Automatic Voltage Regulator System With Fractional Order PID Controller Designed Optimally Using Gradient Based Optimization Technique

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Abstract - This article attempts to explore the use of the Fractional-Order Proportional Integral Derivative (FOPID) controller in the ideal design of the Automatic Voltage Regulator (AVR), taking into account its superior control characteristics and increased tuning flexibility compared to the traditional PID regulator. The tuning method for FOPID is more challenging than that of its conventional equivalent since it has two additional tuning parameters. A self-regulated off-line optimal tuning solution based on the Gradient-Based Optimization (GBO) algorithm is used in the current study to address the mentioned problem. By reducing the chosen Fitness Function (FF), which in the current study is chosen as Integral Time Absolute Error (ITAE), the best FOPID gains can be realized. The outcomes demonstrate that, among the AVR designs taken into consideration, the proposed AVR design offers the most ideal dynamic response and improved stability, demonstrating its effectiveness and significance.

Keywords— Automatic Voltage Regulator, Fractional Order PID Controller, Gradient-Based Optimizer, Optimal Control System Design, Metaheuristic

I. INTRODUCTION

Proportional-Integral-Derivative (PID) control has long been recognized as a robust and widely adopted control technique in various industries. However, traditional PID control operates with integer order differentiators and integrators. In recent years, Fractional-Order Proportional-Integral-Derivative (FOPID) control has gained significant attention due to its ability to capture more complex dynamics and achieve enhanced control performance. FOPID control extends the traditional PID control by introducing fractional-order differentiation and integration [1]. This article provides a comprehensive analysis of FOPID control, including its theoretical foundations, tuning methods, and applications in diverse fields.

Fractional calculus provides a mathematical framework to describe systems involving non-integer order differentiation and integration. It generalizes the concepts of differentiation and integration to fractional orders, allowing for the analysis and control of complex dynamical systems. The key operators in fractional calculus are the fractional integral (of order α) and fractional derivative (of order β) [2-3].

The FOPID control structure extends the classical PID control by replacing the integer order differentiation and integration with fractional-order counterparts. It consists of three main components.

Fractional Proportional (FP) Term: The FP term multiplies the error signal by a fractional proportional gain α, capturing the current deviation from the setpoint.

Fractional Integral (FI) term integrates the error signal with a fractional integral gain β, providing a corrective action for steady-state errors over time [4].

Fractional Derivative (FD) FD term differentiates the error signal using a fractional derivative gain γ, capturing the system's dynamic response [5].

FOPID Transfer Function:

The transfer function of an FOPID controller can be represented in the Laplace domain as:

C(s) = Kp + Ki/s^α + Kd * s^β,

where Kp, Ki, and Kd are the proportional, integral, and derivative gains, respectively, and α, β ∈ (0, 2) represent the fractional orders.

Tuning Methods for FOPID Control:

Analytical tuning methods aim to determine the optimal values of the FOPID controller parameters based on system specifications and performance requirements. Some popular approaches include:

Fractional Order Ziegler-Nichols (FOZN) Tuning extension of the classical Ziegler-Nichols method, FOZN tuning involves determining the critical gain and period for the FOPID controller based on the system response to a step input.

Symmetrical Optimum (SO) Method provides an analytical expression to calculate the FOPID controller parameters by optimizing a performance index related to system performance and robustness [6-9].

Optimization-Based Tuning utilize optimization algorithms to find the optimal FOPID controller parameters that minimize a specific cost function. These methods often require system identification and model-based optimization techniques, such as Genetic Algorithms (GA) tuning searches the parameter space to find the best FOPID controller parameters by iteratively evolving a population of candidate solutions using genetic operators. Particle Swarm Optimization (PSO the FOPID controller parameters by simulating the social behavior of a swarm of particles, where each particle represents a potential solution.

Fractional order control (FOC) has gained significant attention in recent years due to its ability to capture complex dynamics and improve control performance. Fractional order controllers utilize non-integer order differentiation and integration, providing greater flexibility in modeling and controlling systems with fractional dynamics. This article explores the principles, approaches, and applications of fractional order controller design. We discuss the theoretical foundations of FOC, different design methods, and showcase its effectiveness in various applications [10-11].

