A Thesis Submitted to the Sylhet Engineering College for the Degree of
Bachelor of Science in Electrical and Electronic Engineering

Whale Optimization Algorithm Based Tuning of PD-PI-PID Controller for Automatic Voltage Regulator Systems

By
Sazidul Alam
&
Md. Abdul Momin

Supervised by
Md. Faiyaj Ahmed Limon
Lecturer
Department of Electrical and Electronic Engineering
Leading University, Sylhet

June, 2025
Sylhet Engineering College, Sylhet
Affiliated with
Shahjalal University of Science & Technology (SUST)

The thesis titled **“Whale Optimization Algorithm Based Tuning of PD-PI-PID Controller for Automatic Voltage Regulator Systems”** submitted by **Sazidul Alam** and **Md. Abdul Momin**; Student ID: **2019338531** and **2019338551**; Session **2019-20**, to the Department of Electrical and Electronic Engineering, Sylhet Engineering College, has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Electrical and Electronic Engineering and approved as to its style and contents.

BOARD OF EXAMINERS

Md. Shahid Iqbal
Assistant Professor and Head
Department of Electrical and Electronic Engineering,
Sylhet Engineering College, Sylhet.

Chairman

Md. Faiyaj Ahmed Limon
Lecturer, Department of Electrical and Electronic Engineering
Leading University, Sylhet.

Supervisor

Salman Fazle Rabby
Assistant Professor, Department of Electrical and Electronic Engineering,
Sylhet Engineering College, Sylhet.

Member

Apurba Biswas
Assistant Professor, Department of Electrical and Electronic Engineering,
Sylhet Engineering College, Sylhet.

Member

Md. Ashraful Alam
Lecturer, Department of Electrical and Electronic Engineering,
Sylhet Engineering College, Sylhet.

Member

Mahedi Kamal Ahmed
Lecturer, Department of Electrical and Electronic Engineering,
Sylhet Engineering College, Sylhet.

Member

Arif Ahammad
Assistant Professor, Department of Electrical and Electronic Engineering,
Shahjalal University of Science & Technology, Sylhet.

Member (External)

Acknowledgements

First and foremost, we offer our deepest gratitude to the Almighty, whose silent presence and infinite grace have been the guiding light throughout our life. In every quiet triumph and every hidden struggle, it is by His will that we have found strength, clarity, and purpose. This work is a humble reflection of the countless blessings He has bestowed upon us, often unseen yet always deeply felt.

We would like to express our deepest appreciation to our respected thesis supervisor, **Md. Faiyaj Ahmed Limon**, for his constant support, invaluable guidance, and constructive feedback. His encouragement and insightful suggestions have greatly enriched our work and learning experience.

We would also like to extend our sincere gratitude to **Md. Shahid Iqbal**, **Salman Fazle Rabby, Md. Ashraful Alam** and who have been our respected course teachers throughout our academic journey. Their dedication to teaching, depth of knowledge, and continuous encouragement have left a profound impact on our learning experience. Each of them, in their unique way, has helped shape our academic foundation and inspired us to pursue excellence with confidence and clarity.

Lastly, with all our love and respect, we express our deepest gratitude to our beloved parents, whose unconditional love, endless sacrifices, and constant prayers have always been the source of our strength. Their unwavering belief in us has been the foundation of all our achievements.

Abstract

This research investigates the optimal tuning of Proportional-Integral-Derivative (PID) and Fractional-Order PID (FOPID) controllers for Automatic Voltage Regulator (AVR) systems using advanced metaheuristic optimization techniques. The study aims to improve the transient response, robustness, and stability of AVR systems, which are critical for maintaining consistent voltage levels in power networks. A two-phase optimization strategy is employed. In the first phase, Particle Swarm Optimization (PSO) is applied to tune various PID-based configurations, identifying the PD-PI-PID cascade controller as the most effective structure. In the second phase, several metaheuristic algorithms are utilized to further refine this controller, with the Whale Optimization Algorithm (WOA) demonstrating superior performance. The optimization process is guided by the Integral of Time-weighted Absolute Error (ITAE) objective function to ensure minimal voltage deviation and enhanced dynamic response. Comparative results reveal that the WOA-tuned PD-PI-PID controller achieves the lowest ITAE value (0.0024692), minimal overshoot (49.08%), and fastest settling time (0.16088 seconds) among all tested configurations. Furthermore, robustness is validated through extensive testing under ±25% and ±50% variations in AVR system parameters, confirming stable performance across uncertain operating conditions. The findings underscore the effectiveness of combining advanced controller structures with metaheuristic optimization to significantly enhance AVR performance, offering a promising approach for robust and efficient voltage regulation in modern power systems.

Keywords: *AVR system, PID controller, FOPID controller, PD-PI-PID cascade, Metaheuristic optimization, PSO, WOA, ITAE, Voltage regulation, Robustness analysis.*

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Overview

One of the core responsibilities of an electric power system is to ensure the supply voltage remains stable and consistent. Fluctuations in voltage can not only harm connected electrical appliances but also reduce their efficiency. Moreover, both active and reactive power flow and thus power losses are directly influenced by voltage levels. Even small voltage deviations can lead to significant changes in reactive power flow. If the voltage strays beyond the permissible range (typically $\pm5\%$ of the rated voltage), it can result in major power losses and, ultimately, economic inefficiency.

To prevent these issues, voltage regulation is implemented at various stages of power system generation, transmission, and distribution. However, this research focuses specifically on voltage regulation at the generation stage, which is typically handled by an Automatic Voltage Regulator (AVR) in systems using conventional synchronous generators.

An AVR plays a crucial role by automatically adjusting the generator's voltage under all operating conditions. The AVR compares the generator’s terminal voltage with a predefined reference voltage and generates an error signal based on the difference. This signal is then used to adjust the field excitation of the alternator, thereby keeping the terminal voltage at the desired level automatically.

Due to the very high inductance of the generator's field winding and continuous load switching, it is almost impossible to achieve the optimal operation of the AVR system. Mostly, the conventional PID regulator is used to enhance the dynamic performance and stability of AVR due to its robustness, simple design and easy implementation [1].

1.2 Automatic Voltage Regulator (AVR)

An Automatic Voltage Regulator (AVR) is a vital component in electrical systems, designed to maintain a stable and consistent voltage output. Its primary role is to stabilize the output voltage of generators or transformers, ensuring that connected loads receive a steady and reliable supply within acceptable limits. AVRs achieve this by regulating the excitation current supplied to the generator’s field windings, which in turn controls the magnetic field strength and thus the output voltage. This regulation is essential to protect electrical equipment from voltage fluctuations. Overvoltage can damage sensitive electronics, while undervoltage can lead to operational failures or reduced performance of equipment.

One of the key strengths of an AVR is its fast response to changes in load. When the electrical demand fluctuates, the AVR quickly adjusts the excitation to maintain a consistent voltage level, ensuring continuous and stable power delivery to connected devices. Due to their reliability and efficiency, AVRs are widely used in various sectors including power plants, industrial facilities, hospitals, data centers, and telecommunications anywhere where voltage stability is crucial.

There are several types of AVRs, each suited for specific needs. Brushless AVRs are commonly used with alternators, static AVRs are applied in transformers, and digital AVRs offer advanced features for precision control and monitoring. While some AVRs can be manually adjusted to set the desired voltage, most modern systems operate automatically, continuously monitoring and adjusting voltage without the need for human intervention.

Beyond voltage regulation, AVRs also play a critical role in improving overall power quality. By maintaining a consistent voltage profile, they enhance the efficiency and reliability of electrical equipment, reduce the risk of system failures, and lower maintenance costs. Many AVR systems are also designed for parallel operation, allowing them to work alongside other generators or the power grid to share load and provide backup during emergencies. To ensure continued reliability, regular maintenance and testing such as connection checks, calibration, and voltage regulation tests are essential. In summary, AVRs are indispensable for maintaining voltage stability, protecting equipment, and supporting efficient power system operation across a wide range of applications.

1.3 Diagram of the AVR

An Automatic Voltage Regulator (AVR) is a device used in generators to automatically maintain a constant output voltage, even when there are fluctuations in the system. As illustrated in Figure 1.1, the AVR operates by converting varying voltage levels into a stable and consistent output through a closed-loop control system. The realistic model of an AVR typically includes various components such as different types of controllers, an amplifier, an exciter, and the generator itself. The system functions by comparing the reference voltage (Vref) with the actual terminal voltage (Vt) through a voltage sensing device, generating an error signal that is processed by the amplifier to control the exciter field voltage (Vf), which ultimately regulates the generator output. These elements work together to ensure effective and reliable voltage regulation, as demonstrated in the comprehensive system diagram shown in Figure 1.1.

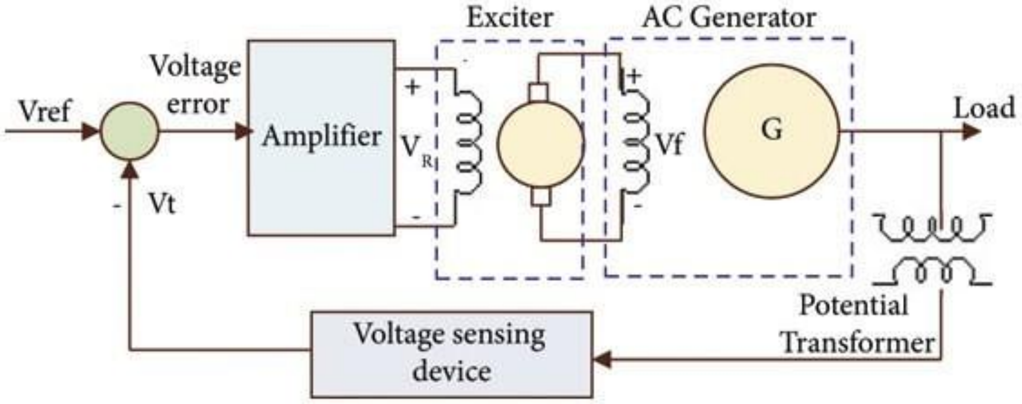

Figure 1.1. Diagram of the AVR system

1.4 Uses of controllers

With the development in the field of soft-computational optimization methods, the optimal design of the FOPID based AVR system has been studied by several researchers around the world. They have utilized several modern methods to achieve an optimized dynamic response and stability using the optimal set of FOPID parameters. Among such methods, the PSO is found to be most extensively applied due to its simple optimization mechanism and easy implementation [2-3]. However, due to uncertainty in PSO's parameter selection, trapping into the local minimum and low convergence rate in the iterative process, the PSO has lost its essence in solving the modern and complex optimization problems [4-5]. There are few other well-known algorithms like artificial bee colony (ABC) [6], biography-based optimization (BBO) [7], grasshopper optimization algorithm (GOA) [8], pattern search algorithm (PSA) [9], improved kidney-inspired algorithm (IKA) [10], whale optimization algorithm (WOA) [11] and slap swarm optimization algorithm (SSA) [11] have been used to obtain the optimal dynamic response of AVR system. However, almost all the mentioned research works have utilized the conventional PID controllers which ultimately result in a sub-optimal response as validated by the outcomes of the current research work. Hence an AI-based optimal controller for the AVR system is still under consideration for the researchers in the current research area. Therefore, this research work evaluates and compares all the mentioned studies with the proposed PD-PI-PID based AVR system to validate the effectiveness of the proposed AVR design. The proposed JOA based FOPID tuning method has been found to be better than the mentioned research works in obtaining the optimal values of FOPID parameters and hence achieves the most optimal dynamic response and stability among the studied AVR systems.

1.5 Research motivation

This study focuses on designing a robust and optimal Automatic Voltage Regulator (AVR) for conventional synchronous generator-based power systems. The primary objective is to achieve effective voltage regulation while improving the system's stability and robustness. To achieve this, the study uses a Fractional Order PID (FOPID) controller with parameters optimally tuned using the Jaya Optimization Algorithm (JOA), which is a modern and intelligent metaheuristic optimization technique.

