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Optimally Tuned PID Controller Design for an AVR System: A Comparison Study

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Abstract – Voltage control is performed to reduce network losses in power systems. Automatic Voltage Regulator (AVR) system is commonly used in power systems to keep output voltage on a constant value defined in a specified range. In order to improve dynamic response of an AVR system and minimize obtained steady state error, researchers focus on developing control schemes and designing controllers for the AVR system. In controller design process, meta-heuristic algorithms are generally preferred to optimally tune the parameters of the controller. In this comparison study, parameters of traditional Proportional-Integral-Derivative (PID) controller, utilized for the voltage control of an AVR system, are tuned using Particle Swarm Optimization (PSO) and Symbiotic Organism Search (SOS) algorithms. Integral of Time-multiplied Absolute Error (ITAE) function which is a widely preferred error-based objective function, is used during the optimization processes. The performances of the designed PID controllers are compared both visually and numerically. Integral of Time-multiplied Square Error (ITSE), Integral of Absolute Value of Error (IAE), and ITAE performance metrics are utilized in addition to maximum overshoot, settling time, rise time and steady-state error values in numerical comparison. It is concluded that ITAE objective function provides better result than both ITSE and IAE metrics in AVR system. In addition, it is seen that the transient response characteristics obtained by SOS algorithm are superior than those obtained by PSO algorithm.

Keywords – Automatic Voltage Regulator (AVR), Proportional-Integral-Derivative (PID) Control, Particle Swarm Optimization (PSO), Symbiotic Organism Search (SOS)

I. INTRODUCTION

Equipments used in electrical power systems are determined according to nominal voltage value. If the continuity of the nominal voltage level cannot be achieved, the efficiency decreases. Note that reactive power flow effective in line losses depends on this voltage value. Therefore, the continuity of the nominal voltage level is important [1].

Automatic Voltage Regulators (AVR) are used to solve the mentioned problem. AVR systems are closed-loop control systems to maintain the voltage level within the specified range. These systems are used with different controllers to achieve better dynamic performance and minimize steady state error. Among the controllers, *Proportional-Integral-Derivative (PID)* controller is widely used because of its easy implementation and robust performance. Traditionally, methods such as the Ziegler-Nichols method and gain-phase margin method are used to decide controller parameters [2]. In addition to traditional methods, self-tuning methods having simpler structure have been widely utilized. In order to tune controller parameters, optimization algorithms are mostly preferred as self-tuning method.

In studies [1-5], PID controller parameters for AVR system were determined by optimization algorithms. Artificial Bee Colony (ABC) algorithm [1], Chaotic Optimization approach (CAO) [2], Learning Based Optimization (LBO)algorithm [3], Particle Swarm Optimization (PSO) algorithm [4], and improved Kidney-inspired Optimization algorithm [5] are some of the algorithms used in PID controller design for AVR system. In [6], PSO and Gravitational Search (GS) algorithms was utilized in a hybrid structure to tune PID controller parameters. The proposed hybrid algorithm was compared to Ziegler-Nichols method and PSO and the researchers observed that the proposed hybrid structure provides more successful results. In [7], a fractional-pid controller structure for AVR system was proposed. PSO algorithm was used to determine the controller parameters. In [8], researchers tuned a PID controller parameters for an AVR system using Cuckoo Search Optimization (CSO) algorithm. A new performance criterion approach was adopted in the optimization algorithm. The results obtained were compared with other algorithms available in the literature.

The main purpose of this study is to design a PID controller for an AVR system and analyse the effect of commonly used error-based objective functions in PID controller design process. PSO and Symbiotic Organism Search (SOS) algorithms are separately employed to tune the PID controller parameters. Integral of Time-multiplied Square Error (ITSE), Integral of Absolute Value of Error (IAE), and Integral of Time-multiplied Absolute Error (ITAE) objective functions are used both in PSO and SOS algorithms to analysis their effect in optimization process. Simulation of the AVR system with designed PID controllers are carried out. Performances of the PID controllers are compared in terms of objective functions, maximum overshoot, settling time, rise time and steady-state error values.

The rest of the paper is organized as follows; Section 2 presents modeling of an AVR system. Section 3 and 4 briefly explain SOS and PSO algorithms, respectively. Implementation of the algorithms and simulation results are given in Section 5. Section 6 concludes the paper.

II. MODELING OF AVR SYSTEM

A simple AVR system consists of amplifier, exciter, generator and sensor components. A time constant and gain constant are required for the transfer function of each component. The parameter ranges of these constants and the values used in this study are given in Table 1 [9].