Fractional order integral controllers (FOIC) focus on using fractional order integration to improve control performance, especially in systems with long memory or those requiring precise tracking of setpoints. The FOIC can handle processes with dominant integrators, non-minimum phase systems, and non-square systems. Design methods for FOIC include fractional order integral controller tuning and optimization-based techniques [12].

This article provides a comprehensive overview of AVR, covering its principles of operation, control strategies, and applications in various industries. Control Strategies for AVR Voltage Feedback Control, the voltage feedback control strategy is the most common method used in AVRs. It involves comparing the sensed output voltage with a reference voltage and generating an error signal. The error signal is then processed by a control algorithm to adjust the excitation current and maintain the desired output voltage.

Adaptive Control techniques are employed in AVRs to optimize the regulation performance under varying operating conditions. These methods utilize adaptive algorithms that continuously adjust the control parameters based on system dynamics, load variations, and environmental changes. Adaptive control enhances the robustness and stability of the AVR, ensuring accurate voltage regulation. AVR Components and Features are stated here [13].

Voltage Regulator Unit (VRU) is the core component of an AVR. It consists of a control circuit, sensing circuit, and power circuit. The control circuit receives the error signal from the voltage feedback mechanism and generates the appropriate control signals for adjusting the excitation current. The sensing circuit measures the output voltage and provides feedback to the control circuit. The power circuit supplies the excitation current to the generator's field winding based on the control signals [13].

Excitation System Components, the AVR works in conjunction with other components in the generator's excitation system, including the main exciter, rotating diodes, and field winding. The main exciter is a small generator connected to the generator's rotor, producing the initial excitation voltage. Rotating diodes convert the AC output of the main exciter to DC, which is then supplied to the field winding to create the magnetic field.

Discussing all these points here, the resulting statement is The tuning method for FOPID is more challenging than that of its conventional equivalent since it has two additional tuning parameters.

A. *AVR Working Principle and Mathematical Modelling*

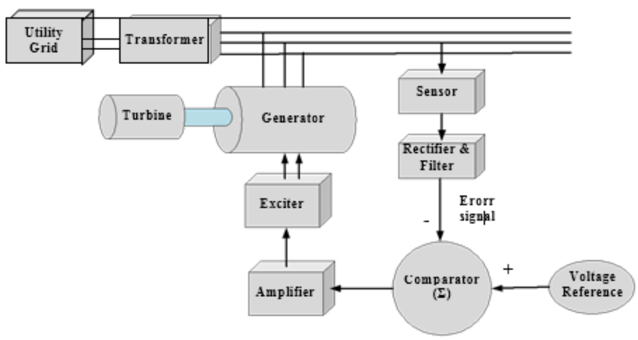

Fig 1. AVR System Conventional

The primary objective of an AVR system is to regulate the output voltage of a power source by compensating for fluctuations in the input voltage or load changes. This is achieved through a closed-loop feedback control mechanism. Let's examine the key components and their functionalities within an AVR system. The sensing circuit of an AVR system measures the output voltage and compares it with a reference value. The reference value represents the desired output voltage level. The difference between the measured voltage and the reference voltage is known as the error signal. The control circuit receives the error signal from the sensing circuit and processes it to generate a suitable control signal. This control signal determines the adjustment required in the output voltage. The excitation system is responsible for modifying the field current of the generator or transformer to regulate the output voltage. It receives the control signal from the control circuit and adjusts the excitation level accordingly. Mathematical modelling plays a crucial role in understanding and analyzing the behavior of AVR systems. By representing the system using mathematical equations, engineers can predict its response to different input conditions and optimize its performance. Here are some common mathematical models used for AVR systems. The transfer function model represents the relationship between the input and output voltages of an AVR system. It is often expressed as a ratio of polynomials, where the coefficients of the polynomials depend on the system's characteristics and parameters. The transfer function model allows engineers to analyze the stability, transient response, and frequency response of the AVR system[14]. The state-space model represents the AVR system as a set of first-order differential equations. It consists of state variables, input variables, output variables, and system matrices. The state-space model provides a comprehensive representation of the system's dynamics and allows for more advanced control design techniques, such as optimal control and observer-based control. While linear models are often used for simplicity, AVR systems can exhibit nonlinear behavior under certain operating conditions. Nonlinear models capture the nonlinearity inherent in the system and provide a more accurate representation of its response. Nonlinear models can be described using techniques such as differential equations, piecewise-linear models, or Volterra series [15-16].

