimization technique. Furthermore, the slight overshoot observed in the results highlights an area for potential improvement, which could be addressed through advanced tuning strategies or minor adjustments to the control design.

Future work could explore alternative control designs to further enhance the system's performance. For instance, integrating a hybrid fuzzy controller with LQR control could potentially yield even greater improvements in the overall performance of the AVR system. Also, it is important to study the performance of the system considering aspects of nonlinearities. Furthermore, the stability analysis of systems employing fuzzy control remains an underexplored area in the existing literature. As a prospective avenue for future research, examining the zero and pole dynamics of the system under the influence of the proposed fuzzy controller within the AVR model presents a compelling opportunity to enhance understanding in this domain.

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