The design aims to enhance the system's transient response, robustness, and overall stability. Key performance indicators such as percentage overshoot (M_p), settling time (t_s), peak time (t_p), and rise time (t_r) are used to evaluate dynamic performance. A comparative analysis is conducted with several recent studies using these metrics to validate the effectiveness of the proposed method.

Furthermore, the stability and robustness of the AVR design are examined under various system parameter changes to ensure reliable operation. The robustness analysis involves systematic parameter variations to evaluate controller performance under realistic scenarios. The comparative results demonstrate that the AVR optimized using JOA performs better than other existing optimization techniques, offering improved stability and control performance. The proposed methodology achieves superior dynamic response while maintaining consistent performance under uncertainties, making it suitable for practical power system applications.

1.6 Objectives of the Study

The primary objective of this research is to enhance the transient response, stability, and robustness of Automatic Voltage Regulator (AVR) systems through systematic controller optimization and validation. To achieve this, the research sets out three specific objectives.

1. Compare multiple PID controller structures using PSO.
2. Optimize the best controller structure (PD-PI-PID) using WOA and other algorithms.
3. Validate the best controller via sensitivity testing.

1.7 Thesis Structure

This thesis is structured into six chapters to systematically present the research.

Chapter 1: Introduction provides an overview of the research area, elucidates the problem statement, and outlines the objectives of the study.

Chapter 2: Literature Review presents a comprehensive review of existing studies on Automatic Voltage Regulator (AVR) systems, various Proportional Integral Derivate (PID) and Fractional Order Proportional-Integral-Derivative (FOPID) controller configurations, and the application of metaheuristic optimization algorithms for their tuning.

Chapter 3: Problem Formulation and AVR Modeling details the mathematical models of the AVR system and its components, the transfer functions of both PID and FOPID controllers, and the formulation of the objective functions utilized in the optimization process.

Chapter 4: Methodology describes the implementation of the Particle Swarm Optimization (PSO) and Whale Optimization Algorithm (WOA) for controller tuning, outlining the experimental setup and procedures.

Chapter 5: Results and Discussion presents and thoroughly analyzes the transient response characteristics, robustness, and stability of the optimized AVR system, offering comparative insights against other established methods.

Chapter 6: Conclusion and Future Work summarizes the key findings of the research and suggests potential directions for future studies in this domain.

1.8 Summary

This chapter establishes the foundation for optimizing Automatic Voltage Regulator (AVR) systems in power generation, emphasizing the critical role of voltage stability in preventing equipment damage and economic losses. While conventional PID controllers are widely used for AVR systems, they often provide sub-optimal performance under varying operating conditions. Existing metaheuristic optimization methods suffer from limitations such as local minima trapping and slow convergence rates. To address these challenges, this research proposes a systematic approach: comparing multiple PID controller structures using PSO, optimizing the best-performing PD-PI-PID structure using WOA, and validating controller robustness through sensitivity testing to achieve superior transient response and stability.

Chapter 2: Literature Review

2.1. PSOGSA-Based PID Optimization for AVR Systems

The stability and quality of electrical power systems rely heavily on maintaining consistent voltage levels, primarily managed by Automatic Voltage Regulator (AVR) systems. Traditional PID controllers are commonly used to improve power quality by minimizing steady-state errors and enhancing transient response. However, challenges like oscillations, overshoots, and tuning complexity persist. Fractional-Order PID (FOPID) controllers offer improved performance through additional tuning parameters, enhancing system stability and robustness. Due to the complexity of tuning FOPID controllers, finding optimal parameters becomes a significant challenge. To address this, researchers increasingly apply metaheuristic optimization algorithms to optimize controller gains and boost AVR performance.

Introduces an optimal PID controller for an AVR system using a new hybrid algorithm, Particle Swarm Optimization and Gravitational Search Algorithm (PSOGSA). The paper demonstrates PSOGSA's effectiveness through transient response and bodes analysis, comparing its results against traditional methods like Ziegler-Nichols (ZN), Particle Swarm Optimization (PSO), and Many Optimizing Liaisons (MOL). The study concludes that the PSOGSA algorithm yields superior results for the AVR system, including better maximum overshoots and settling times, and enhanced stability in the frequency domain by minimizing the Integral Time multiplied by the Absolute Error (ITAE) [12].

2.2. MPA-Based FOPID Tuning for AVR Systems

Presents a novel tuning method for the FOPID controller in AVR systems, employing the Marine Predators Algorithm (MPA). The MPA-FOPID controller's performance is evaluated through step response and trajectory tracking analysis, demonstrating its exceptional ability to enhance AVR transient response when compared to other FOPID controllers optimized by metaheuristic algorithms such as SA-MRFO, GBO, ChBWO, NSGA II, and PSO. The research emphasizes the FOPID controller's potential due to its fractional exponential terms, offering new control opportunities and improved performance over traditional PID controllers, while also validating MPA's superior convergence accuracy [13].

2.3. SSA-Based FOPID Controller for AVR Dynamic Response Enhancement

Investigates the use of the FOPID controller in AVR systems, leveraging its superior transient and steady-state performance. Given the increased complexity of FOPID tuning due to its two additional parameters (μ and λ), the paper employs the Salp Swarm Optimization (SSA) algorithm to select optimal FOPID gains. The study demonstrates that the proposed SSA-based FOPID tuning method surpasses other established techniques like DE, PSO, ABC, GOA, BBO, and PSA in terms of dynamic response and stability measures, using ITAE as the objective function [14].

2.4. Comparative Analysis of Optimization-Based PID Tuning for AVR Systems

Provides a comparative analysis for designing an optimal PID controller for an AVR system using various optimization techniques. The evaluated algorithms include Particle Swarm Optimization (PSO), Cuckoo Search Optimization (CSO), Moth Flame Optimization (MFO), Water Cycle Optimization (WCO), Teaching–Learning-Based Optimization (TLBO), and Hill Climbing Optimization (HCO). The performance assessment is based on transient response parameters such as rise time, settling time, percentage overshoot, and the Integral Time Absolute Error (ITAE) as a performance index. The findings indicate that all optimization techniques improve system performance, with HCO generally providing superior results for overshoot and settling time [15].

2.5 HBA-Based FOPID Controller Optimization for AVR Systems

Proposes the application of the Honey Badger Algorithm (HBA) for optimally tuning a FOPID controller in an AVR system. The study analyzes the transient response of HBA-FOPID, HBA-PID, and HBA-PI controllers, utilizing the Integral Time-Weighted Squared Error (ITSE) as the objective function. It concludes that the HBA-FOPID controller achieves remarkable performance, including lower overshoot and settling time, and superior frequency response characteristics (gain and phase margin), compared to other HBA-tuned controllers [15].

2.6 JOA-Based FOPID Optimization for AVR Transient Response Enhancement

Explores the use of the FOPID controller in AVR systems, noting its flexibility despite the complexity of tuning its five parameters. The paper introduces the Jaya Optimization Algorithm (JOA) to determine optimal FOPID gains, aiming to achieve an optimal transient response and enhanced stability for the AVR system. The study presents a comprehensive comparison of JOA with other well-known AI-based approaches, including DE, PSO, ABC, BBO, GOA, PSA, IKA, WOA, and SSA, demonstrating JOA's superior performance in reducing overshoot and improving overall transient response. The Integral Time Absolute Error (ITAE) is chosen as the fitness function for this optimization [16].

2.7 PSO-Based Fuzzy PID Controller for Generator AVR Systems

Conventional PID controllers are commonly used in Automatic Voltage Regulator (AVR) systems but often fail to deliver optimal performance under dynamic conditions due to limited tuning flexibility. Fractional Order PID (FOPID) controllers offer improved control by introducing two extra tuning parameters, though their optimization is more complex. While metaheuristic algorithms like PSO and GA have been used for FOPID tuning, they suffer from issues such as premature convergence and random behavior. This study addresses these challenges by proposing a Gradient-Based Optimization (GBO) algorithm, which efficiently tunes the FOPID controller by minimizing the Integral Time-weighted Absolute Error (ITAE). The proposed method demonstrates superior performance in dynamic response, stability, and robustness compared to existing approaches. However, it remains limited by offline tuning, higher computational load, and lack of real-time or hardware validation [17].

2.8 PSO-Based PID Controller Tuning for AVR Systems

The paper "Tunning PID controller using particle swarm optimization algorithm on automatic voltage regulator system" by Aranza et al. (2016) significantly contributes to the field by demonstrating the efficacy of Particle Swarm Optimization (PSO) for optimally tuning PID controller gains (Kp, Ki, and Kd) in Automatic Voltage Regulator (AVR) systems. A key contribution is the empirical evidence showing that a PID controller tuned with PSO yields superior transient response characteristics, including lower overshoot, faster peak time, quicker rise time, and significantly reduced settling time, compared to traditional Ziegler-Nichols (ZN) [18].

2.9 Summary

This chapter reviews metaheuristic optimization techniques for PID and FOPID controller tuning in AVR systems, demonstrating the superiority of advanced algorithms like PSOGSA, MPA, SSA, HBA, and JOA over traditional methods such as Ziegler-Nichols tuning. While these metaheuristic approaches achieve better transient response, reduced overshoot, and improved stability by optimizing objective functions like ITAE and ITSE, they face limitations including computational complexity, offline tuning constraints, and lack of real-time validation. To overcome these challenges, this research proposes a systematic optimization approach combining advanced algorithms with cascade controller structures to achieve enhanced performance and robustness under dynamic operating conditions.

Chapter 3: Problem Formulation and AVR Modeling

3.1 AVR System and Control Objective

Voltage stability is crucial in power systems to ensure high power quality, system security, and reliable operation of electrical equipment. The Automatic Voltage Regulator (AVR) plays a key role in maintaining the terminal voltage of the generator at desired levels by automatically adjusting the field excitation current in response to load variations and system disturbances. However, due to its inherent nonlinear dynamics and the complex interaction between multiple system components including the amplifier, exciter, generator, and sensor, the AVR system often suffers from oscillatory behavior, excessive overshoot, slow settling time, and poor response characteristics under varying operating conditions. These performance limitations can lead to voltage fluctuations that may damage sensitive equipment and reduce overall system efficiency.

This work aims to improve AVR system performance by designing optimized PID-based controllers using metaheuristic algorithms. By employing cascade PID configurations and optimizing parameters through PSO and WOA algorithms, the research seeks to achieve superior voltage regulation with reduced overshoot, faster settling times, and enhanced robustness against disturbances and parameter variations.

3.2 Mathematical Modeling of an AVR System

This section presents the transfer function modelling of the complete AVR system in the frequency domain. To ease the mathematical modelling, process the AVR system, its major components such as exciter, amplifier, sensor and generator are treated as linear devices. The transfer function models for these devices are represented by a time constant gain, as depicted in Equations 3.1-3.5 [23].

Amplifier transfer function

$$\mathrm{G_A(s)} = \frac{\mathrm{K_A}}{1 + sT_A} \tag{3.1}$$

Exciter Transfer function

$$G_E(s) = \frac{K_E}{1 + sT_E} \tag{3.2}$$

Generator transfer function

$$G_G(s) = \frac{K_G}{1 + sT_G} \tag{3.3}$$

Sensor transfer function

$$G_S(s) = \frac{K_S}{1 + sT_S} \tag{3.4}$$

The total open-loop AVR system

$$G(s) = G_A(s)G_E(s)G_G(s)G_S(s) \tag{3.5}$$

3.3 Components of the AVR System

The AVR system is modeled using four first-order transfer functions representing the amplifier, exciter, generator, and sensor, with the following parameters as shown in Table 3.1 [24]:

Table 3.1. AVR System Component Parameters.

