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AVR System Optimization through Optimum Design of PID Controller

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***Abstract*—In this paper, a peculiar design method for determining the optimal proportional –integral-derivative (PID) controller parameters in the AVR system using the particle swarm optimization (PSO) algorithm is presented. The use of PSO method to search productively the optimal PID controller parameters in an automatic voltage regulator (AVR) system is exposed in detail in this paper. The suggested approach had superior features, like stable convergence characteristic, easy implementations and good computational efficiency. Fast tuning of optimum PID controller parameters turns out high-quality solution. A time-domain performance criterion function was also defined, in order to collaborate estimating the performance of the PSO-PID controller. Compare with the genetic algorithm (GA) and Ziegler-Nichols methods, this method was absolutely more efficient and robust in improving the step response of an AVR system.**

Key words*—PID controller, PSO controller, optimal control, particle swarm optimization, AVR system.

I. INTRODUCTION

DURING the past decades, the process control techniques in the industry have made great advances. Numerous control methods such as neural control, adaptive control, and fuzzy control have been studied [1]—[5]. Among them, the well-known is the proportional-integral-derivative (PID) controller, which has been widely used in industry because of its simple structure and robust performance in a wide range of operating conditions. Several heuristic methods have been proposed for the tuning of PID controllers. The first method used the classical tuning rules proposed by Ziegler and Nichols. In general, it is often tough to determine optimal or near optimal PID parameters with the Ziegler-Nichols formula [1]—[3].

For the above reasons, it is highly desirable to increase the capability of PID controllers by adding new features. Many artificial intelligence (AI) techniques have been employed to improve the controller performance for a wide range of plants while preserving their basic characteristics. AI techniques such a fuzzy system, neural network, and neural-fuzzy logic have been widely applied for proper tuning of PID controller parameters [1], [2].

Numerous random search methods, such as a simulated annealing (SA) and genetic algorithm (GA)[2]-[9], have received much interest for achieving high efficiency and searching global optimal solution in problem area. The GA method is usually faster than the SA method because the GA has parallel search techniques, which is used to reproduce natural genetic operations. GA has high potential in global optimization; therefore it has received great attention in control system such as the searching the parameters of optimal PID controller. Even though GA is widely used in many control system applications, its genetic operations would still result in tremendous computational efforts [5], [6]. In order to overcome the disadvantages, GA is offered with the use of real-value representation to get a number of advantages in numerical function optimization over binary encoding because, conversion of chromosomes to binary type is not needed in numerical function optimization[3]-[5], [6].

Even though to solve complex optimization problems the GA methods have been engaged auspiciously, recent scholars have find out some insufficiencies in GA performance. The efficiency is degraded apparently in highly epi-static objective functions applications [i.e., where correlation of the parameters being optimized (the crossover and mutation operations can’t ensure better fitness of offspring because chromosomes in the population have similar structures and their average fitness is high toward the end of the evolutionary process)][11], [15]. Moreover, the premature convergence of GA degrades its performance and reduces its search capability [11].

Particle swarm optimization (PSO), is one of the modern heuristic algorithms developed through simulation of a simplified social system, which was introduced by kennedy and eberhart, and has been found to be robust in solving continuous nonlinear optimization problems [12]—[16]. With stable convergence characteristic and very short calculation time a high-quality solution can be generated by using PSO technique than other stochastic methods [15]—[17]. Much research is going on for proving the potential of PSO in solving complex power system operation problems. Researchers have presented a PSO voltage control (VVC) considering voltage security assessment and reactive power. The method is compared with the enumeration method on particle power system and reactive tabu system (RTS) and has shown genuine results [17]. And also solved efficiently the practical distribution state estimation problem [18] by using hybrid PSO method. As the PSO method is an excellent optimization methodology and a promising approach for solving the optimal PID controller parameters problem; therefore, this study develops the PSO-PID controller to search optimal PID parameters. This controller is called the PSO-PID controller.

The controller performance is evaluated by the integral performance criteria in frequency domain, but these criteria have their own advantages and disadvantages [5], [6]. In this paper, the performance of a PSO-PID controller that was applied to the complex control system is evaluated by a sample performance criterion in time domain.