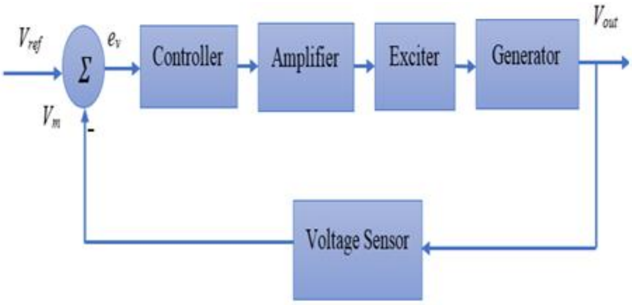

Fig 2. AVR Block Diagram

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$$GFOPID\ (s) = Kp + Kis^{-\lambda} + Kd\ s^{\mu} \quad [1]$$

$$G_A(s) = \frac{K_A}{1 + ST_A} \quad [2]$$

$$G_E(s) = \frac{K_E}{1 + ST_E} \quad [3]$$

$$G_G(s) = \frac{K_G}{1 + ST_G} \quad [4]$$

$$G_S(s) = \frac{K_S}{1 + ST_S} \quad [5]$$

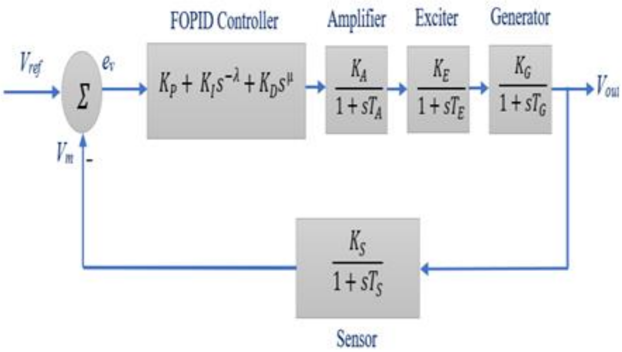

Fig 3. FOPID –AVR

After putting the values

K_A=10,
K_E=1

K_G=1

K_S =1

T_A=0.1

T_E =0.4
T_G= 1,T_S=0.01

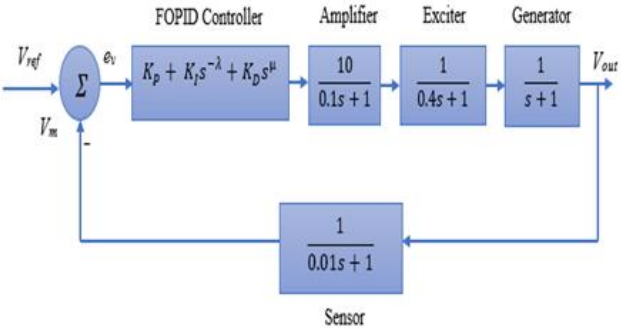

Fig 4. AVR model with final values

II. PROPOSED METHODOLOGY

Optimisation is the process of selecting the optimal solution from among all viable options. This is accomplished in SI-based optimisation approaches by minimising or maximising a pre-defined fitness function (FF) [17-18]. In cases where traditional optimisation strategies fail to produce acceptable results, these optimisation methods can achieve exceptional performance [19]. SI approaches can achieve a good quality solution in a comparatively shorter period than standard optimisation techniques for complicated optimisation issues (Nondeterministic polynomial time-hard tasks). Because of the aforementioned reasons, this work investigates the implementation of the Gradient-based optimisation algorithm, one of the most recent SI-based optimisation techniques. The functioning mechanism, as well as its mathematical underpinning, are thoroughly explained in the next sections.

A. Initialization

Individually, the GBO generates a primary population from a uniform random distribution. In a D-dimensional explore domain, the population has N trajectories agents, with each population agent termed "trajectory.".

$$Xn = Xmin + rand(0,1)\ (Xmax - Xmin) \quad [6]$$

Where Xmin Xmax rand (0, 1) is a random number in the range [0 1], and, and are the limits of the decision variables X.