Component	Gain (K)	Time Constant (T)
Amplifier	$K_A = 10$	$T_A = 0.01\,s$
Exciter	$K_E = 1$	$T_E = 0.4\,s$
Generator	$K_G = 1$	$T_G = 1.0\,s$
Sensor	$K_S = 1$	$T_S = 0.05\,s$

3.4 Transfer Function of the Uncontrolled AVR System

The open-loop system (without controller) represents the fundamental behavior of the AVR system in its natural state, providing essential insight into the inherent system characteristics and stability properties. This uncontrolled configuration serves as the baseline for evaluating controller performance improvements and understanding the system's natural response to voltage disturbances. The open-loop system is represented by the following composite transfer function shown in Equation 3.6:

$$G(s) = \frac{10}{(1 + 0.01s)(1 + 0.4s)(1 + 1s)(1 + 0.05s)} \tag{3.6}$$

3.5 Uncontrolled AVR System Response Analysis

The step response characteristics of the AVR system without any controller implementation reveal significant performance deficiencies that necessitate advanced control intervention for optimal voltage regulation. As demonstrated in Figure 3.1, the uncontrolled AVR system exhibits severe dynamic response limitations including excessive overshoot where the output voltage significantly exceeds the desired reference value, followed by substantial undershoot that drives the system response below the target level, creating undesirable oscillatory behavior that compromises system stability. Furthermore, the system demonstrates prolonged settling time, requiring an extended duration to reach steady-state conditions, which is detrimental to rapid voltage regulation requirements in practical power system applications. Most critically, the uncontrolled system suffers from a substantial steady-state error, indicating a permanent deviation between the actual output voltage and the desired reference voltage, which directly violates the fundamental objective of maintaining precise voltage levels in power generation systems. These performance inadequacies, characterized by poor transient response, insufficient damping, and unacceptable steady-state accuracy, clearly justify the need for implementing sophisticated PID-based controllers with metaheuristic optimization to achieve superior voltage regulation performance, enhanced system stability, and reliable operation under varying load conditions.

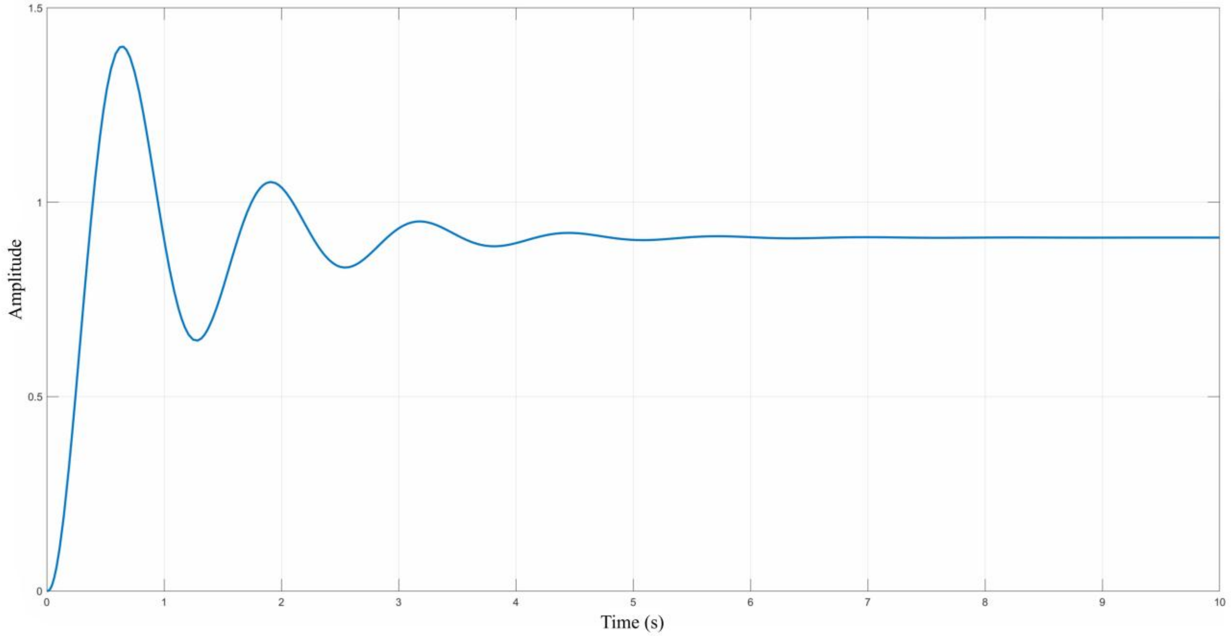

Figure 3.1. Step response of AVR system without a controller.

3.6 Flowchart of the Proposed Optimization Strategy

The Whale Optimization Algorithm (WOA) has been employed in this study as the core optimization strategy for tuning the parameters of the PD, PI, and PID controllers in the Automatic Voltage Regulator (AVR) system. The algorithm is inspired by the bubble-net hunting behavior of humpback whales and operates through exploration and exploitation phases to converge toward the global optimum solution. At the beginning, an initial population of search agents is generated, and their fitness values are evaluated. Based on these values, the best agent is identified, which guides the rest of the population during the optimization process. The position update mechanism is governed by control parameters A and P, which determine whether the algorithm should exploit around the best solution or explore new regions in the search space. Iteratively, the positions of the search agents are updated according to the mathematical models of WOA until the maximum number of iterations is reached. The outcome provides optimized controller parameters ensuring enhanced dynamic performance of the AVR system. Figure 3.2 shows the flowchart of the proposed WOA-based optimal PD-PI-PID tuning strategy.

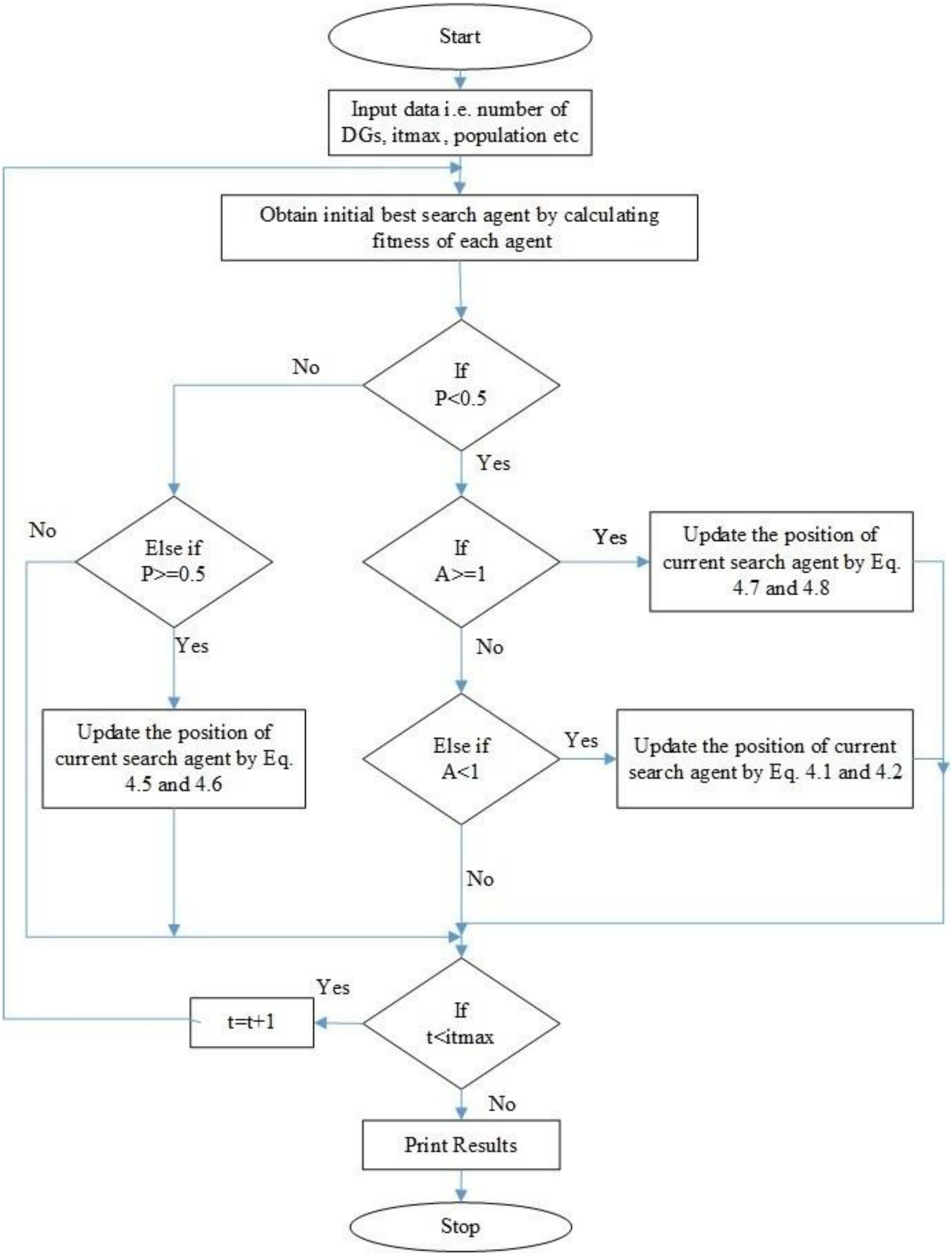

Figure 3.2. Flowchart of proposed WOA based optimal PD-PI-PID tuning for AVR system.

3.7 Summary

This chapter presents the mathematical modeling and problem formulation for AVR system optimization, establishing transfer function models for the amplifier, exciter, generator, and sensor components with their respective gains and time constants. The uncontrolled AVR system exhibits poor transient response characteristics including excessive overshoot and slow settling time, necessitating advanced controller integration. A comprehensive two-phase optimization strategy is proposed: Phase 1 employs PSO to evaluate multiple PID-based controller structures (PID, PI-PD, PD-PI, and cascade PD-PI-PID), while Phase 2 utilizes advanced metaheuristic algorithms including WOA, MPA, and HBA to optimize the best-performing PD-PI-PID cascade structure. The methodology aims to achieve superior voltage regulation with minimal ITAE, reduced overshoot, faster settling time, and enhanced robustness against parameter variations, establishing an optimal control solution for AVR systems.

Chapter 4: Methodology

4.1 Overview of the Proposed Methodology

The primary objective of this research is to enhance the transient response, stability, and robustness of Automatic Voltage Regulator (AVR) systems through optimal controller tuning. To achieve this, a comprehensive two-phase approach leveraging metaheuristic optimization algorithms was adopted. The methodology focuses on systematically identifying and optimizing controller structures to deliver superior performance under various operating conditions. This involves the mathematical modeling of the AVR system, integration of controllers, definition of the objective function, and the application of optimization algorithms to minimize this function, thereby determining optimal controller parameters.

4.2 Sequential Controller Structure Selection and Optimization

4.2.1 Phase 1: Controller Structure Selection Using Particle Swarm Optimization (PSO)

The first phase aimed to identify the most effective PID controller configuration for AVR systems. Various conventional and cascade PID structures were evaluated using the Particle Swarm Optimization (PSO) algorithm due to its simplicity and proven effectiveness in control applications.

Multiple controller configurations were tested, including PI-(1+P)-PID, PI-PI-PID, PID-PI-PID, PD-PI- PID, and several Fractional Order PID (FOPID) variants such as PIλ-PI-PIDμ. Each structure was tuned using PSO to determine optimal gains (KP, KI, KD) and, where applicable, fractional orders (λ, μ).

The optimization objective was to minimize the Integral of Time-weighted Absolute Error (ITAE), defined as in Equation 4.1:

$$ITAE = \int_0^T t\left|V_{ref} - V_t\right|dt \tag{4.1}$$

4.2.2 Phase 2: Tuning the Selected PD-PI-PID Controller with Various Algorithms

The second phase focused on refining the PD-PI-PID controller by tuning it with multiple advanced methods of mathematics. The aim was to identify the algorithm yielding the best transient response.