Controlling of the reactive power flow and the generator voltage is done by the generator excitation system using an automatic voltage regulator (AVR) [19]. The terminal voltage amplitude of a synchronous generator at a specified level is done by AVR. Hence, AVR system's stability would seriously affect the security of the power system. In this paper, to test the performance of the proposed PSO-PID controller a practical high-order AVR system including a PID controller is adopted.

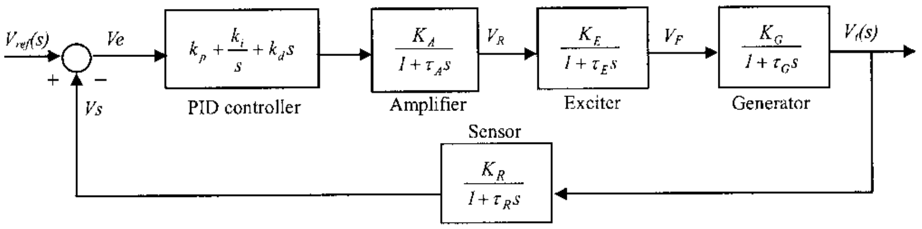


Figure-1: Automatic Voltage Regulator (AVR) system Block diagram including PID controller.

In this paper, in solving the optimal PID controller parameters, many performance estimation schemes are performed to examine whether this method has better performance than the real-value GA method, also demonstrating how to employ the PSO method to obtain the optimal PID controller parameters of an AVR system.

II. LINEARIZED MODEL OF AN AVR SYSTEM

A. *PID Controller*

The PID controller is used to reduce or eliminate the steady-state error as well as to improve the dynamic response. The transient response is improved by using derivate controller which adds a finite zero to the open-loop plant transfer function. A pole at the origin is added by the integral controller so that system type is increased by one and the steady-state error is decreased because of a step function to zero. The PID controller transfer function is

$$C(s) = k_p + \frac{Ki}{s} + K_d s \qquad (1)$$

B. *Linearized Model of an AVR System*

The role of an AVR is to detain the terminal voltage amplitude of asynchronous generator at a specified level. A simple AVR system consists of four main blocks, namely amplifier, exciter, generator and sensor. By ignoring the saturation or other nonlinearities and considering the major time constant, these blocks must be linearized to find out transfer function and for mathematical modeling. The reasonable transfer function of these blocks may be represented as follows respectively.

- Amplifier model.

The amplifier model's gain is represented by K_A and a time constant is represented by τ_A; the transfer function is

$$\frac{V_R(s)}{V_e(s)} = \frac{K_A}{1+\tau_A s} \qquad (2)$$

Typical values of K_A are in the range of 10 to 400. The amplifier time constant is ranging from 0.02 to 0.1s which is very small.

- Exciter model.

The transfer function of an exciter model is having a gain K_E and a single time constant τ_E, transfer function is

$$\frac{V_F(s)}{V_R(s)} = \frac{K_E}{1+\tau_E s} \qquad (3)$$

Range of K_E is 10 to 400. The range of time constant τ_E is 0.5 to 1.0 s.

- Generator model.

Relation between the generator terminal voltage and field voltage is represented by the generator model's transfer function which is having gain K_G and a time constant τ_G as follows

$$\frac{V_t(s)}{V_F(s)} = \frac{K_G}{1+\tau_G s} \qquad (4)$$

As these constants are load dependent, from full load to no load, K_G may vary from 0.7 to 1.0, τ_G from 1.0 to 2.0.

- Sensor model.

The first-order transfer function of the sensor model is given by

$$\frac{V_s(s)}{V_t(s)} = \frac{K_R}{1+\tau_R s} \qquad (5)$$

Time constant ranging from of 0.001 to 0.06s, which is very small.

To evaluate the PID controller, the time domain performance criterion is proposed as

$$W(K) = (1-e^{-\beta}).(M_p+E_{ss}) + e^{-\beta}.(t_s - t_r) \qquad (6)$$

Where K is $[k_p, k_i, k_d]$ and β is the weighting factor.

