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Multi-Objective Optimization Approach to PID Tuning in AVR Systems: A Comparison of Ziegler–Nichols, GA and PSO

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Abstract

In this study, a comparative analysis of PID controller parameter optimization methods for Automatic Voltage Regulator (AVR) system is presented. AVR model is created in MATLAB/Simulink environment and controlled with PID controller. In the first stage, Ziegler-Nichols (ZN) method is used to determine the initial controller parameters. Then, single-objective Genetic Algorithm (GA) is applied which minimizes Integral of Time-weighted Squared Error (ITSE) performance criterion. A multi-objective GA structure is developed which includes overshoot and settling time criteria. Similarly, Particle Swarm Optimization (PSO) algorithm is applied as both single-objective and multi-objective just like Genetic algorithm. Step responses obtained with each method are evaluated according to overshoot, settling time, rise time and ITSE criteria. The results show that multi-objective PSO algorithm provides the most successful performance compared to traditional methods in dynamic response and error minimization.

Key words: Automatic Voltage Regulator (AVR), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Integral of Time-weighted Squared Error (ITSE),

1. Introduction

Electricity networks are interconnected systems that provide energy flow from electricity generation systems to consumption systems. It is very important that this energy is delivered in a quality manner that meets demand. Power imbalances on the load side of the network cause changes in the voltage level of the generator on the production side. The stability of the voltage in a power system is one of the main control parameters because the devices connected to the network operate at a certain voltage level [1]. If this voltage is not properly controlled, voltage sags may occur [2].

Automatic Voltage Regulators (AVR) regulate the generator output voltage by maintaining the terminal voltage at its nominal value, thereby ensuring a continuous and high-quality energy flow [3]. The basic components of an AVR system include an amplifier, an exciter, a generator, and a voltage sensor. These components form a closed-loop system with feedback, as illustrated in Figure 1.

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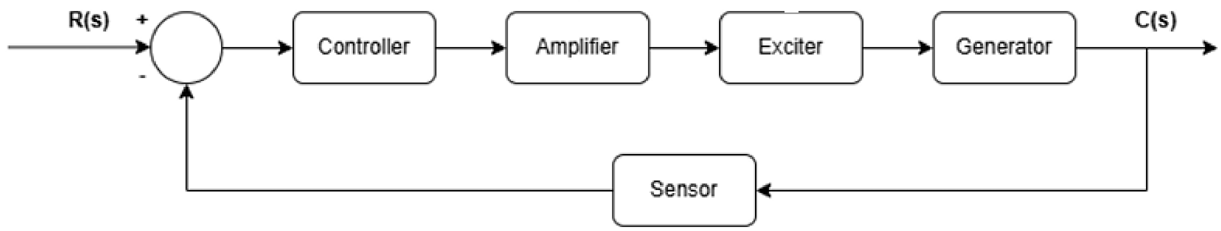

Figure 1. Closed-loop control structure of the AVR system

There are many control methods used for AVR. The most commonly used is the Proportional-Integral-Derivates (PID) controller. These controller coefficients are determined to ensure that the system is operated appropriately. In addition to classical methods, artificial intelligence techniques are also widely used to determine controller parameters [4]. A summary of recent studies applying such optimization-based approaches to PID/FOPID controller design in AVR systems is presented in Table 1.

Table 1. Literature-based optimization methods applied to AVR systems and their objective

Ref	Applied Methods	Objective and Performance
[5]	ARO (Artificial Rabbits)	In the AVR system, the voltage profile is improved by optimizing the PID gains with ARO. The method is an alternative to GA/PSO.
[6]	SA–WSO (Simulated Annealing – White Shark Optimizer)	In the AVR system, PID and FOPID gains were optimized according to multiple performance criteria. GA and PSO comparisons were made.
[7]	Literature Review (GA, PSO, GWO, TLBO...)	How PID/FOPID controllers for AVR systems are developed with different optimization algorithms is classified in detail.
[8]	Model reduction (BBBC, PSO)	Low order models of the AVR system were analyzed with BBBC and PSO. PID gain optimization was not performed.
[19]	GA, PSO	PID control parameters for DC motor are optimized with GA and PSO. Although the implementation is different, there is methodological similarity.
[10]	Multi-criteria evaluation (criterion mapping)	A method is proposed in which PID controller gains are determined by weighted evaluation under multiple criteria. AVR system is not used.
[11]	ALO (Ant Lion Optimizer)	By optimizing PID parameters with ALO, performance criteria such as overshoot and ITAE in the AVR system have been improved.
[12]	GMO (Geometric Mean Optimizer)	FOPID controller is applied to AVR system and gains are optimized with GMO algorithm.
[13]	Multiple algorithm comparison	Controllers such as PID, FOPID, FOPIDD in the AVR system are evaluated with 20 different optimization algorithms. It includes extensive comparisons including GA and PSO.
[14]	SOA (Seagull Optimization Algorithm)	FOPID controller is applied to AVR system and gains are optimized with SOA algorithm. Comparison is made with other FOPID approaches.