The GSR in GBO is in charge of supplying random behaviour, which subsequently improves the algorithm's capacity to divert attention while it is being optimised. The site of the trajectory can be estimated using Equation (7) based on the GSR, direction of movement, and initial position of the search agent.

B. Gradient search rule (GSR

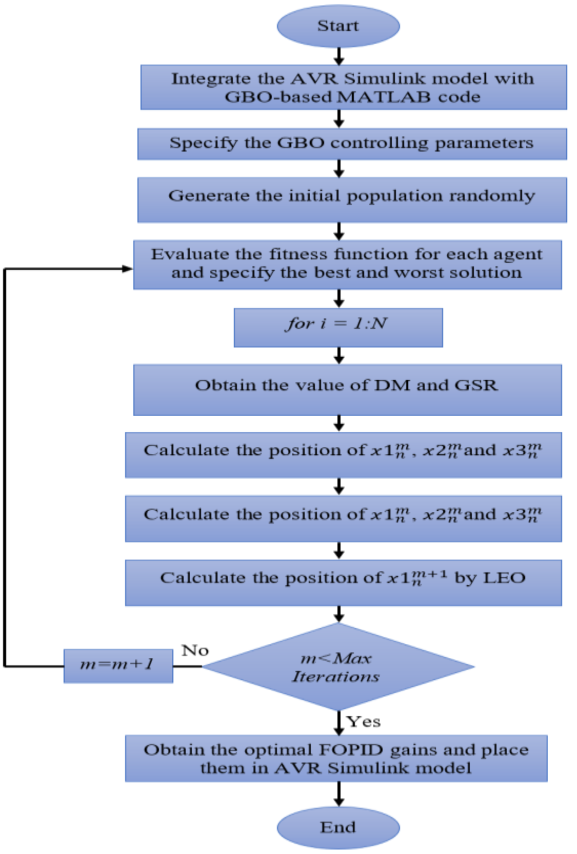

Fig 5. Flowchart for FOPID-AVR design using the GBO algorithm

$$X1_n^m = x_n^m - randn \times \rho_1 \times \frac{2\Delta x \times x_n^m}{(x_{worst} - x_{best} + \varepsilon)} + rand \times \rho_2 \qquad [6]$$

$$\rho 1 = 2 \times rand \times \alpha - \alpha \qquad [7]$$

$$\alpha = \left|\beta \times \sin\left(\frac{3\pi}{2} + \sin\left(\beta \times \frac{3\pi}{2}\right)\right)\right| \qquad [8]$$

$$\beta = \beta min + (\beta max - \beta \min) \times \left(1 - \left(\left(\frac{m}{M}\right)^3\right)^2\right) \qquad [9]$$

Where β_{min} and β_{max} are 0.2 and 1.2, respectively, and reflect the current iteration's minimum and maximum iterations, respectively. Within the range [0, 0.1], is a constant number.

$$\rho 2 = 2 \times rand \times \alpha - \alpha \qquad [10]$$

$$\Delta x = rand(1{:}N) \times |step| \qquad [11]$$

$$step = \frac{(xbest - xr1^m) + \delta}{2} \qquad [12]$$

$$\delta = 2 \times rand \times \left(\left|\frac{x_{r1}^m + x_{r2}^m + x_{r3}^m + x_{r4}^m}{4} - x_n^m\right|\right) \qquad [13]$$

where rand (1:N) is a random number with N dimensions, r1, r2, r3, and r4 are numbers arbitrarily picked from [1 N].

In the following section the algorithm of GBO is shown according the work in this article.

Step 1. Initialization
Assign values for parameters pr, ε, and M
Generate an initial population $X_0 = [x_{0,1}, x_{0,2}, ..., x_{0,D}]$
Evaluate the objective function value
$f(X_0)$, n=1, ..., N
Specify the best and worst solutions x_{best}^m and x_{worst}^m
Step 2. Main loop
While (m<M)
for $n = 1 : N$
for $i = 1 : D$
Select randomly $r1 \neq r2 \neq r3 \neq r4 \neq n$ in the range of [1, N]
Calculate the position $x_{n,i}^{m+1}$ using Eq. 5
end for
Local escaping operator
if $rand < pr$
Calculate the position x_{LEO}^m using Eq. 6
$X_n^{m+1} = x_{LEO}^m$
end
Update the positions x_{best}^m and x_{worst}^m
end for
m=m+1
end
Step 3. return x_{best}^m