The performance criterion $W(K)$ can satisfy the designer requirements using the weighting factor β value. To reduce the steady state error and the overshoot, β is set to be larger than 0.7. On the other hand, to reduce the settling time and the rise time, β is set to be smaller than 0.7. In this paper, β is set in range of 0.8 to 1.5.

III. PSO-PID CONTROLLER

A PID controller using the PSO algorithm was used to improve the step transient response of AVR of a generator. It was also called the PSO-PID controller. The PSO algorithm was mainly utilized to determine three optimal controller parameters k_p,k_i, and k_d such that the controlled system could obtain a good step response output.

For searching the controller parameters by applying the PSO method, the "particle" would be replaced by "individual" and the "group" would be replaced by the "population", in this paper. Three controller parameters k_p, k_i, k_d are defined to compose an individual K hence, these members are assigned as real values. If there are n individuals in a population, then the dimension of a population is *nx3*.

The evaluation function f which is a reciprocal of the performance criterion *W (K)* is given out as

$$f = \frac{1}{W(K)} \tag{7}$$

Before evaluating the evaluation value of an individual we need to test the closed-loop system stability by using the Routh-Hurwitz criterion to restrict the evaluation value of each individual of the population within a reasonable range. The individual is said to be a feasible individual if it satisfies the Routh-Hurwitz stability test applied to the characteristic equation of the system, and the value of *W(K)* is small. In the reverse case, the *W(K)* value of the individual is penalized with a very large positive constant.

IV. DYNAMIC BEHAVIORS ESTIMATION

In order to examine the dynamic behaviors and convergence characteristic of the proposed method, two statistical indexes, namely the mean value (μ) and the standard deviation (σ) of evaluation values of all individuals in the population during the computing processes, were used. The accuracy of the algorithm can be displayed by the mean value, and the convergence speed of the algorithm can be measured by the standard deviation. The formulas for calculating the mean value and the standard deviation of evaluation values are as follows,

$$\mu = \frac{\sum_{i=1}^{n} f(Ki)}{n} \tag{8}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f(Ki) - \mu\right)^2} \tag{9}$$

Where *f(ki)* is the evaluation value of the individual k_i and n is the population size.

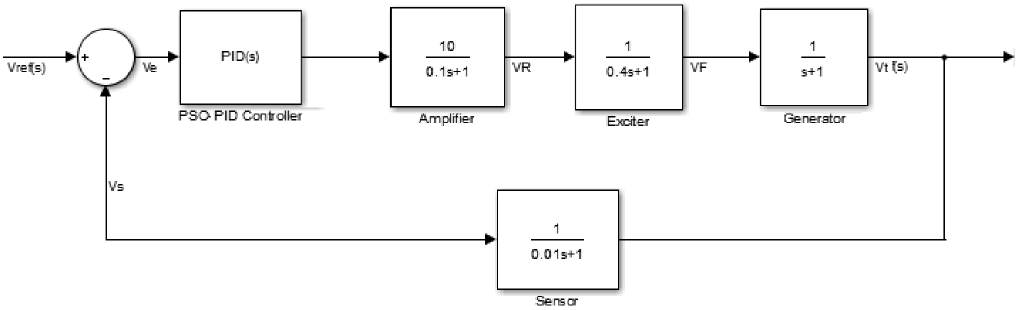


Figure-2: Automatic Voltage Regulator (AVR) system Block diagram including PSO-PID controller.

V. RESULTS

controller parameters	Min.Value	Max.Value
Kp	0	1.5
Ki	0	1
Kd	0	1

Table-1: Minimum and Maximum values of controller parameters.