[15]	SWO (Spider Wasp Optimizer)	PID parameters in the AVR system were optimized with the SWO algorithm.
[16]	PSO	The performance of multi-objective functions for PID controller gains in the AVR system was evaluated by optimizing with PSO.
[17]	DO (Dandelion Optimizer)	Sigmoid based FOPID (SFOPID) controller is implemented in AVR system and optimized with DO algorithm. Experimental validation is done.

2. Materials and Method

In this part of the study, the gain parameters of the classical PID controller applied to the (AVR) system were optimized with different methods.

In the first stage, the initial gains were obtained using the classical Ziegler–Nichols (ZN) method in order to observe the basic behavior of the system. Then, multi-objective optimization was performed with Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques and the obtained results were compared with each other.

In the multi-objective optimization, the objective function was determined as ITSE (Integral of Time-weighted Squared Error), overshoot, and settling time.
The AVR system model was created in the MATLAB/Simulink environment; and the optimization algorithms were integrated into the simulations via MATLAB script files.

2.1. Ziegler-Nichols Method

The classical method used to determine the parameters of the controller is Ziegler-Nichols (ZN). This method was first proposed by Ziegler-Nichols in 1942 [18]. PID parameters are calculated with the help of predefined tables. The parameters determined with these calculations may not be the optimum parameters for the controller because the operations performed in this method are very time consuming and the proposed method does not guarantee to provide the best parameters.

When starting ZN, K_d and K_i are taken as zero and K_p is increased starting from a small number. The behavior of the system is monitored and the K_{cr} point is found. The K_{cr} point is the point where the system oscillates at a constant amplitude. Then this point is determined as the critical point K_{cr}, and P_{cr} represents the critical period value. After these two values are calculated, the desired controller design is made using Table 2.

Table 2. Ziegler–Nichols Table with Closed Loop Method

Controller Type	K_p	K_i	K_d
P Controller	$0.5K_{cr}$	-	-

PI Controller	$0.45\mathrm{K_{cr}}$	$\frac{0.54\mathrm{K_{cr}}}{\mathrm{P_{cr}}}$	-
PID Controller	$0.6\mathrm{K_{cr}}$	$\frac{1.2\mathrm{K_{cr}}}{\mathrm{P_{cr}}}$	$\frac{0.6\mathrm{K_{cr}}\mathrm{P_{cr}}}{8}$

At the end of all operations, the PID parameters calculated with ZN are; $K_p = 0.06$, $K_i = 0.1459$, $K_d = 0.0062$.

2.2. Genetic Algorithm (GA) and Multi-Objective Genetic Algorithm (GA)

In this part of the study, PID controller parameters were calculated in two ways as GA and multi-optimization GA. In GA, single-objective optimization targeting the error size was used and Integral of Time-weighted Squared Error (ITSE) was selected as the objective function. ITSE function applies the penalty process by taking the square of the error value depending on time and is presented in equation 1.

$$J = \int_0^T t.e\,(t)^2 dt \tag{1}$$

It has been observed that targeted optimization based on error magnitude alone is insufficient in improving PID parameters at the desired level. Therefore, instead of approaches focusing on only one criterion, multi-objective objective functions that consider multiple performance criteria simultaneously come to the fore [16].