Algorithms applied included COA, MPA, MFO, ABC_PSO, PSO, RSA, TSA, WOA, WSO, and HBA. The Whale Optimization Algorithm (WOA) was of particular interest due to its balance of exploration and exploitation.

Each algorithm aimed to minimize the ITAE function to obtain the optimal controller parameters. The resulting controller performances were then compared based on key dynamic response metrics. WOA consistently achieved the lowest ITAE values, fastest settling times, and lowest overshoots, making it the best candidate for AVR tuning.

4.3 Optimization Process Overview

The metaheuristic optimization process begins with random initialization of controller parameters within defined bounds. Each candidate solution's fitness is evaluated using the ITAE function. The algorithm updates candidates based on its internal logic (e.g., social behavior in PSO, hunting strategy in WOA) over successive iterations.

This iterative process continues until a convergence threshold or maximum iteration count is reached. The optimal gains found through this process significantly enhance the AVR's performance in terms of reduced overshoot, settling time, and steady-state errors.

4.4 Summary

This chapter presents a two-phase optimization methodology where PSO identifies PD-PI-PID as the optimal controller structure, and WOA achieves the best parameter tuning with lowest ITAE, fastest settling time, and minimal overshoot among ten tested metaheuristic algorithms for AVR systems.

Chapter 5: Result and Analysis

5.1 Controller Structure Comparison Using PSO

Various PID structures were tuned with PSO to identify the best configuration. PD-PI-PID showed the most promising results:

- Best ITAE = 0.0054819
- Maximum Overshoot = 109.49%
- Settling Time = 0.26209 s

Table 5.1. Performance Comparison of Different Controller Structures.

Controller	Best ITAE	Maximum Overshoot	Settling Time	Rise Time	Steady State Error
PI-(1+P)-PID [25]	0.038539	64.39%	0.67645 s	0.058023 s	3.16E-08
PI-PI-PID [25]	0.040901	63.79%	0.69547 s	0.05926 s	7.65E-08
PID-PI-PID [26]	0.0069385	118.65%	0.28329 s	0.014943 s	9.61E-09
PI-PID-PID [27]	0.0068088	120.02%	0.28252 s	0.014907 s	7.09E-08
(1+PI)-PID-PI [25]	0.038531	64.98%	0.65431 s	0.077165 s	2.55E-07
PID-(1+PI)-PI	0.040913	71.34%	0.64294 s	0.064111 s	2.76E-07
PD-PI-PID [25]	0.0054819	109.49%	0.26209 s	0.014693 s	6.33E-10
PI-PD-PID [25]	0.0067785	121.85%	0.25367 s	0.014843 s	1.18E-09
PID-PID [28]	0.012864	95.63%	0.28168 s	0.021671 s	1.30E-08
PI$^{\lambda}$-PI-PID [13]	0.041458	59.06%	0.74535 s	0.067732 s	1.05E-08
PI-PI-PID$^{\mu}$ [3]	0.029264	74.53%	0.53404 s	0.038252 s	7.66E-08
PI$^{\lambda}$-(1+PI)- PID$^{\mu}$ [29]	0.027631	72.82%	0.54172 s	0.043885 s	1.08E-07
PI$^{\lambda}$-PID-PI [30]	0.040931	65.44%	0.69307 s	0.063547 s	4.25E-08
PD$^{\mu}$-PI-PID [9]	0.0055375	143.33%	0.20694 s	0.011493 s	7.45E-08
PI-PD$^{\mu}$-PID [31]	0.0047663	148.95%	0.20759 s	0.0093824 s	2.02E-08
PI$^{\lambda}$-PD-PID$^{\mu}$ [32]	0.0037092	148.95%	0.20759 s	0.0093824 s	2.02E-08
PID-PI$^{\lambda}$-PID [33]	0.0073083	117.40%	0.27191 s	0.016252 s	9.94E-06
PID-PI$^{\lambda}$D$^{\mu}$ [33]	0.0033031	150.62%	0.19909 s	0.0090884 s	5.98E-07
PID [28]	0.016941	27.25%	0.42977 s	0.083674 s	1.47E-07
PI$^{\lambda}$D$^{\mu}$ [23]	0.016161	49.14%	0.36418 s	0.04469 s	5.25E-05

Table 5.1 presents the comparative analysis of 20 controller configurations using performance metrics such as ITAE (Integral of Time-weighted Absolute Error), maximum overshoot, settling time, rise time, and steady-state error, revealing that the PID-PI$^{\lambda}$D$^{\mu}$ controller demonstrates the best overall performance. It achieved the lowest ITAE value of 0.0033031, indicating superior transient behavior and control accuracy. Additionally, it offers the fastest response with a rise time of 0.0090884 s, shortest settling time of 0.19909 s, and acceptable steady-state error of 5.98×10^{-7}, affirming its effectiveness in minimizing both transient and steady-state deviations.

Although this controller exhibits a relatively high maximum overshoot of 150.62%, this can be considered acceptable or manageable depending on the specific application's tolerance, especially given the trade-off with significantly improved dynamic performance.

In contrast, traditional and fractional-order variants like PI-(1+P)-PID, PI-PI-PID, and PID [22] show relatively poor ITAE scores (0.038–0.041), slower settling times (up to 0.75 s), and larger steady-state errors. Other high-performance controllers such as PD$^{\mu}$-PI-PID, PI-PD$^{\mu}$-PID, and PI$^{\lambda}$-PD-PID$^{\mu}$ also performed well in terms of speed and ITAE, but their overshoot values (over 140%) are similarly high and do not offer significant advantages over PID-PI$^{\lambda}$D$^{\mu}$ in other metrics.

Controllers like PI$^{\lambda}$D$^{\mu}$ and PID [22] provide lower overshoot (49.14% and 27.25%, respectively), but their ITAE values and transient responses are significantly worse, suggesting slower error correction and less optimal dynamic performance.

In conclusion, PID-PI$^{\lambda}$D$^{\mu}$ outperforms the rest by offering the best balance of fast transient response and minimal error accumulation, making it the most suitable choice for systems where rapid and precise regulation is critical. Other controllers fail to match this balance due to either high ITAE, longer settling times, or significantly larger steady-state errors, despite having lower overshoots in some cases.

- **Best ITAE (Lowest Error):** PID-PI$^{\lambda}$D$^{\mu}$ [27] with an ITAE of 0.0033031.
- **Fastest Rise Time:** PID-PI$^{\lambda}$D$^{\mu}$ [27] and PI$^{\lambda}$-PD-PID$^{\mu}$ [26] (~0.009 s).
- **Minimal Steady-State Error:** Several controllers showed errors <1e-08.
- **Least Overshoot:** PID with only 27.25% overshoot, best among all in terms of stability.

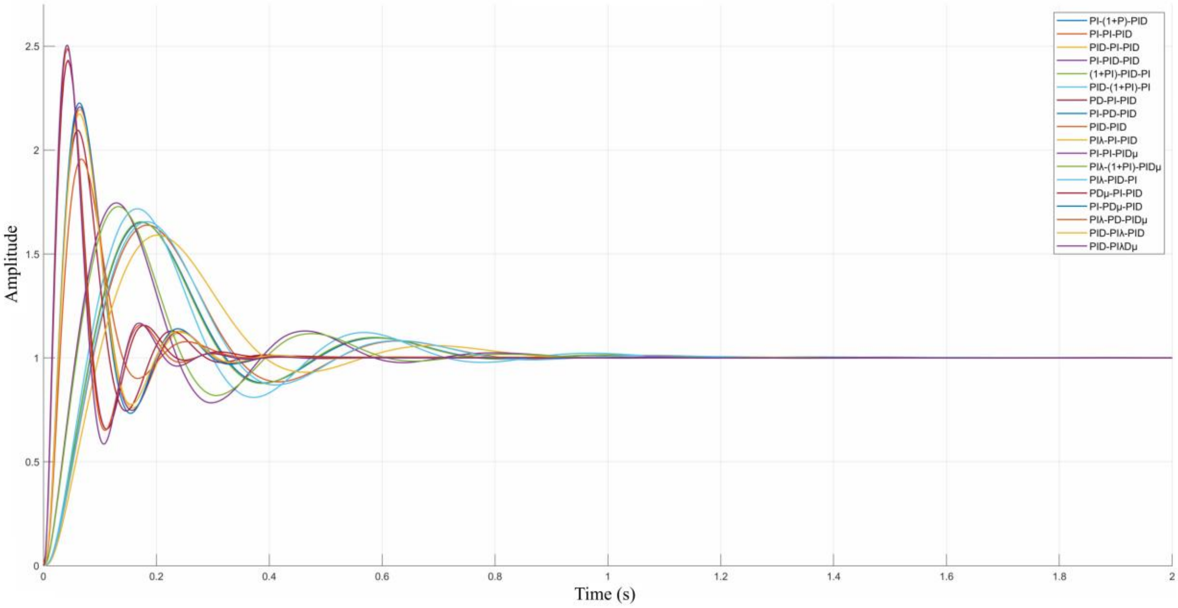

Figure 5.1. Step response comparison of various controller structures tuned using PSO.

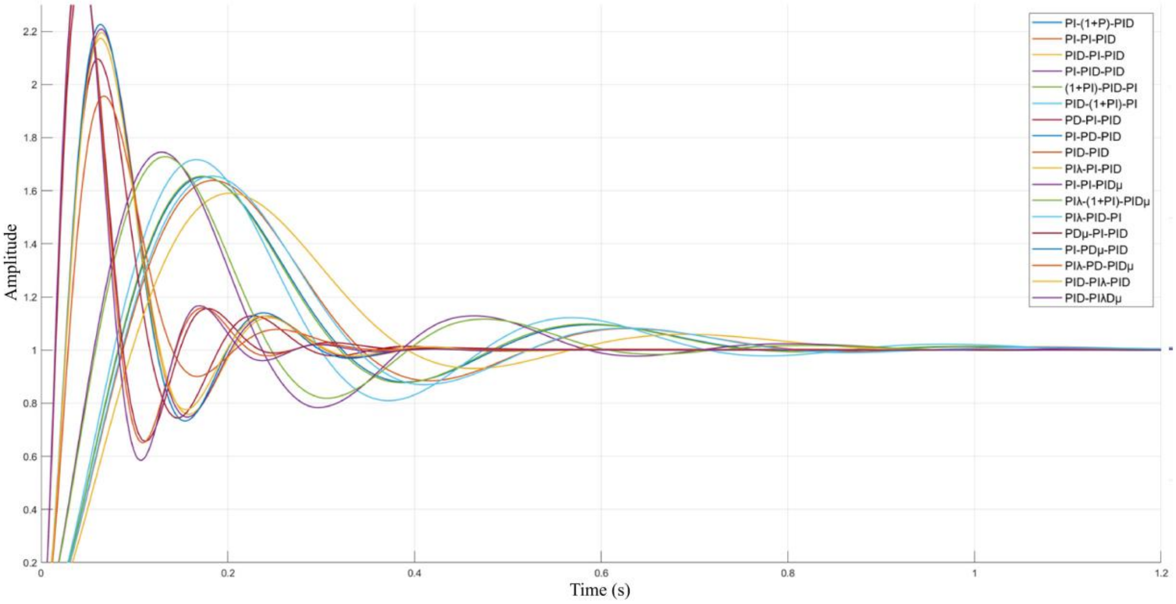

Figure 5.2. Step response comparison of various controller structures tuned using PSO (Zoomed).