Table 1. Parameters of AVR subsystems [9]

Components	Limits of Parameters	Used values
Amplifier	10≤Ka≤40, 0.02≤ $Ta \leq 0.1$	Ka=10, Ta=0.1
Exciter	1≤Ke≤ 10, 0.4≤ $Te \leq 1$	Ke=1, Te=0.4
Generator	0.7 ≤Kg≤ 1, 1≤ $Tg \leq 2$	Kg=1, Tg=1
Sensor	0.001≤ $Ts \leq 0.06$	Ks=1, Ts=0.01

The block diagram of the AVR system described above is given in Figure 1.

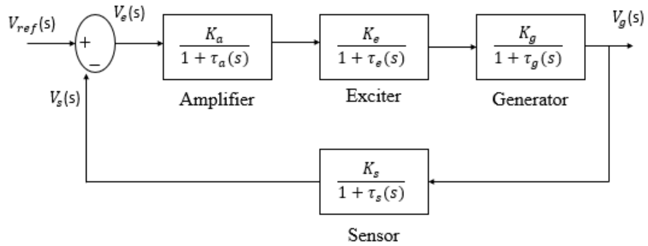

Fig 1. Block diagram of an AVR system without controller

To improve dynamic performance of the AVR system and minimize steady-state error a PID controller is used. The block diagram of such a controlled system and its corresponding transfer function are given in Figure 2 and Eq (1), respectively. In Figure 2, K_p, K_i and K_d represent proportional gain, integral gain, and derivative gain of the PID controller, respectively.

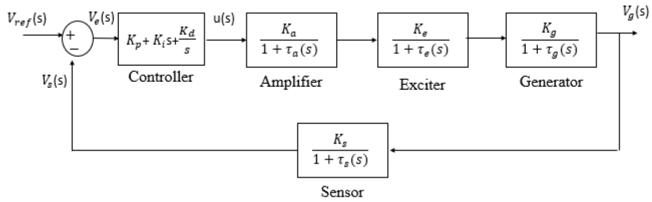

Fig 2. Block diagram of a PID controlled AVR system.

$$\frac{V_g(s)}{V_{ref}(s)} = \frac{(s^2K_d + sK_p + K_i)(K_aK_eK_g)(1+s\tau_s)}{s(1+s\tau_a)(1+s\tau_e)(1+s\tau_g)(1+s\tau_s)+(K_aK_eK_gK_s)(s^2K_d+sK_p+K_i)} \quad (1)$$

III. SYMBIOTIC ORGANISM SEARCH ALGORITHM

The word symbiotic refers to the relationship established between two different species to survive. It was introduced by De Bary more than 135 years ago [10]. The basis of the SOS algorithm is to mimic the relationship between species in nature. The most common relationships are; mutualism, commensalism and parasitism phases. In the mutualism phase, both types benefit, while in the commensalism phase, one-type benefits and the other is unaffected, in the parasitism phase, one benefits and the other one is damaged. The algorithm is modeled mathematically based on these three phases. The process of the algorithm is descried as follows [11].

- Start
- Repeat phases
- Until convergence criteria is met

The algorithm initially generates random populations at a specific lower and upper limit ranges, then calculates the fitness value. The search continues until the number of iterations or convergence criteria is met and eventually the best fitness value and the best organism value are updated [11]. The flowchart of the SOS optimization is given in Figure 3.

IV. PARTICLE SWARM OPTIMIZATION ALGORITHM

The particle swarm optimization algorithm developed by Kennedy and Eberhart is a herd-based evolutionary algorithm [12]. The algorithm is based on the fact that birds within the flock move according to the position of the bird closest to the food. In order to model the movements of the swarm, position and velocity update equations of the particles are used. The equations of the velocity and position are given below, respectively.

$$V_i^{k+1} = w^k V_i^k + c_1 r_1 (P_{best}^k - X_i^k) + c_2 r_2 (G_{best}^k - X_i^k) \quad (2)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (3)$$

where k is the iteration number, i is the index of the particle, w is the inertia weight that directly effect the velocity, c1 and c2 are the acceleration factors called cognition and social constants, respectively, r1 and r2 are the random numbers between 0 and 1, Pbest is the best local solution, Gbest is the best global solution, and Vi and Xi are the velocity and position of the particle i, respectively.