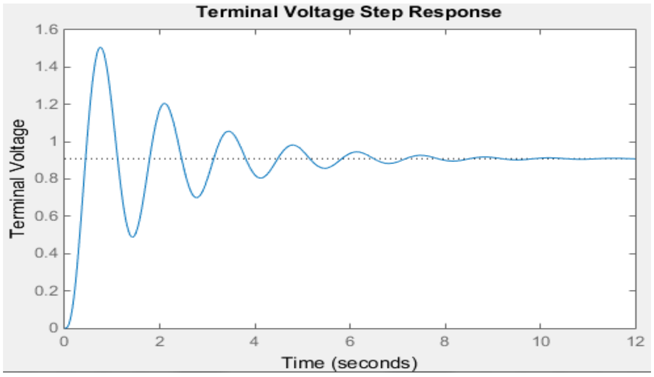


Figure-3: Step response of the Terminal voltage in AVR system before including PID controller.

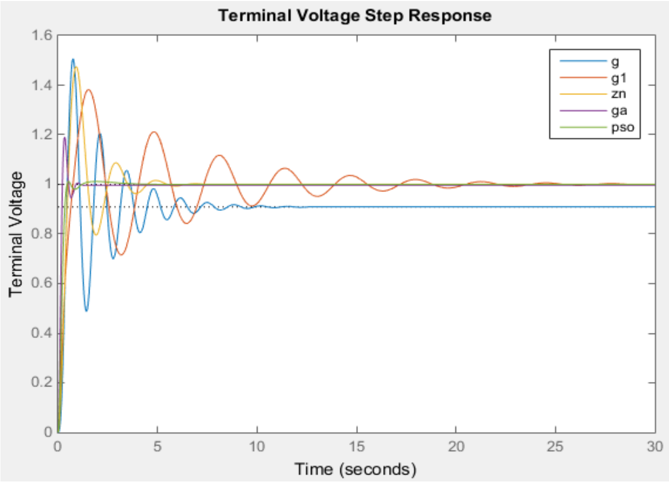
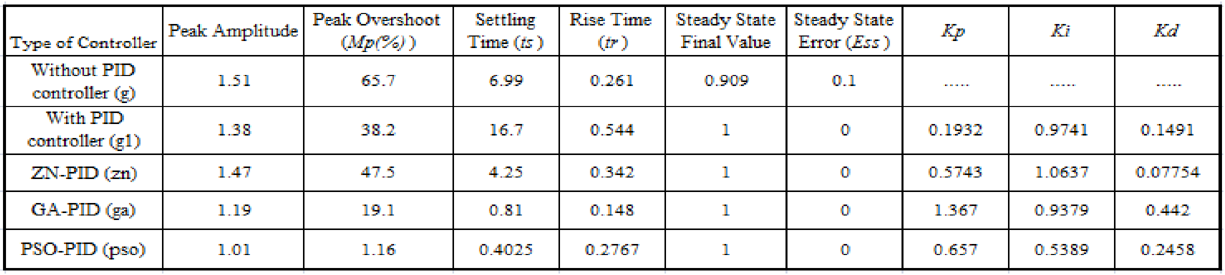
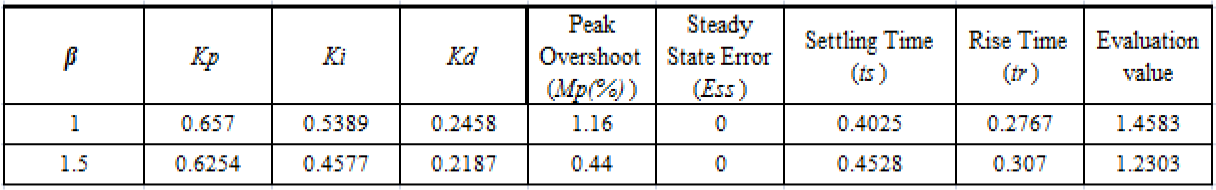


Figure-4: Step response of the Terminal voltage in AVR system by using different controllers.



