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Bat Algorithm for Optimal Tuning of PID Controller in an AVR System

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Abstract. This paper presents a new design approach based on bat algorithm for optimal design of proportional-integral-derivative controller in automatic voltage regulator system. The bat algorithm is iterated to reach the optimal or the near optimal of controller parameters in order to improve the automatic voltage regulator step response characteristics. Conducted simulations show the effectiveness and the efficiency of the proposed approach. Furthermore, it can improve the dynamic of the automatic voltage Regulator system even at load condition uncertainties. Conducted experiments have demonstrated that the proposed approach can outperform the well-known particle swarm optimization based technique.

Keywords: Automatic Voltage Regulator (AVR), Bat algorithm (BA), PID controller, Optimization.

1 Introduction

Over the past two decades, electric utilities operate their power systems at full power and often closer to their stability limits, which can seriously affect the security of the entire power system. Therefore, damping of generator terminal voltage oscillation following disturbances has become a priority and a great concern. In practice, this role is devoted to the generator excitation system in order to maintain generator voltage and to control the reactive power flow using an automatic voltage regulator [1]. Despite the potential of the modern control techniques, the Proportional Integral Derivative (PID) type controller is still widely used for AVR system [2]. Given that the optimal setting of PID controller gains is a multimodal optimization problem and more complex due to nonlinearity and time- variability of real world power system operation. Therefore, the traditional techniques are not completely systemic and most of them occasionally yield poor performance in practice, so they are not suitable for such a problem.

In order to overcome theses drawbacks, metaheuristic approaches have received increased attention from researchers dealing with AVR's control problems. In 2004, Giang presented a PSO based PID type controller for AVR system to find the optimal parameters of the PID controller so that the desired system specifications are satisfied [3]. Kim and Cho developed an optimal tuning method using hybrid Genetic Algorithm (GA) and Bacterial Foraging (BF) technique to improve the performance of PID control of AVR system [4]. In order to obtain an optimal PID controller for an AVR, Mukherjee and Ghoshal presented a craziness based particle swarm optimization (CRPSO) and binary coded genetic algorithm [5]. Ching-Chang suggested a real-valued genetic algorithm (RGA) and a particle swarm optimization (PSO) to design PID controller for AVR system [6]. Shayeghi and Dadashpour presented an anarchic society optimization based PID control of an Automatic voltage regulator system [7].

More recently, Bendjeghaba and Ishak suggested an improved harmony search algorithm for optimal tuning of PID parameters in AVR system [8]. In this paper, an efficient bio-inspired approach is proposed for the same purpose and a practical high order AVR system with a PID controller is adopted to investigate the performance of the proposed approach.

The approach is based on the recent bio-inspired algorithm developed by Yang in [9], namely the Bat algorithm. it has been found to be very efficient and shown significant potential in solving various hard optimisation problems. Such as Optimal capacitor placement [10], clustering [11], combined heat and power economic dispatch problem [12], image processing [13], and Phishing website detection [14].

The paper is structured as flows. Section II presents the linearized model of an AVR system with PID controller. In section III we describe the basics of the BA. The proposed BA-PID is explained in section IV. Numerical simulation and comparisons are provided in Section V. Finally, Section VI provides some conclusions.

2 Linearized model of an AVR system with PID controller

2.1 PID Controller

The PID controller is used to improve the dynamic response as well as to reduce or eliminate the steady-state error. The transfer function of PID controller is done by:

$$G_{PID}(s) = k_P + \frac{k_I}{s} + K_D s \qquad (1)$$

2.2 Linearized model of an AVR

The role of an AVR is to hold the terminal voltage magnitude of a synchronous generator at a specified level. The AVR system contains four major parts, namely: amplifier, exciter, generator and sensor. Thus, the real model of an AVR is as shown in Fig. 1.