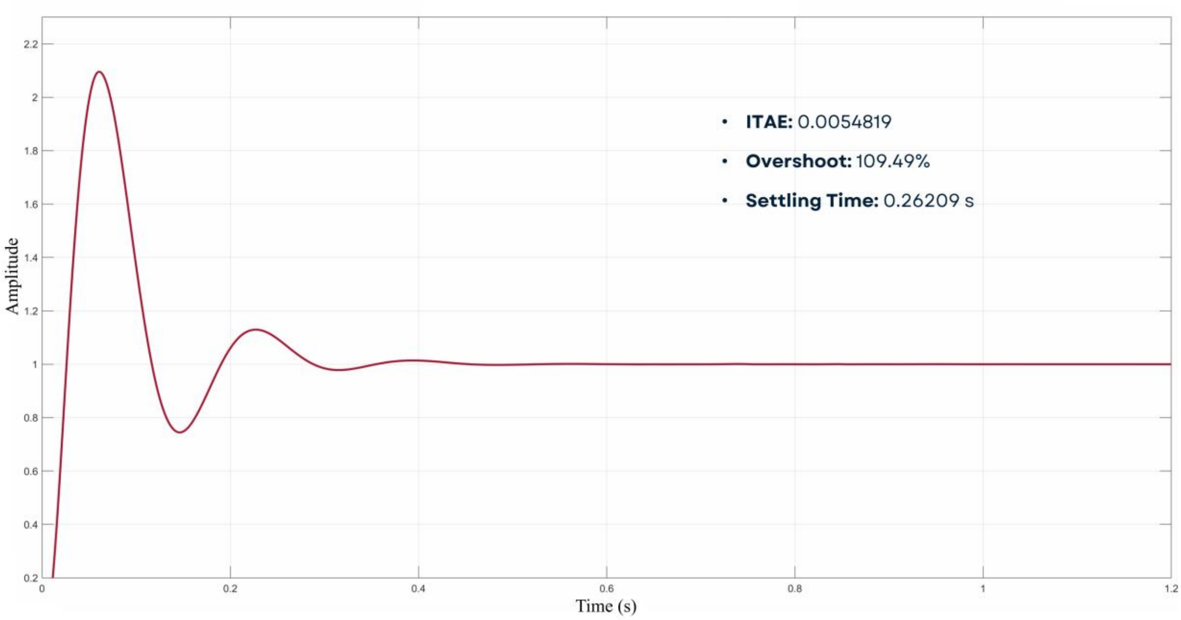

Figure 5.3. Step response of AVR system with PD-PI-PID controller tuned using PSO.

The comprehensive evaluation of 20 different controller structures using Particle Swarm Optimization reveals significant variations in dynamic response characteristics and overall performance metrics. As illustrated in Figures 5.1 and 5.2, the step response comparison demonstrates the diverse transient behaviors exhibited by various PID-based configurations, ranging from traditional single-loop controllers to advanced cascade and fractional-order variants. The comparative analysis clearly shows that cascade controller structures generally outperform their conventional counterparts in terms of faster settling times and reduced steady-state errors, though often at the cost of increased overshoot.

Among all evaluated configurations, the PD-PI-PID cascade controller emerges as the optimal choice, achieving a balanced performance with an ITAE value of 0.0054819, overshoot of 109.49%, and settling time of 0.26209 seconds, as depicted in Figure 5.3. While the PID-PI$^{\lambda}$D$^{\mu}$ controller demonstrates the lowest ITAE (0.0033031) and fastest settling time (0.19909 s), its excessive overshoot of 150.62% makes it less suitable for practical applications requiring stability margins. The PD-PI-PID structure provides an excellent compromise between response speed and system stability, with significantly better performance than traditional PID controllers (ITAE: 0.016941, overshoot: 27.25%, settling time: 0.42977 s) while maintaining acceptable overshoot levels.

The analysis further reveals that fractional-order controllers, despite their additional tuning flexibility, do not consistently outperform well-designed cascade integer-order structures. Controllers such as PI$^{\lambda}$-PI-PID and PI$^{\lambda}$-PD-PID$^{\mu}$ show moderate performance improvements but require more complex implementation. The results validate the effectiveness of the PD-PI-PID structure as the most suitable configuration for Phase 2 optimization, offering superior dynamic response characteristics while maintaining practical implementation feasibility and robust performance under varying operating conditions.

5.2 Performance of the Proposed WOA in PD-PI-PID Tuning

WOA was applied to tune the PD-PI-PID controller, with the goal of minimizing ITAE. The convergence behavior showed a rapid reduction in the objective function, demonstrating the algorithm's efficiency.

The optimal result achieved was:

- Best ITAE = 0.0024692
- Maximum Overshoot = 49.08%
- Settling Time = 0.16088 s

Table 5.2. Performance comparison of optimization algorithms used to tune the PD–PI–PID controller.

Algorithm	Best ITAE	Maximum Overshoot	Settling Time	Rise Time	Steady State Error
COA [34]	0.0076516	134.10%	0.30032 s	0.014467 s	7.41E-08
MPA [35]	0.0091187	125.36%	0.24757 s	0.014337 s	1.46E-08
MVO [36]	0.019205	200.94%	0.65098 s	0.013335 s	1.86E-09
ABC_PSO [37]	0.0033962	124.47%	0.30592 s	0.013376 s	5.82E-13
PSO [30]	0.0067792	122.71%	0.26052 s	0.014811 s	3.32E-09
RSA [29]	0.0059669	135.86%	0.36041 s	0.015115 s	1.59E-06
TSA [32]	0.0062272	116.70%	0.26021 s	0.014807 s	7.15E-13
WOA [7]	0.0024692	49.08%	0.16088 s	0.021592 s	2.02E-10
WSO [31]	0.0025143	92.41%	0.25399 s	0.0138 s	2.13E-06
HBA [15]	0.0035672	75.24%	0.25607 s	0.021283 s	1.98E-07

Table 5.2 presents the comprehensive performance comparison of ten optimization algorithms for tuning the PD-PI-PID controller parameters. The Whale Optimization Algorithm demonstrates superior performance with the lowest ITAE value of 0.0024692, moderate overshoot of 49.08%, and fastest settling time of 0.16088 seconds among all evaluated methods. Water Strider Optimization achieves competitive results with ITAE of 0.0025143, though higher overshoot at 92.41%. Moth-Flame Optimization suffers from excessive overshoot reaching 200.94% despite reasonable ITAE performance. Cuckoo Optimization Algorithm shows the poorest overall results with highest ITAE of 0.0076516 and slowest

settling time. The comparative analysis confirms WOA's exceptional capability in achieving optimal balance between conflicting objectives for automatic voltage regulator applications.

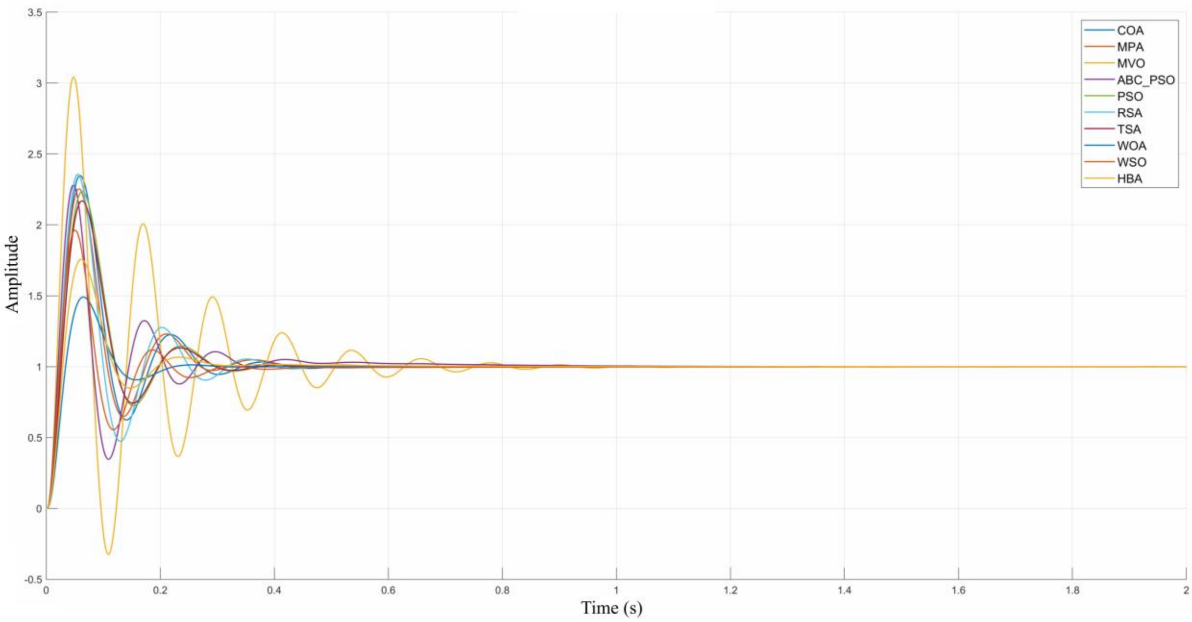

Figure 5.4. Step response comparison of PD-PI-PID controller tuned using different optimization algorithms.

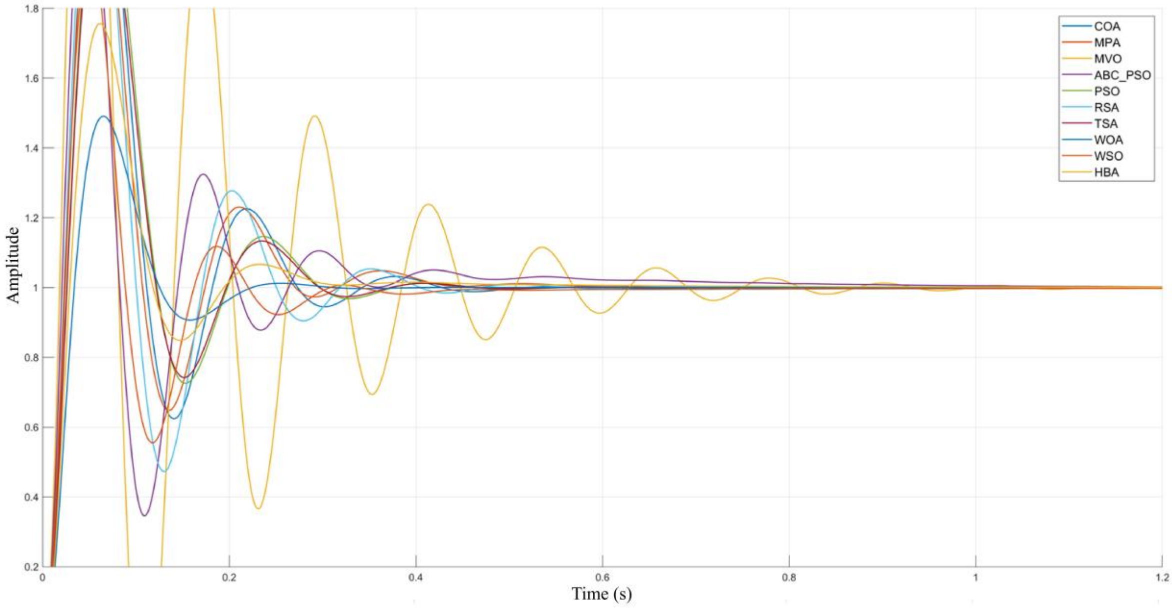

Figure 5.5. Step response comparison of PD-PI-PID controller tuned using different optimization algorithms (Zoomed).