Type of Controller	Peak Amplitude	Peak Overshoot (Mp(%))	Settling Time (ts)	Rise Time (tr)	Steady State Final Value	Steady State Error (Ess)	Kp	Ki	Kd
Without PID controller (g)	1.51	65.7	6.99	0.261	0.909	0.1	.....	.....	.....
With PID controller (g1)	1.38	38.2	16.7	0.544	1	0	0.1932	0.9741	0.1491
ZN-PID (zn)	1.47	47.5	4.25	0.342	1	0	0.5743	1.0637	0.07754
GA-PID (ga)	1.19	19.1	0.81	0.148	1	0	1.367	0.9379	0.442
PSO-PID (pso)	1.01	1.16	0.4025	0.2767	1	0	0.657	0.5389	0.2458

Table-2: AVR system performance by using different controllers.



β	Kp	Ki	Kd	Peak Overshoot (Mp(%))	Steady State Error (Ess)	Settling Time (ts)	Rise Time (tr)	Evaluation value
1	0.657	0.5389	0.2458	1.16	0	0.4025	0.2767	1.4583
1.5	0.6254	0.4577	0.2187	0.44	0	0.4528	0.307	1.2303

Table-3: Performance of PSO-PID controller in AVR system for different values of β.

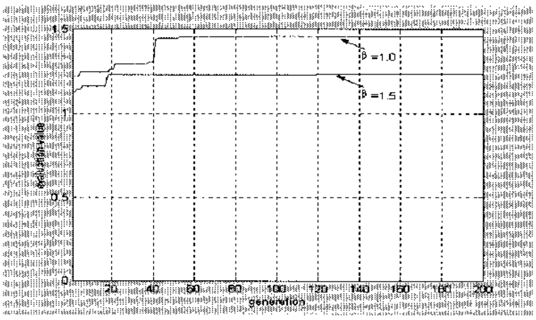


Figure-5: PSO-PID controller's Convergence tendency for different values of β.

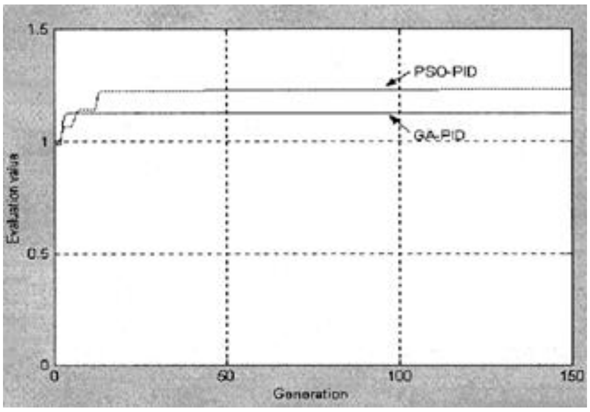


Figure-6: Evaluation value's Convergence tendency for GA-PID and PSO-PID controllers.

The block diagram of the AVR system with a PID controller is shown in Figure-2. The lower and upper bounds of the three controller parameters were as shown in Table-1. Figure-3 shows the original terminal voltage step response of the AVR system without a PID controller. Figure-4 shows the terminal voltage step response of the AVR system with different PID controllers. Figure-5 shows the convergence characteristics of the PSO-PID controller.

Comparison of the performance of an AVR system for different methods is shown in Table-2. Overview of particle swarm optimization is presented in APPENDEX-A, and searching procedure for PSO-PID controller is presented in APPENDEX-B. As can be seen, the PSO method can prompt convergence and obtain good evaluation value. For searching the optimal PID controller parameters efficiently and quickly, the PSO-PID controller can be applied shows results. The PSO-PID controller has good performance than other PID controllers according to the above performance criteria. The PSO-PID controller could create very perfect step response of the AVR system, which shows that the PSO-PID controller is better than other PID controllers.

VI. CONCLUSION

This paper presents a peculiar design method for determining the PID controller parameters applying the PSO method. The method consolidates the PSO algorithm with the time-domain performance criterion into a PSO-PID controller. Through the simulation of a practical AVR system, the results show that the PSO-PID controller can perform an efficient search for the optimal PID controller parameters.

From the results, it is clear that the PSO method can avoid the shortcoming of premature convergence of GA method and can obtain higher quality solution with better robust stability and more computation efficiency, and can solve the tuning and searching problems of PID controller parameters more quickly and easily than the GA method.