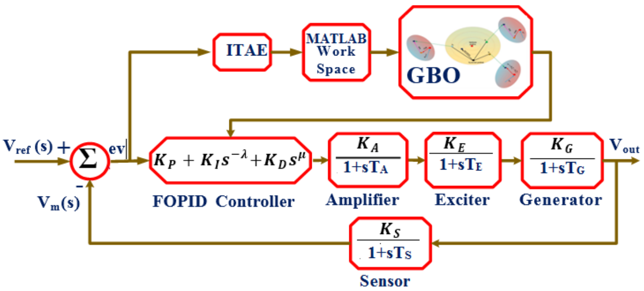

Fig 6. AVR tuning based GBO FOPID

Figure 6 is showing the simulation performed and studied in the research work. The simulation is carried out in MATLAB. It is visible in the figure that the control loop system designed is a closed loop. The loop is showing different blocks of descriptive nomenclature of amplifier exciter generator sensor with their respective PID based order transfer functions. The resulting voltage comes out as Vout. And the feedback is Vm.

III. RESULT AND DISCUSSION

The section here is showing the results and analysis been carried out with the block diagram simulations and the algorithm wind stated in this research article the performed GBO algorithm has been successfully implemented and the results are been shown in the section below figure number 7 here giving the GBO response to figure figures till 12 are only on the simulations and algorithm based studies.