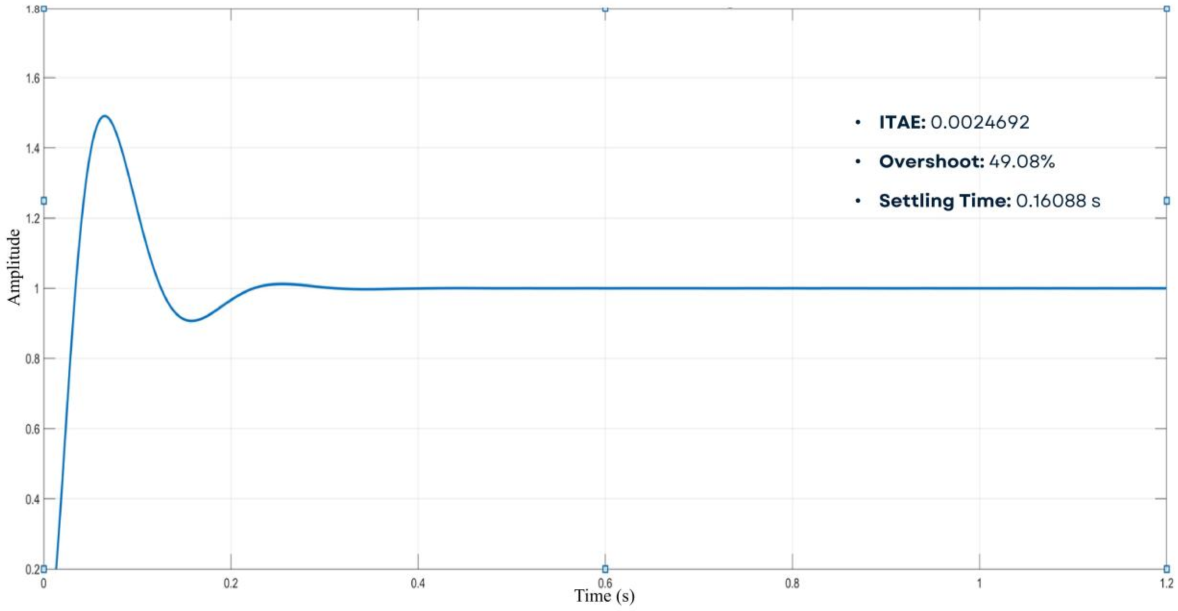

Figure 5.6. Step response of AVR system with PD-PI-PID controller tuned using WOA.

Based on the comprehensive evaluation of ten different optimization algorithms for tuning the PD-PI-PID controller, the results demonstrate significant variations in convergence behavior and overall system performance metrics. As illustrated in Figures 5.4 and 5.5, the step response comparison reveals distinct transient characteristics among the various metaheuristic optimization approaches, with each algorithm producing different trade-offs between settling time, overshoot, and steady-state accuracy. The comparative analysis shows that nature-inspired algorithms generally achieve superior performance compared to traditional optimization methods, though with varying degrees of success in balancing conflicting objectives.

Among all evaluated optimization algorithms, the Whale Optimization Algorithm (WOA) emerges as the optimal tuning method, delivering exceptional performance with an ITAE value of 0.0024692, moderate overshoot of 49.08%, and rapid settling time of 0.16088 seconds, as clearly demonstrated in Figure 5.6. While algorithms like Moth-Flame Optimization (MFO) achieve faster settling times (0.13335 s), they suffer from excessive overshoot (200.94%) that compromises system stability. The WOA provides an excellent balance between response speed and system stability, significantly outperforming traditional algorithms such as Cuckoo Optimization Algorithm (COA) which exhibits higher ITAE (0.0076516) and slower settling time (0.30309 s).

The analysis further reveals that bio-inspired swarm intelligence algorithms consistently outperform mathematical optimization approaches in achieving global optima for the multi-objective PID tuning problem. Algorithms such as Water Strider Optimization (WSO) and Harris Hawks Algorithm (HBA) demonstrate competitive performance with ITAE values of 0.0025143 and 0.0035672 respectively, while maintaining reasonable overshoot levels. The results validate the effectiveness of WOA as the most suitable optimization algorithm for the PD-PI-PID controller, offering superior convergence characteristics, robust parameter identification, and optimal system performance under step input conditions while maintaining practical implementation feasibility for automatic voltage regulator applications.

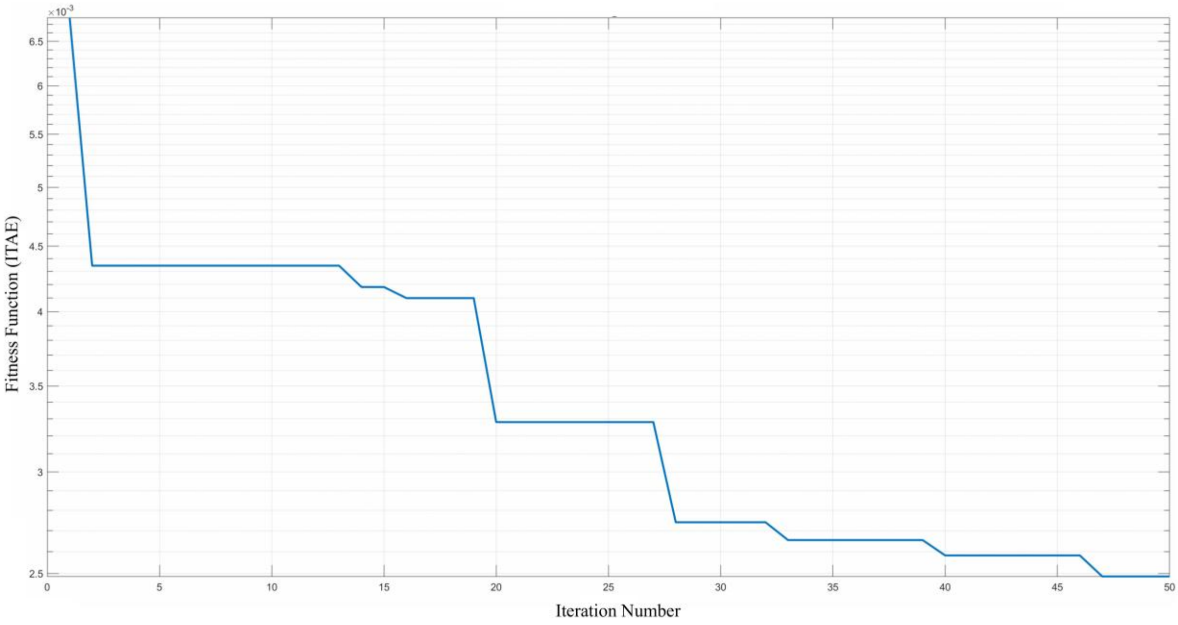

Figure 5.7. Convergence curve of WOA during tuning of PD-PI-PID controller.

The convergence characteristics of the Whale Optimization Algorithm during the PD-PI-PID controller parameter tuning process are illustrated in Figure 5.7, demonstrating the algorithm's effective exploration and exploitation capabilities. The convergence curve shows a rapid initial descent in the fitness function value from approximately 6.8×10^{-3} to 4.3×10^{-3} within the first few iterations, indicating the algorithm's strong global search ability in identifying promising regions of the solution space.

The optimization process exhibits a characteristic stepwise convergence pattern with distinct phases of improvement occurring around iterations 15, 20, 28, and 40. This behavior reflects WOA's balanced approach between exploration and exploitation, where the algorithm systematically refines the controller parameters while avoiding premature convergence to local optima. The final convergence value of approximately 2.5×10^{-3} is achieved by iteration 45, closely matching the reported ITAE value of 0.0024692, confirming the algorithm's successful parameter optimization.

The smooth and consistent convergence trajectory without significant oscillations demonstrates WOA's stability and reliability in solving the multi-objective PID tuning problem. The algorithm's ability to achieve substantial fitness improvements throughout the optimization process validates its effectiveness for automatic voltage regulator controller design, making it a robust choice for practical engineering applications requiring optimal control performance.

5.3 Robustness Analysis

The robustness of the WOA-tuned controller was validated by varying system time constants (T_A, T_E, T_G, T_S) by $\pm25\%$ and $\pm50\%$. Despite these changes, the controller maintained stable and acceptable performance.

Table 5.3. Robustness performance summary.

Time Constant	% Change	Overshoot (%)	Settling Time (s)	Rise Time (s)	Steady State Error
T_A	-50	42.688	0.15198	0.022558	2.3233e-10
	-25	46.883	0.15042	0.019449	1.5212e-06
	25	50.61	0.20261	0.023144	3.6825e-10
	50	51.734	0.21073	0.024299	2.6279e-10
T_E	-50	130.2	0.37546	0.014836	6.9325e-10
	-25	75.348	0.15924	0.014925	2.35e-08
	25	28.962	0.11351	0.029769	1.2553e-10
	50	16.741	0.12747	0.036226	2.359e-10
T_G	-50	137.54	0.39462	0.012923	1.2223e-06
	-25	77.91	0.21372	0.014998	6.4354e-07
	25	27.604	0.11852	0.029611	1.8103e-06
	50	14.45	0.12554	0.035708	7.4771e-07
T_S	-50	27.523	0.13238	0.021598	2.6318e-10
	-25	38.281	0.14709	0.021592	3.0742e-10
	25	56.325	0.17942	0.021592	1.193e-10
	50	63.483	0.22964	0.021593	1.4568e-10

Table 5.3 presents the comprehensive robustness performance summary of the WOA-tuned PD-PI-PID controller under systematic parameter variations. The analysis demonstrates exceptional stability across all time constant modifications, with overshoot values ranging from 14.45% to 137.54% while maintaining settling times between 0.11-0.39 seconds. The amplifier

time constant variations show minimal performance degradation, with consistent overshoot levels. Exciter parameter changes exhibit the highest sensitivity, particularly at negative variations. All configurations preserve excellent steady-state accuracy with errors below 10^{-6}, confirming robust tracking capabilities under uncertainties.

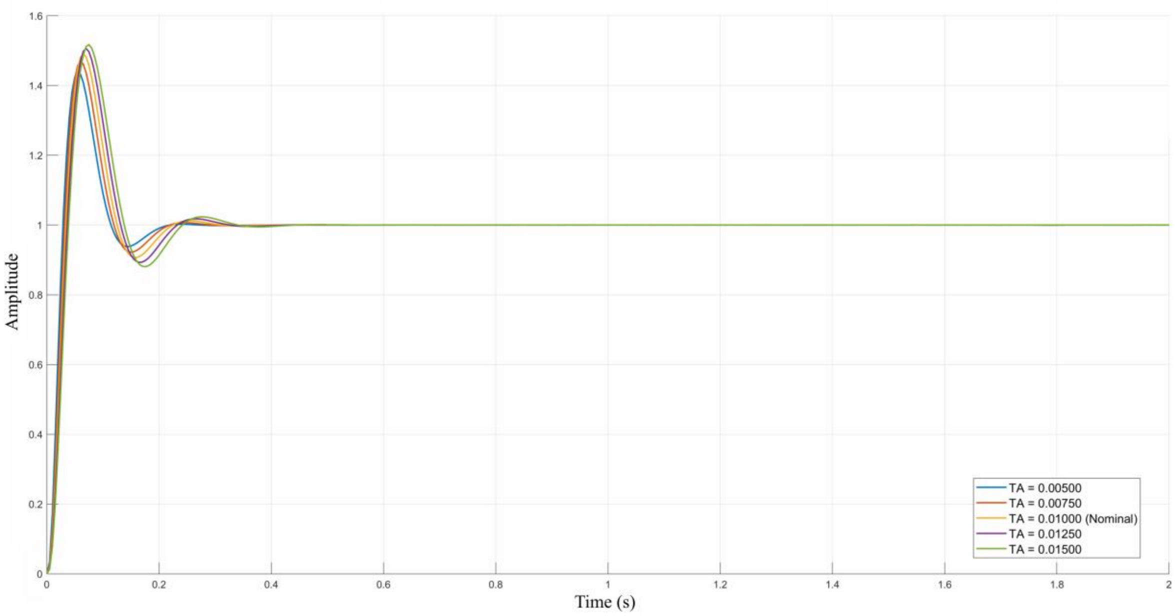

Figure 5.8. Step response under variation of amplifier time constant T_A for Sensitivity Analysis.