The multi-objective objective function used in this study is defined to optimize the performance criteria ITSE (Integral of Time-weighted Squared Error), overshoot and settling time simultaneously. In the second stage of the study, the objective function based on these criteria was created and the Multi-objective Genetic Algorithm (Multi-objective GA) was applied in the optimization process. The defined objective function is presented in Equation 2.

$$J = ITSE + \alpha.Overshoot + \beta.Settling\,Time \tag{2}$$

Overshoot is the maximum value that the system exceeds the reference value and the point where the system reacts the most is the peak value. Setting time is the time it takes for the system to reach the reference degree. Since all purposes are of equal importance, α=β=1 is taken. By using these three, the system's error will be reduced and the system will reach the peak value faster and more stable.

The PID parameters obtained with Single-Objective GA are $K_p = 0.6514$, $K_i = 0.5210$, $K_d = 0.2873$. .
The PID parameters obtained with Multi-Objective GA are $K_p = 0.4099$, $K_i = 0.2782$, $K_d = 0.1304$.

2.3. Particle Swarm Optimization and Multi-Objective Particle Swarm Optimization

Particle swarm optimization (PSO) is a heuristic algorithm inspired by the nature of gregarious animals such as birds and fish, developed by Kennedy and Eberhart in 1995 [16].

In PSO, each individual searching is called a particle, while the population formed by individuals coming together is called a swarm. The fitness function is used to understand how close an individual is to the solution, and this state that is closest to the solution is expressed as pbest. The state of the particle closest to the solution in the entire swarm is expressed as gbest. In each iteration, these values are updated and the new motion and states of each particle are set. This cycle is repeated until the desired parameter is reached. The equations used for the particle's speed ($v_i(t)$) and position ($x_i(t)$) are presented in equations (3) and (4), respectively.

$$v_i\ (t+1) = w.v_i(t) + c_1.r_1 * (pbest - x) + c_2.r_2 * (gbest - x) \tag{3}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{4}$$

c_1 is the cognitive coefficient, c_2 is the social coefficient, w is the inertia coefficient, r_1 , r_2 are random values. While c_1 is kept high in more exploratory systems, c_2 can gain weight in cases where fast solutions are desired.

In this study, PSO algorithm was used in the optimization of PID controller parameters; both single-objective (ITSE-based) and multi-objective versions were implemented. The objective function used for single-objective optimization is presented in Equation 1. In the multi-objective PSO application, the performance criteria (ITSE, overshoot and settling time) previously defined in the GA method were employed, and the related objective function is given in Equation 2. The parameters of the PSO algorithm were set as follows: inertia weight w=0.7, and $c_1 = c_2 = 1.5$ [19].

The PID parameter obtained with Single-Objective PSO are K_p =0.6496, $K_i = 05189$, $K_d = 0.2856$.

The PID parameters obtained with Multi-Objective GA are K_p =0.4141, $K_i = 0.2812$, $K_d = 0.1318$.

3. Results

In this section, the system responses obtained as a result of optimizing the PID controller parameters with Ziegler–Nichols (ZN), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) methods are presented comparatively. The optimization process was carried out both as single-objective (based on ITSE criteria only) and multi-objective (ITSE, overshoot and settling time), and the gain values of each method were obtained. Simulations were carried out in

MATLAB/Simulink environment, and the obtained step response graphs and performance metrics are given in this section. The obtained results clearly show the effect of the used algorithms on the system performance.