The implementation of the PSO algorithm is described as follows:

- Initialize the particles with random velocities and positions.
- Evaluate and compare objective values of the particles in the population and obtain the local best value (Pbest) of the population for current iteration, keep the Pbest value in memory
- Compare the Pbest value to global best (Gbest) value, which is initially assigned to Pbest value, and assign global best (Gbest) value to the position of the particle with the best objective function value
- Update the velocities of the particles by using (2)
- Move each particle to their new position by using (3) [9].

The flowchart of the PSO optimization is given in Figure 4.

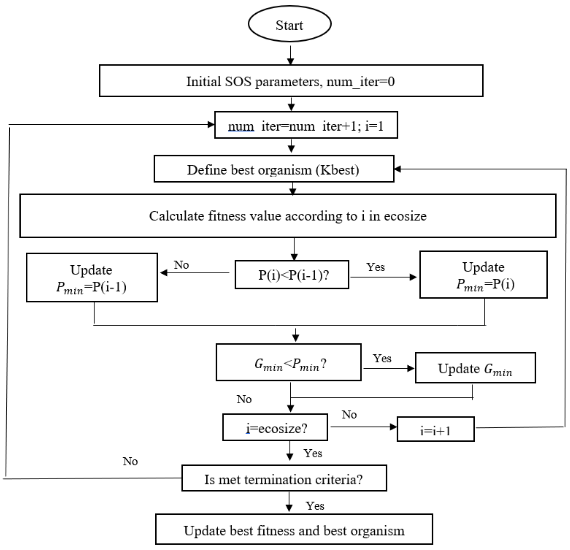

Fig 3. Flowchart of the SOS algorithm

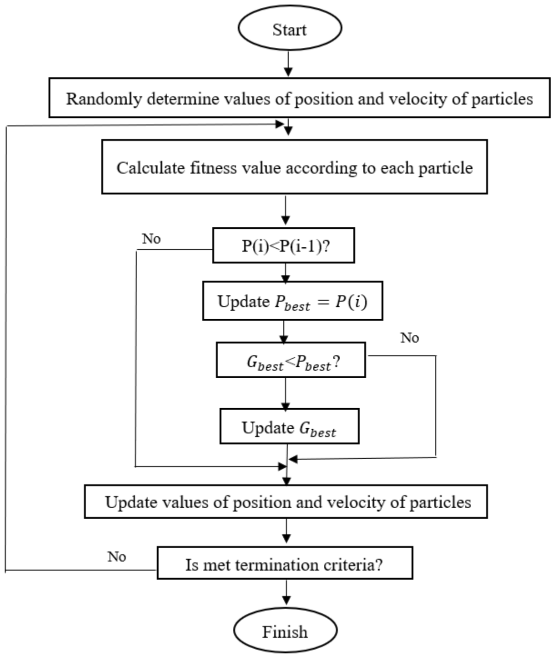

Fig 4. Flowchart of the PSO algorithm

V. SIMULATION RESULTS

In order to tune K_p, K_i and K_d parameters of PID controller both SOS and PSO algorithms are employed. The lower limits of all gains are set to 0. The upper limits of K_p, K_i and K_d are set to 2, 1, and 1, respectively. Three different error-based objective functions, i.e. IAE, ITSE, and ITAE, are separately utilized by both of the optimization algorithms. The objective functions are given in Eqs (4-6).

In both optimization algorithms, initial populations are randomly assigned, and the objective function is calculated for each generated population value. By comparing the objective function with the previous one, the minimum value is kept and when the termination criterion is met, the population variables that make the objective function minimum are saved.

$$ITAE = \int_0^\infty t\left|e(t)\right|dt \tag{4}$$

$$ITSE = \int_0^\infty te^2(t)dt \tag{5}$$

$$IAE = \int_0^\infty \left|e(t)\right|dt \tag{6}$$

where *e(t)* is the error signal at time *t*.

For both algorithms, the number of populations was 20 and the number of iterations was 50. The algorithms were run 20 times since they start at random initial positions. Transient response analysis of the system with tuned K_p, K_i and K_d parameters were examined.

The best values obtained for each objective function of the SOS algorithm are given in Table 2 and the best values obtained for each objective function of the PSO algorithm are given in Table 3.