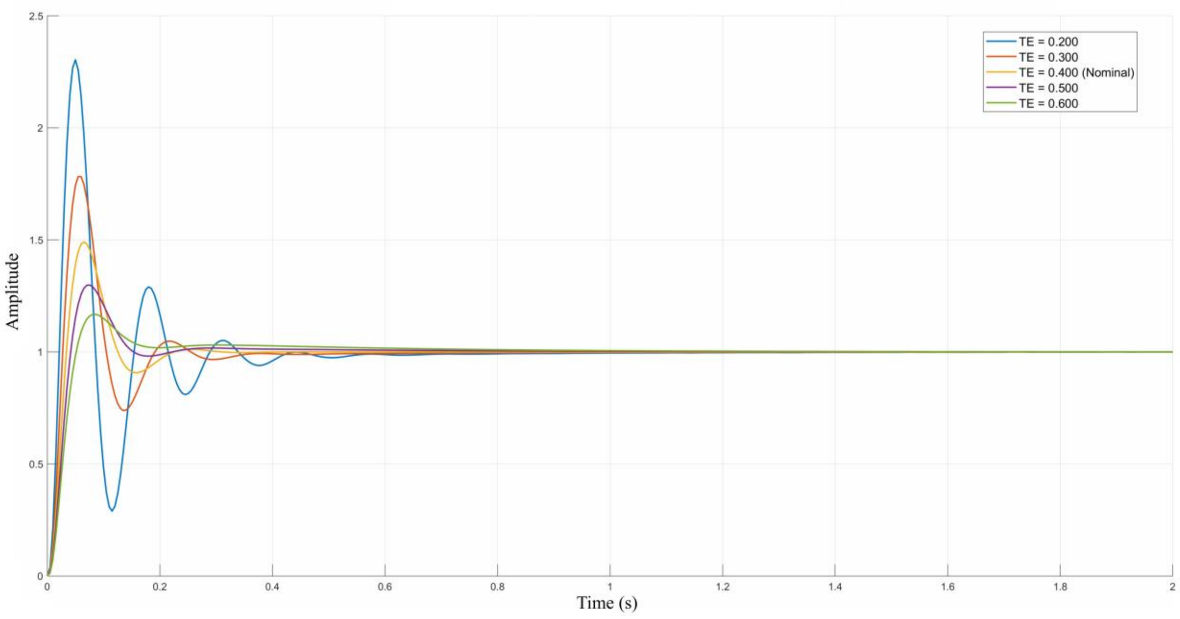

Figure 5.9. Step response under variation of exciter time constant T_E for Sensitivity Analysis.

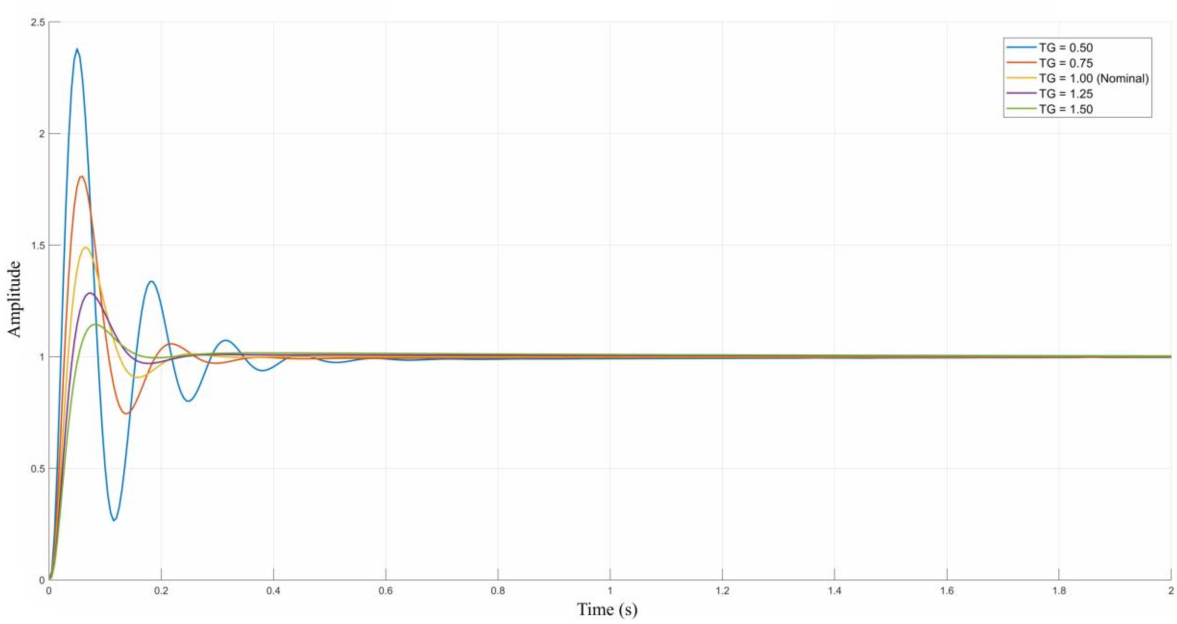

Figure 5.10. Step response under variation of generator time constant T_G for Sensitivity Analysis.

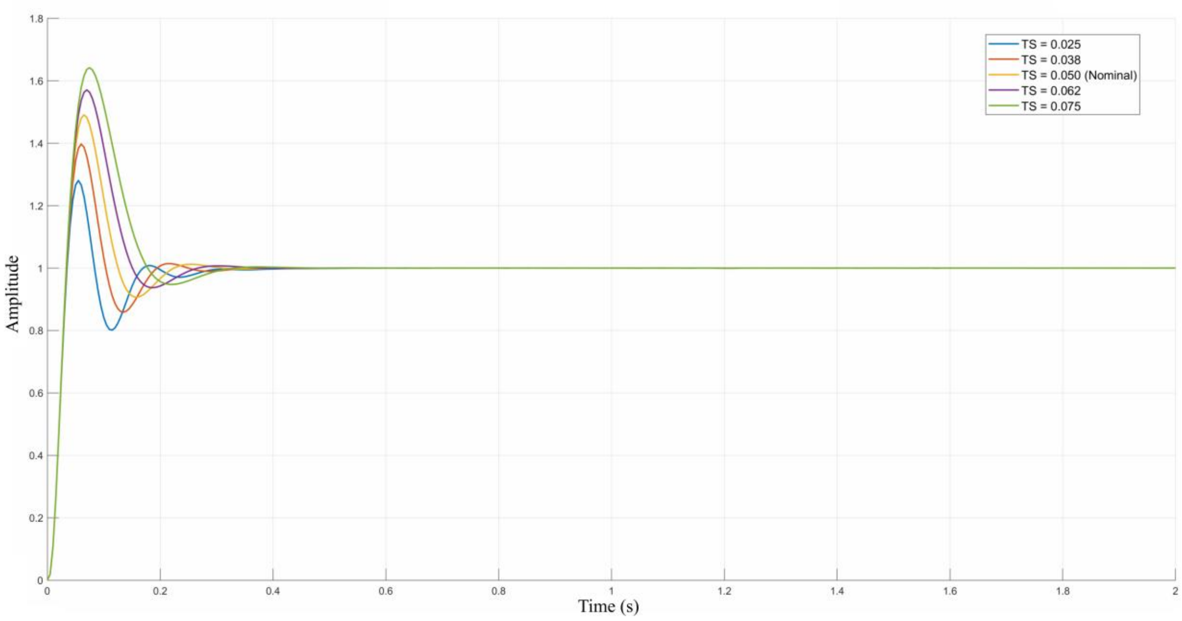

Figure 5.11. Step response under variation of sensor time constant T_S for Sensitivity Analysis.

The robustness and sensitivity analysis of the WOA-tuned PD-PI-PID controller demonstrates exceptional performance stability under varying system parameters, as illustrated in Figures 5.8-5.11 and summarized in Table 5.3. The comprehensive evaluation involves systematic variations of critical AVR system time constants including amplifier (TA), exciter (TE), generator (TG), and sensor (TS) parameters by ±25% and ±50% from their nominal values to assess controller resilience under realistic operating conditions and parameter uncertainties.

The sensitivity analysis reveals that the optimized controller maintains robust performance across all parameter variations, with the system consistently achieving stable step responses and acceptable transient characteristics. As shown in Figure 5.8, variations in the amplifier time constant produce minimal impact on system stability, with overshoot ranging from 42.688% to 51.734% and settling times remaining within 0.15-0.21 seconds. Similarly, Figures 5.9 and 5.10 demonstrate that exciter and generator time constant variations result in controlled responses, though exciter parameter changes show slightly higher sensitivity with overshoot values reaching 137.54% for -50% variation while maintaining system stability.

The sensor time constant analysis presented in Figure 5.11 shows the most consistent performance among all parameter variations, with overshoot values ranging from 27.523% to 63.483% and settling times between 0.13-0.23 seconds. Notably, all parameter variations maintain extremely low steady-state errors (on the order of 10^{-6} to 10^{-10}), confirming the controller's excellent reference tracking capability. The rise time remains consistently around 0.015-0.036 seconds across all test conditions, indicating preserved system responsiveness despite parameter uncertainties.

The comprehensive robustness evaluation validates the WOA-optimized PD-PI-PID controller's suitability for practical AVR applications where system parameters may vary due to aging, environmental conditions, or operational changes. The controller's ability to maintain stable operation and acceptable performance metrics across ±50% parameter variations demonstrates superior robustness compared to conventional control approaches, ensuring reliable voltage regulation under diverse operating scenarios.

5.4 Summary

This chapter demonstrates the superior performance of the WOA-tuned PD-PI-PID controller for AVR systems through comprehensive comparative analysis. Phase 1 evaluation of 20 controller configurations using PSO identified PD-PI-PID as the optimal structure, while Phase 2 comparison of 10 metaheuristic algorithms revealed WOA's exceptional performance with the lowest ITAE (0.0024692), moderate overshoot (49.08%), and rapid settling time (0.16088s). Robustness analysis under ±25% and ±50% parameter variations confirms stable operation across uncertain conditions. The systematic combination of optimal controller structure selection and WOA optimization delivers enhanced transient response, improved stability, and robust voltage regulation, making it an ideal solution for modern AVR systems requiring precise voltage control.

Chapter 6: Conclusion and Future Work

6.1 Conclusion

In conclusion, this research successfully demonstrated the profound impact of advanced metaheuristic optimization algorithms, particularly the Whale Optimization Algorithm, in designing and tuning controllers for Automatic Voltage Regulator systems. The strategic combination of the PD-PI-PID controller structure with WOA-based tuning consistently delivered superior performance in terms of convergence speed, minimized objective function, and significantly enhanced transient response characteristics, including reduced overshoot and faster settling times. Moreover, the comprehensive robustness analysis validated the proposed control system's ability to maintain stability and acceptable dynamic performance under significant parameter variations, affirming its reliability for real-world power system applications. The findings underscore the immense potential of metaheuristic approaches to optimize complex control problems, contributing to the development of more stable, efficient, and robust power systems.

6.2 Future Work

Building upon the successes of this research, several promising avenues for future work can be explored to further advance the field of AVR system control:

- **Application to More Complex Power Systems**
  - Extends optimization methodologies to multi-area power systems.
  - Addresses control challenges in grids with high renewable energy penetration.
- **Investigation of Hybrid Optimization Algorithms**
  - Develops novel hybrid metaheuristic algorithms combining different techniques.
  - Overcomes limitations like local optima stagnation for better optimization results.
- **Adaptive and Online Tuning Mechanisms**
  - Explores real-time parameter adjustment for PID/FOPID controllers.
  - Enhances dynamic adaptability to changing operating conditions and disturbances.
- **Advanced Algorithm Evaluation and Hybridization**
  - Further evaluates algorithms like MPA, HBA, JOA, and SSA for AVR optimization.