A drop in the terminal voltage magnitude accompanies an increase in the reactive power load of the generator. The voltage magnitude is sensed through a potential transformer on one phase. This voltage is rectified and compared to a dc set point signal. The amplified error signal controls the exciter field and increases the exciter terminal voltage. Thus, the generator field current is increased, which results in an increase in the generated e.m.f. The reactive power generation is increased to a new equilibrium, raising the terminal voltage to the desired value.

In order to model the four aforementioned components and determine their transfer functions. Each component must be linearized taking into account the major time constant and ignores the saturation or other nonlinearities. The approximate transfer functions of these components may be represented, respectively, as follows [3].

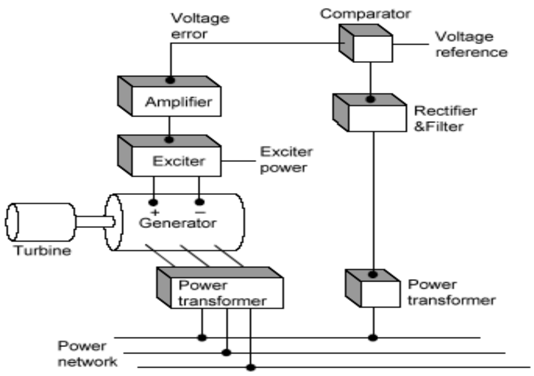

Fig. 1. Real Model of an AVR System [1].

- Amplifier Model

The amplifier is represented by a gain K_a and a time constant τ_a, and the transfer function is:

$$\frac{V_R(S)}{V_e(S)} = \frac{K_a}{1 + \tau_a S} \quad (2)$$

- Exciter Model

In the simplest form, the transfer function of a modern exciter may be represented by a single time constant τ_e and a gain K_e :

$$\frac{V_F(S)}{V_R(S)} = \frac{K_e}{1 + \tau_e S} \tag{3}$$

The time constant of modern exciters are very small.

- Generator Model

In the linearized model, the transfer function relating the generator terminal voltage to its field voltage can be represented by a gain K_g and a time constant τ_g and the transfer function is:

$$\frac{V_t(S)}{V_F(S)} = \frac{K_g}{1 + \tau_g S} \tag{4}$$

These constants are load-dependent

- Sensor Model

The sensor is modelled by a simple first order transfer function, given by:

$$\frac{V_s(S)}{V_t(S)} = \frac{K_s}{1 + \tau_s S} \tag{5}$$

Utilizing the above models, the AVR block diagram compensated with PID is shown in Figure 2.

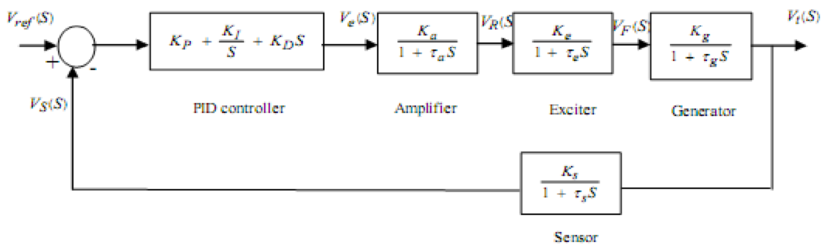

Fig. 2. Block Diagram of an AVR System

3 Basics of Bat-inspired Algorithm

Bat-inspired algorithm is a metaheuristic search optimization developed by Yang [9]. The bat algorithm is based on the echolocation behaviour of micro bats with varying pulse emission and loudness. The idealization of echolocation can be summarized as follows: Each virtual bat flies randomly with a velocity v_i at position (solution) x_i with a varying frequency at i^{th} step. Search is intensified by a local random walk. Selection of the best continues until certain stop criteria are met. The basic steps of BA can be summarized as the pseudo code shown in appendix.