Table 2. Best values for each objective function in SOS algorithm

SOS	Objective function	Iteration	Kp	Ki	Kd	Overshoot (%)	Rise time	Peak time	Settling time (2% band)
ITAE	0,041621	47	0,965	0,67	0,305	13,8	0,19	0,417	0,967
ITSE	0,00876	12	1,122	0,942	0,546	20,940	0,127	0,291	0,7532
IAE	0,19533	15	1,240	0,889	0,514	22,45	0,13	0,301	0,768

Table 3. Best values for each objective function in PSO algorithm

PSO	Objective function	Iteration	Kp	Ki	Kd	Overshoot (%)	Rise time	Peak time	Settling time (2% band)
ITAE	0,0454	39	0,850	0,595	0,246	11,4	0,223	0,484	0,723
ITSE	0,0088	41	1,134	0,876	0,522	20,43	0,1307	0,298	0,773
IAE	0,1956	46	1,194	0,834	0,500	21,128	0,1331	0,306	0,785

In Figure 5, the AVR system responses obtained using the PID controller set with different objective functions in the SOS algorithm are given. As can be seen from the figure, settling time and overshoot in ITAE objective function is less than other the objective functions. In Figure 6, the AVR system responses obtained using the PID controller set with different objective functions in the PSO algorithm are given. As can be seen from the figure, settling time and overshoot in ITAE objective function is less than the other ones.

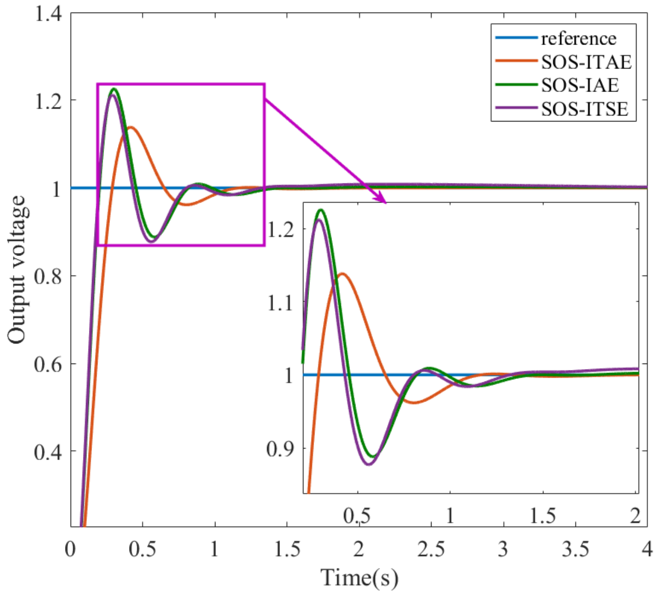

Fig 5. AVR voltage responses using PID controller tuned with different objective functions in SOS algorithm

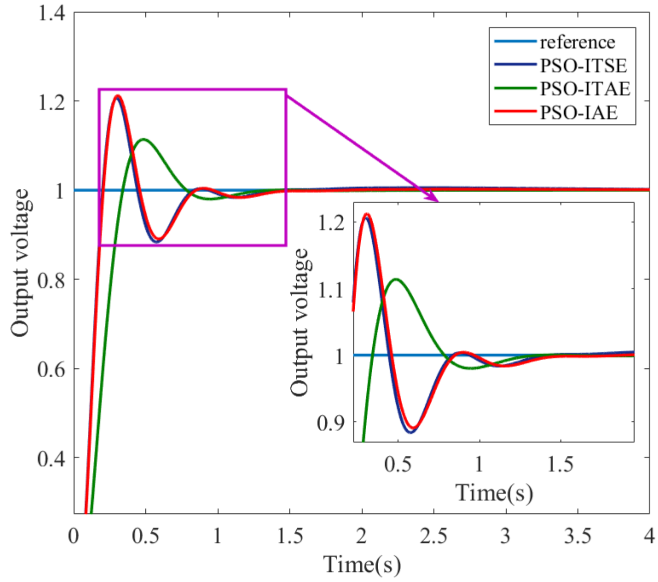

Fig 6. AVR voltage responses using PID controller set tuned different objective functions in PSO algorithm

The output voltage values obtained for each objective function in SOS and PSO algorithms are given in Figure 7, Figure 8 and Figure 9. When the results obtained are examined, it is seen that two of the transient response characteristics obtained by SOS algorithm for ITAE objective function are better than the ones obtained by PSO algorithm. For ITSE objective function, three of the transient response characteristics obtained by SOS algorithm are better than the PSO algorithm. Finally, for IAE objective function, three of the transient response characteristics obtained by SOS algorithm are better than PSO algorithm.