APPENDEX-A

PARTICLE SWARM ALGORITHM

In 1995, Kennedy and Eberhart announced the particle swarm optimization (PSO) method. It is one of the optimization techniques and a kind of evolutionary computation technique. The method has been found to be robust in solving problems featuring nonlinearity and non-differentiability, multiple optima, and high dimensionality through adaptation, which is derived from the social-psychological theory. The characteristics of the method are as follows.

- The method is advanced from research on swarm such as bird flocking and fish schooling.
- It can be freely realized and has stable convergence characteristic with good computational efficiency.

Unlike in other evolutionary computational algorithms, which use evolutionary operators to manipulate the particle (individual), each particle in PSO flies in the search space with velocity which is dynamically adjusted according to its computations flying experience and its own flying experience. In g-dimensional search space each particle is treated as a volume-less particle.

In the problem space each particle keeps track of its coordinates, which are associated with the best solution (evaluating value) it has achieved so far. This value is known as pbest. Global version of the particle swarm optimizer tracks another best value which is the overall best value and its location obtained so far by any particle in the group is called gbest.

In PSO concept, at each time step, change the velocity of each particle toward its pbest and gbest locations. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest locations.

APPENDEX-B

SEARCHING PROCEDURE FOR PSO-PID CONTROLLER

The searching procedure for PSO-PID controller is shown below.

Step-1: For the three controller parameters specify the lower and upper bounds and initialize randomly the individuals of the population including searching points, velocities, pbests and gbest.

Step-2: To test the closed-loop system stability for each initial individual *K* of the population, use the Routh-Hurwitz criterion and calculate four performance criteria values in the time domain, specifically M_p, E_{ss}, t_r and t_s.

Step-3: Using the evaluation function *f* given by (7), determine the evaluation value of each individual in the population.

Step-4: Compare each individual's evaluation value with its pbest. The 'gbest' stand for the best evaluation value among the pbest.

Step-5: The member velocity of each individual is modified according to

$$v_{j,g}^{(t+1)} = \mathcal{W}.v_j^{(t)} + q_1 * rand() * (\mathrm{pbest}_{j,g} - k_{j,g}^{(t)}) +$$

$$q_2 * Rand() * (\mathrm{gbest}_g - k_{j,g}^{(t)}) \qquad (10)$$

Where j = 1,2,……….,n, g = 1,2,3,….m., and the value of$\mathcal{W}$is set by

$$\mathcal{W} = \mathcal{W}\mathrm{max} - \frac{\mathcal{W}\mathrm{max} - \mathcal{W}\mathrm{min}}{\mathrm{iter}_{\mathrm{max}}} \mathrm{X\ iter}$$

When g is 1, $\upsilon_{j,1}$ represents the change in velocity of K_p controller parameter. When g is 2, $\upsilon_{j,2}$ represents the change in velocity of K_i controller parameter.

Step-6: If $v_{j,g}^{(t+1)} > V_g^{\max}$, then $v_{j,g}^{(t+1)} = V_g^{\max}$

If $v_{j,g}^{(t+1)} < V_g^{\min}$, then$v_{j,g}^{(t+1)} = V_g^{\min}$.

Step-7: Modify the member position of each individual *K* according to

$$k_{j,g}^{(t+1)} = k_{j,g}^{(t)} + v_{j,g}^{(t+1)},$$

$$k_g^{\min} \leq k_{j,g}^{(t+1)} \leq k_g^{\max}$$

Step-8: If the number of iterations reaches the maximum, then go to Step-9. Otherwise, go to Step-2.

Step-9: The individual that generates the latest gbest is an optimal controller parameter.

Where,

n	number of particles in a group;
m	number of members in a particle;
t	pointer of iterations (generations);
$\upsilon_{j,g}^{(t)}$	velocity of particle j at iteration t;
w	inertia weight factor;
q_1, q_2	acceleration constant set to be 2;
Rand()	random number between 0 and 1;
rand()	random number between 0 and 1;
$K_{j,g}^{(t)}$	current position of particle j at iteration t;
pbestj	pbest of particle j;
gbest	gbest of the group.

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