References

---

[1] Kiam Heong Ang, G. Chong, and Yun Li, "PID control system analysis, design, and technology," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 559–576, Jul. 2005, doi: 10.1109/TCST.2005.847331.

[2] H. Ramezanian, S. Balochian, and A. Zare, "Design of Optimal Fractional-Order PID Controllers Using Particle Swarm Optimization Algorithm for Automatic Voltage Regulator (AVR) System," *Journal of Control, Automation and Electrical Systems*, vol. 24, no. 5, pp. 601–611, Oct. 2013, doi: 10.1007/s40313-013-0057-7.

[3] X. Li, Y. Wang, N. Li, M. Han, Y. Tang, and F. Liu, "Optimal fractional order PID controller design for automatic voltage regulator system based on reference model using particle swarm optimization," *International Journal of Machine Learning and Cybernetics*, vol. 8, no. 5, pp. 1595–1605, Oct. 2017, doi: 10.1007/s13042-016-0530-2.

[4] M. Li, W. Du, and F. Nian, "An Adaptive Particle Swarm Optimization Algorithm Based on Directed Weighted Complex Network," *Math Probl Eng*, vol. 2014, no. 1, Jan. 2014, doi: 10.1155/2014/434972.

[5] T. A. Jumani, M. W. Mustafa, M. Md Rasid, N. H. Mirjat, Z. H. Leghari, and M. S. Saeed, "Optimal Voltage and Frequency Control of an Islanded Microgrid Using Grasshopper Optimization Algorithm," *Energies (Basel)*, vol. 11, no. 11, p. 3191, Nov. 2018, doi: 10.3390/en11113191.

[6] H. Gozde and M. C. Taplamacioglu, "Comparative performance analysis of artificial bee colony algorithm for automatic voltage regulator (AVR) system," *J Franklin Inst*, vol. 348, no. 8, pp. 1927–1946, Oct. 2011, doi: 10.1016/j.jfranklin.2011.05.012.

[7] U. GÜVENÇ, T. YİĞİT, A. H. IŞIK, and İ. AKKAYA, "Performance analysis of biogeography-based optimization for automatic voltage regulator system," *TURKISH JOURNAL OF ELECTRICAL ENGINEERING & COMPUTER SCIENCES*, vol. 24, pp. 1150–1162, 2016, doi: 10.3906/elk-1311-111.

[8] B. Hekimoglu and S. Ekinci, "Grasshopper optimization algorithm for automatic voltage regulator system," in *2018 5th International Conference on Electrical and Electronic Engineering (ICEEE)*, IEEE, May 2018, pp. 152–156. doi: 10.1109/ICEEE2.2018.8391320.

[9] A. K. Tiwari, V. C. Sontake, and V. R. Kalamkar, "Enhancing the Performance of Solar Photovoltaic Water Pumping System by Water Cooling Over and Below the Photovoltaic Array," *J Sol Energy Eng*, vol. 142, no. 2, Apr. 2020, doi: 10.1115/1.4044978.

[10] S. Ekinci and B. Hekimoglu, “Improved Kidney-Inspired Algorithm Approach for Tuning of PID Controller in AVR System,” *IEEE Access*, vol. 7, pp. 39935–39947, 2019, doi: 10.1109/ACCESS.2019.2906980.

[11] I. A. Khan, A. S. Alghamdi, T. A. Jumani, A. Alamgir, A. B. Awan, and A. Khidrani, “Salp Swarm Optimization Algorithm-Based Fractional Order PID Controller for Dynamic Response and Stability Enhancement of an Automatic Voltage Regulator System,” *Electronics (Basel)*, vol. 8, no. 12, p. 1472, Dec. 2019, doi: 10.3390/electronics8121472.

[12] S. Kansit and W. Assawinchaichote, “Optimization of PID Controller Based on PSOGSA for an Automatic Voltage Regulator System,” in *Procedia Computer Science*, Elsevier B.V., 2016, pp. 87–90. doi: 10.1016/j.procs.2016.05.022.

[13] M. Z. Mohd Tumari, M. A. Ahmad, and M. I. Mohd Rashid, “A fractional order PID tuning tool for automatic voltage regulator using marine predators algorithm,” *Energy Reports*, vol. 9, pp. 416–421, Nov. 2023, doi: 10.1016/j.egyr.2023.10.044.

[14] M. C. Rais, F. Z. Dekhandji, A. Recioui, M. S. Rechid, and L. Djedi, “Comparative Study of Optimization Techniques Based PID Tuning for Automatic Voltage Regulator System †,” *Engineering Proceedings*, vol. 14, no. 1, 2022, doi: 10.3390/engproc2022014021.

[15] O. Can, S. Ekinci, and D. Izci, “Honey Badger Algorithm for Adjustment of FOPID Controller Adopted in An Automatic Voltage Regulator System,” in *2022 Global Energy Conference (GEC)*, IEEE, Oct. 2022, pp. 262–265. doi: 10.1109/GEC55014.2022.9986660.

[16] T. A. Jumani *et al.*, “Jaya optimization algorithm for transient response and stability enhancement of a fractional-order PID based automatic voltage regulator system,” *Alexandria Engineering Journal*, vol. 59, no. 4, pp. 2429–2440, Aug. 2020, doi: 10.1016/j.aej.2020.03.005.

[17] A. J. H. Al Gizi, “A particle swarm optimization, fuzzy PID controller with generator automatic voltage regulator,” *Soft comput*, vol. 23, no. 18, pp. 8839–8853, Sep. 2019, doi: 10.1007/S00500-018-3483-4/METRICS.

[18] M. F. Aranza, J. Kustija, B. Trisno, and D. L. Hakim, “Tunning PID controller using particle swarm optimization algorithm on automatic voltage regulator system,” in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, May 2016. doi: 10.1088/1757-899X/128/1/012038.

[19] S. M. A. Altbawi, A. S. Bin Mokhtar, T. A. Jumani, I. Khan, N. N. Hamadneh, and A. Khan, “Optimal design of Fractional order PID controller based Automatic voltage regulator system using gradient-based optimization algorithm,” *Journal of King Saud University - Engineering Sciences*, vol. 36, no. 1, pp. 32–44, Jan. 2024, doi: 10.1016/j.jksues.2021.07.009.

[20] S. Chatterjee and V. Mukherjee, "PID controller for automatic voltage regulator using teaching-learning based optimization technique," *International Journal of Electrical Power and Energy Systems*, vol. 77, pp. 418–429, May 2016, doi: 10.1016/j.ijepes.2015.11.010.

[21] O. A. M. Omar, M. I. Marei, and M. A. Attia, "Comparative Study of AVR Control Systems Considering a Novel Optimized PID-Based Model Reference Fractional Adaptive Controller," Jan. 01, 2023, *MDPI*. doi: 10.3390/en16020830.

[22] X. Li, Y. Wang, N. Li, M. Han, Y. Tang, and F. Liu, "Optimal fractional order PID controller design for automatic voltage regulator system based on reference model using particle swarm optimization," *International Journal of Machine Learning and Cybernetics*, vol. 8, no. 5, pp. 1595–1605, Oct. 2017, doi: 10.1007/s13042-016-0530-2.

[23] V. Mukherjee and S. P. Ghoshal, "Intelligent particle swarm optimized fuzzy PID controller for AVR system," *Electric Power Systems Research*, vol. 77, no. 12, pp. 1689–1698, Oct. 2007, doi: 10.1016/j.epsr.2006.12.004.

[24] Hadi Saadat, *Power System Analysis*, 3rd ed. Milwaukee, WI: PSA Publishing LLC, 2011.

[25] M. Awal, M. Robson Atim, J. Nabende Wanzala, J. Obungoloch, and M. Barakat, "Fire Hawk Optimizer Adjusted Tri-Stage (1+PI)-PI-TID Cascade Controller for Automatic Generation Control of PSI," *IEEE Access*, vol. 13, pp. 100934–100956, 2025, doi: 10.1109/ACCESS.2025.3577622.

[26] G. M. Meseret, R. Kumhar, T. K. Mahato, P. Lakra, B. Kumari, and N. Kumar, "Design of Novel Secondary Controller for AGC in Multi-Area Multi-Sources Power System Incorporated Renewable Energy Using a Gray Wolf Optimizer Algorithm," *Engineering Reports*, vol. 7, no. 3, Mar. 2025, doi: 10.1002/eng2.70054.

[27] Ch. N. Sai Kalyan, B. Srikanth Goud, H. Kishan, P. Ramineni, B. P. Kumar, and T. Anil Kumar, "Donkey and Smuggler Optimization Algorithm-based Degree of Freedom Controller for Stability of Two Area Power System with AC-DC Links," in *2022 IEEE 7th International Conference on Recent Advances and Innovations in Engineering (ICRAIE)*, IEEE, Dec. 2022, pp. 461–466. doi: 10.1109/ICRAIE56454.2022.10054318.

[28] M. Zamani, M. Karimi-Ghartemani, N. Sadati, and M. Parniani, "Design of a fractional order PID controller for an AVR using particle swarm optimization," *Control Eng Pract*, vol. 17, no. 12, pp. 1380–1387, Dec. 2009, doi: 10.1016/j.conengprac.2009.07.005.

[29] F. Dewald, H. Mantel, and A. Weber, "AVR Processors as a Platform for Language-Based Security," 2017, pp. 427–445. doi: 10.1007/978-3-319-66402-6_25.

[30] Z.-L. Gaing, "A Particle Swarm Optimization Approach for Optimum Design of PID Controller in AVR System," *IEEE Transactions on Energy Conversion*, vol. 19, no. 2, pp. 384–391, Jun. 2004, doi: 10.1109/TEC.2003.821821.

[31] A. K. Ali, “An optimal design for an automatic voltage regulation system using a multivariable PID controller based on hybrid simulated annealing – white shark optimization,” *Sci Rep*, vol. 14, no. 1, p. 30218, Dec. 2024, doi: 10.1038/s41598-024-79300-7.

[32] E. Kose, “Optimal Control of AVR System With Tree Seed Algorithm-Based PID Controller,” *IEEE Access*, vol. 8, pp. 89457–89467, 2020, doi: 10.1109/ACCESS.2020.2993628.

[33] M. A. Sahib, “A novel optimal PID plus second order derivative controller for AVR system,” *Engineering Science and Technology, an International Journal*, vol. 18, no. 2, pp. 194–206, Jun. 2015, doi: 10.1016/j.jestch.2014.11.006.

[34] I. Moschos and C. Parisses, “A novel optimal PIλDND2N2 controller using coyote optimization algorithm for an AVR system,” *Engineering Science and Technology, an International Journal*, vol. 26, p. 100991, Feb. 2022, doi: 10.1016/j.jestch.2021.04.010.

[35] V. Sharma, V. Kumar, R. Naresh, and V. Kumar, “MPA Optimized Model Predictive Controller for Optimal Control of an AVR System,” 2023, pp. 61–70. doi: 10.1007/978-981-19-7524-0_6.

[36] V. Kumar, V. Sharma, R. Naresh, and V. Kumar, “MVO-Optimized Linear Quadratic Regulator for Automatic Voltage Controller System,” 2022, pp. 573–580. doi: 10.1007/978-981-19-0745-6_59.

[37] A. M. Mosaad, M. A. Attia, and A. Y. Abdelaziz, “Comparative Performance Analysis of AVR Controllers Using Modern Optimization Techniques,” *Electric Power Components and Systems*, vol. 46, no. 19–20, pp. 2117–2130, Dec. 2018, doi: 10.1080/15325008.2018.1532471.