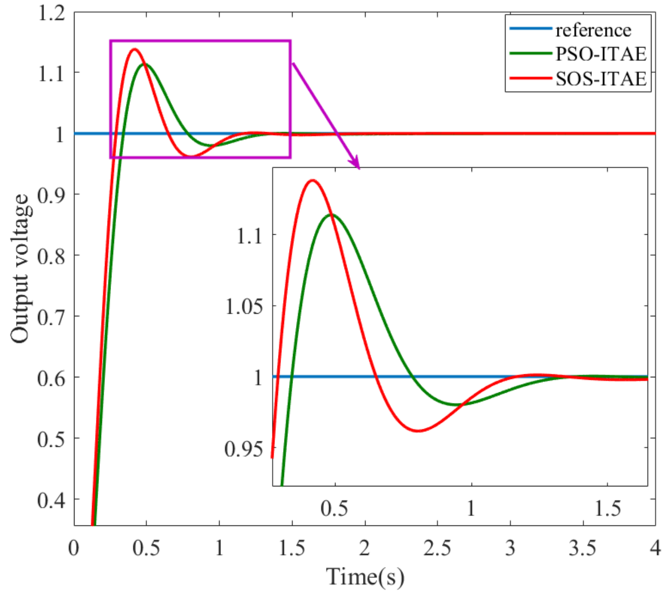

Fig 7. AVR voltage responses using PID controller tuned with ITAE objective function in SOS and PSO algorithms

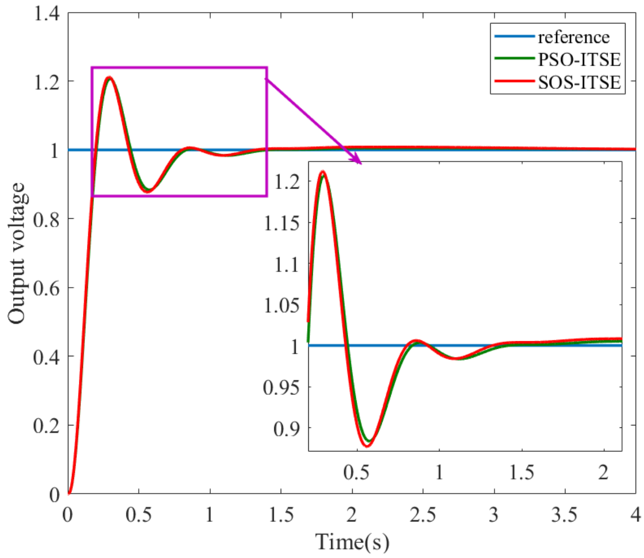

Fig 8. AVR voltage responses using PID controller tuned with ITSE objective function in SOS and PSO algorithms

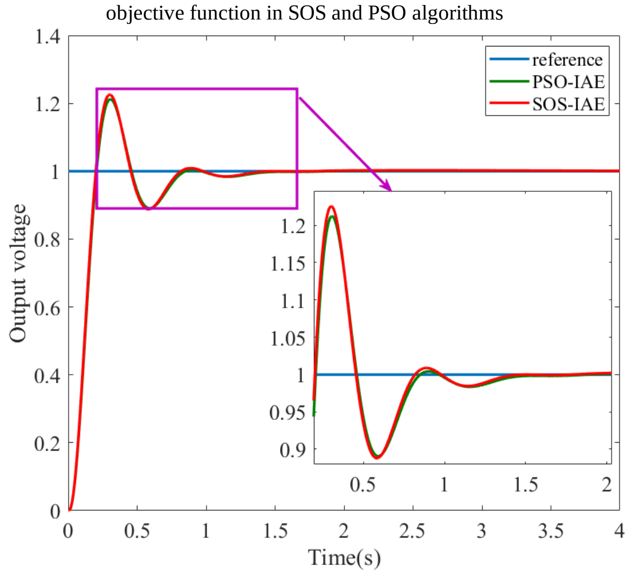

Fig 9. OVR voltage responses using PID controller set with IAE objective function in SOS and PSO algorithms

VI. CONCLUSIONS

In this study, design of a PID controller for AVR system to keep output voltage constant in electrical power systems is presented. PSO and SOS optimization algorithms were used to tune the controller parameters. For each algorithm, transient response analysis of the system with designed PID controller was examined and performance comparison was made. In addition, three different objective functions, namely IAE, ITSE, ITAE, were used to analyse the effect of objective functions used in optimization algorithms and the results were analysed. According to the results obtained, ITAE objective function gives better result for both algorithms in AVR system among the error-based objective functions. When the responses of objective functions for both algorithms are considered, it is seen that the transient response characteristics obtained by SOS algorithm are better than those obtained by PSO algorithm.

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