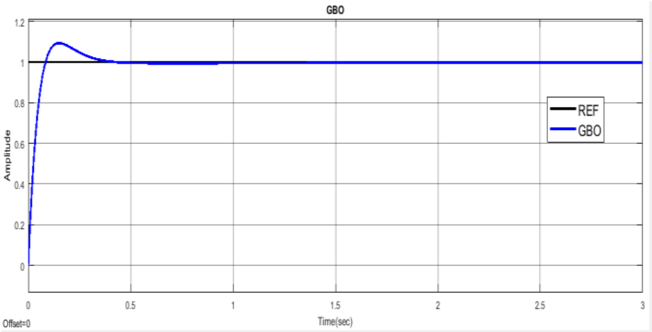

Fig 7. GBO using Response

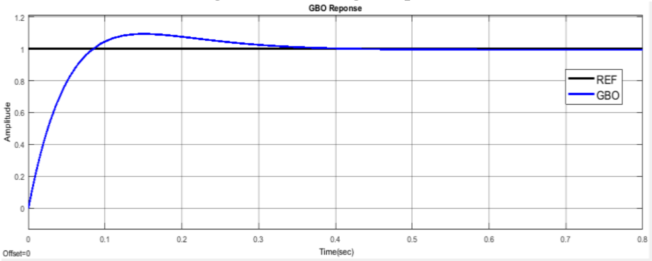

Fig 8. GBO-FOPID Based AVR

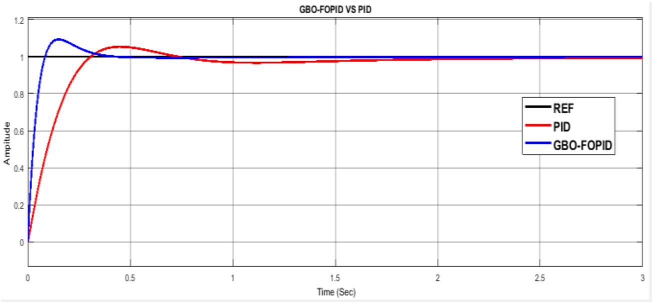

Fig 9. GBO-FOPID Vs PID

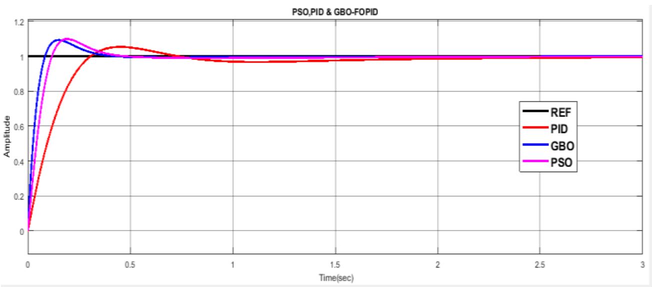

Fig 10.Comparsion of GBO with PID and PSO

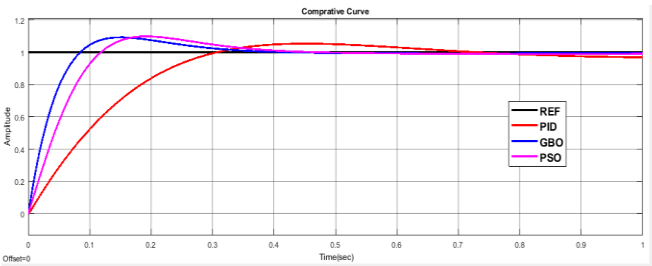

Fig 11.Comparsion of GBO with PID and PSO (Zoom)

The figure 7 is showing the results of AVR GBO-FOPID based system response. It clear from that system is stable vary earlier and transient time is very less. When we reduce the simulation time at 0.8sec then we have a zoom analysis of proposed method which is shown in figure 8.the comparison between conventional PID, PSO and proposed technique is showing in figure 9 and figure 10. For that is it clear that proposed technique showing good response as compared to others. The form the results it is clear that proposed technique is given better and quick response as compared to other. Figure 13 displays the AVR system's dynamic response when applying proposed method.

Table 1 GBO Values

S.No.	Output	Values
1	Best Value	3.2e-4
2	Average	1.2e-1
3	Worst Value	8.9e-7
4	Iteration	15

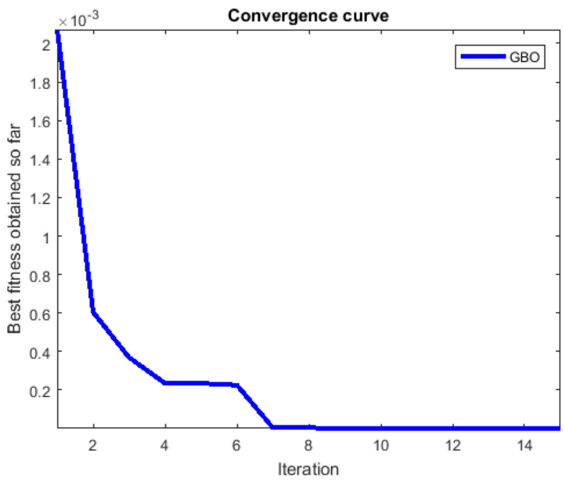

Fig 12. GBO Convergence curev

Transfer function proposed system

$$\frac{V_{ref}(s)}{V_m(s)} = \frac{0.06124s^{2.6062} + 6.124s^{1.6062} + 0.09961s^{1.4932} + 0.14861s + 9.961s^{0.4932} + 14.861}{0.0004s^{4.4932} + 0.0454s^{3.4932} + 0.555s^{2.4932} + 6.124s^{1.6062} + 1.51s^{1.4932} + 10.961s^{0.4932} + 14.861}$$

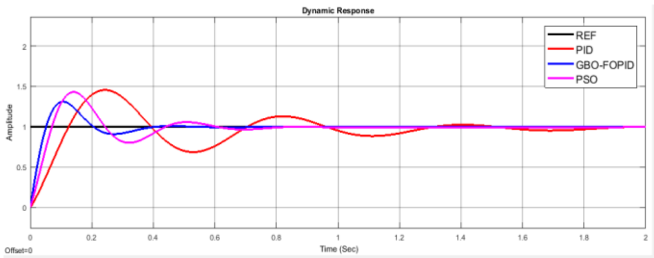

Fig 13. Dynamic Response Comparison

IV CONCLUSION

The proposed method AVR system is controlled by a GBO-based algorithm. This strategy produces comparable results to traditional PID and PSO algorithms. Both normal and dynamic response are analysed to validate the suggested mechanism of response, and the proposed technique results are dependable and very accurate. When compared to other approaches, the peak overshoot and settling time are rather short. In the future, to control it, machine learning algorithms may provide more rapid and accurate responses.

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