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Fuzzy PID Controller Design for Enhanced Voltage Regulation in Automatic Voltage Regulator System

1st Mou Das Mahapatra
Dept. of Electrical Engineering
Dr. B. C. Roy Engineering College
Durgapur, India
mou.dasmahapatra@bcrec.ac.in

2nd Kuntal Konar
Dept. of Electrical Engineering
Dr. B. C. Roy Engineering College
Durgapur, India
kuntal.konar26@gmail.com

3rd Surajit Mahato
Dept. of Electrical Engineering
Dr. B. C. Roy Engineering College
Durgapur, India
surajitmahato73@gmail.com

4th Vikash Kumar
Dept. of Electrical Engineering
Dr. B. C. Roy Engineering College
Durgapur, India
krnick46@gmail.com

5th Pritam Dey
Dept. of Electrical Engineering
Dr. B. C. Roy Engineering College
Durgapur, India
pritamdey818@gmail.com

***Abstract*—This paper presents a comprehensive investigation into the application of a fuzzy proportional-integral-derivative (FPID) controller for improving voltage regulation in automatic voltage regulator (AVR) systems. The conventional Proportional-Integral-Derivative (PID) control strategy is augmented with fuzzy logic (FL) to address the challenges associated with nonlinearities, uncertainties, and dynamic variations in power systems. This paper delves into the design process, including the selection of appropriate fuzzy sets, membership functions (MF), and rule base construction. Special emphasis is placed on the tuning of fuzzy parameters to optimize the controller's performance in voltage regulation tasks. Comparative studies are conducted to evaluate the FPID controller against traditional PID, simple fuzzy controllers (FCs), and recently published literature to showcase its superior adaptability in scenarios where precise system models are challenging to attain. Simulation results are obtained in MATLAB/SIMULINK to demonstrate the efficacy of the FPID controller in maintaining voltage stability, reducing settling time, overshooting, improving the transient response of the AVR system, and contributing to its robustness in the presence of changing system time constants.**

***Index Terms*—Automatic Voltage Regulator, Proportional–Integral–Derivative Controller, Fuzzy Controller, Fuzzy Proportional–Integral–Derivative Controller, Transient Analysis**

I. Introduction

The stability and reliability of electrical power systems are fundamental to the seamless functioning of modern societies. One critical aspect of maintaining power system integrity is ensuring that the voltage supplied to electrical loads remains within acceptable limits, despite variations in input voltage and changing load conditions. To address this crucial requirement, AVR systems have become indispensable components in power generation, distribution, and utilization [1]. The main function of an AVR in a power system is to regulate the voltage at the output terminals of an alternator so that it remains within a specified range, maintaining a stable and desired level even under varying load conditions and changes in the input voltage [2].

Even in cases where the system is stable, AVR finds it challenging to provide fast response due to the high mechanical and electrical inertia of the synchronous generator and time constants. Therefore, many control techniques have been applied to the AVR system in order to enhance its performance and guarantee an effective, steady, and robust dynamic reaction to changes in terminal voltage. However, a survey reveals that because of its versatility and ease of use, PID controller architecture is mostly successfully used in research [3].

Rather than using a traditional PID controller, gain parameters must be designed optimally in order to prevent overshoot and long settling times. The gains of the PID controllers have been tuned using recently developed new algorithms such as ant colony optimization method with a constrained nelder–mead algorithm [4], stochastic fractal search algorithm [5], biogeography-based optimization (BBO) [6], improved kidney-inspired algorithm [7], and world cup optimization algorithm (WCO) [8] to achieve optimal design. Optimal and robust design of PID parameters using Taguchi combined genetic algorithm method [9], tree seed algorithm [10], and nonlinear sine cosine algorithm [11] have been reported for AVR system.

The sliding mode controller, internal model control for reduced-order model have been proposed in [12] and [13], respectively. Real structured parametric uncertainties based on $H\infty$ and μ-analysis for AVR system has been reported in [14], where as $H2/H\infty$ loop shaping approaches has been used to design fractional order PID (FOPID) for AVR system [15]. Fast and optimal tuning of the FOPID controller uses the memorizable-smoothed functional algorithm [16] and cuckoo search algorithm [17] for the AVR system. In [18], an emotional deep neural network is used for PID controller parameter tuning. [19] have employed neural networks (NN), FL, and neuro-fuzzy techniques, while [20] uses FL for optimal PID settings in the AVR system.

This article provides an ideal design for different fuzzy

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