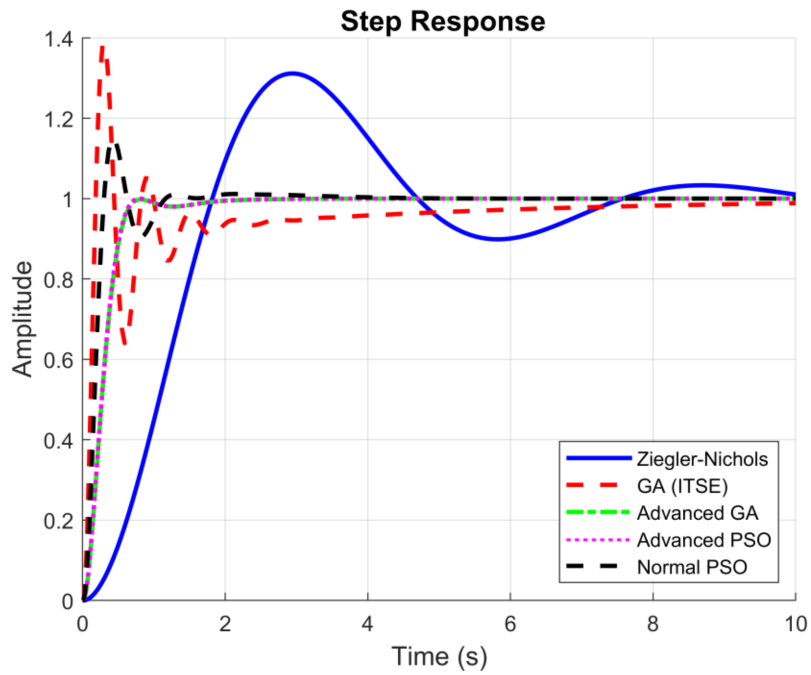

Figure 2. Step responses of the PID controller system tuned with Ziegler–Nichols, GA and PSO methods

When the step responses given in Figure 2 are examined, it is clearly seen that the controller obtained with the classical Ziegler–Nichols (ZN) method still cannot reach the steady state within 10 seconds. This shows that the PID gains determined only with the ZN method seriously limit the system performance.

An analysis of the system performance criteria in Table 3 reveals that the PSO algorithm exhibits superior performance, especially compared to the GA algorithm, in terms of settling time, overshoot, rise time and ITSE values [9]. In particular, Normal PSO stands out by achieving both low overshoot (15.07%) and short settling time (1.09 s). On the other hand, the GA (ITSE) method could not fully provide the desired system behavior due to the high overshoot rate despite the low ITSE value.

When multi-objective optimizations are compared, it is observed that the Multi-Objective GA provides significant improvements compared to classical GA. Similarly, Multi-Objective PSO yields a more stable and balanced response compared to Normal PSO. Moreover, when the multi-objective versions of GA and PSO are directly compared, the Multi-Objective PSO exhibits a slight superiority, offering a shorter settling time (0.64 seconds) and a lower ITSE value (0.02638).

These findings clearly demonstrate that the choice of optimization algorithms plays a critical roşe in PID controller design, directly affecting the system performance, and that multi-objective optimization approaches provide more balanced results than single-objective methods.

Table 3. Comparison of system performance criteria for different PID tuning methods

Method	Overshoot	Settling Time	Rise Time	ITSE
ZN	31.123	Devam ediyor	1.2257	0.893
GA	38.313	5.3463	0.1407	0.074423
Multi-Objective GA	≈ 0	0.68431	0.43758	0.026861
PSO	15.065	0.64886	0.40229	0.026383
Multi-Objective PSO	≈ 0	1.0925	0.1924	0.013276

4. Discussion

In this study, the gain parameters of the PID controller applied to the AVR system were optimized using Ziegler–Nichols (ZN), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) methods. When the obtained step responses and performance criteria were examined, it was observed that the controller designed with the classical method ZN could not reach the steady state within 10 seconds of simulation time and the overshoot was quite high. This confirms that the ZN method can only be used for initial gain estimation, as stated in the literature; however, it does not guarantee optimum results [18].

When the comparative performance of the GA and PSO algorithms is examined, it is seen that the PSO algorithm exhibits superior performance compared to GA, especially in terms of dynamic criteria such as settling time, overshoot and rise time. This finding is also consistent with the previous studies showing that PSO stands out with its more balanced convergence structure [6], [16].

In multi-objective optimization applications, it has been determined that both GA and PSO algorithms provide more balanced and successful results compared to their classical (single-objective) versions. While the Multi-Objective GA provides lower ITSE and shorter settling time compared to classical GA, the Multi-Objective PSO stands out with its low overshoot rate and short settling time. According to the performance comparison given in Table 2, the Multi-Objective PSO algorithm gave the most successful results with a settling time of 0.64 seconds and an ITSE value of 0.02638 [9].

Conclusions

In this study, the gain parameters of the PID controller applied to the AVR system were optimized with GA and PSO algorithms, in comparison with the Ziegler–Nichols method. The obtained results show the inadequacy of the classical method. In particular, the multi-objective PSO algorithm provided the most successful performance with low overshoot and short settling time. These findings revealed the positive effect of multi-objective optimization strategies on the system response.

In future studies, it is suggested to apply different multi-objective approaches to time-delayed models. In addition, it is considered that the controller performance can be further improved by adapting current optimization algorithms such as ARO, SWO, and SOA to their multi-objective structures.

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