Firstly, the initial position x_i, velocity v_i and frequency f_i are initialized for each bat. For each time step t, the movement of the virtual bats is given by updating their velocity and position using (1), (2) and (3) as follows:

$$f_i = f_{\min} + (f_{\min} - f_{\max})\beta \quad (6)$$

$$v_i^j(t) = v_i^j(t-1) + \left[x_{cgbest}^j - x_i^j(t-1)\right] f_i \quad (7)$$

$$x_i^j(t) = x_i^j(t-1) + v_i^j(t) \quad (8)$$

Where β denots a randomly generated number within the interval $[0,1]$. The result of equation (6) is used to control the space and the range of bats mouvement. The variable x_{cgbest}^j represents the current global best solution for decision variable j, which is achieved comparing all the solutions provided by the n bats.

For the local search part, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk:

$$x_i^{new} = x_i^{old} + \sigma A_{mean}^{Old} \quad (9)$$

Where, σ is a random number and A_{mean}^{Old} is the average loudness of all the bats at this time step.

4 Implementation BA-PID controller

In this paper, a PID controller using bat algorithm was proposed to improve the dynamic of an AVR system. The block diagram of a practical AVR system using BA -PID is shown in Fig. 3.

4.1 Fitness function

To improve the step transient response of an AVR system, the main goal of the proposed BA-PID controller in this block diagram is to adjust optimally as fast as possible the PID controller parameters by minimization of predetermined fitness function. In time domain, the fitness can be formed by different performance specifications. In this paper and for the purpose of comparison, the following performance function is used [6]:

$$F(K) = ITAE.\left((1 - e^{-\rho}) \,.\, (M_p + E_{ss}) + e^{-\rho} \,.\, (t_s - t_r)\right) \quad (10)$$

Where $K = [K_P, K_I, K_D]$ is a parameter set of PID controller, ρ is a weighting factor, $ITAE$, M_p , E_{ss} , t_s and t_r are respectively the integral of time multiplied by absolute-error value, the maximum overshoot, the steady state error, the settling time and the rising time of the performance criteria in the time domain.

4.2 BA-PID mechanism in AVR system

The bat algorithm generates initial random population of feasible candidate solutions. Then, all bats of the population are handled in the three-dimensional (PID gains) search space with the aim to guide the search to the best location in the search space using their pulse emission and loudness.

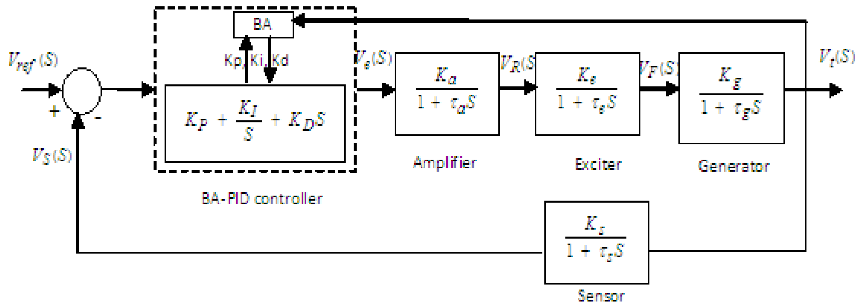

Fig. 3. Block diagram of an AVR system with IHSA-PID controller.

5 Simulation results

The proposed approach is implemented in MATLAB language on the Pentium-4 dual core 1.66 GHz PC and preliminary numerical tests were used to set the values of the BA control parameters. The best obtained ones are presented in Table 1.

Table 1. BA control parameters values.

Parameter	Designation	value
n	Population size	20
ng	Number of generation	100
fmin	Frequency minimum	00
fmax	Frequency maximum	01
A	Loudness	0.15
r	Pulse rate	0.70

To investigate the efficiency and the performance of the proposed approach, a practical high-order AVR system as shown in Fig.4, was tested. The parameters of the block diagram are chosen as:

$K_a = 10$, $K_e = K_g = K_s = 1.0$, $\tau_a = 0.1\,s$, $\tau_e = 0.4\,s$, $\tau_s = 0.01\,s$, $\tau_g = 1.0\,s$.

Only K_a is load dependent, where the lower and upper bounds of the PID controller parameters are: $0.0 \leq K_P \leq 1.5$, $0.0 \leq K_I, K_D \leq 1.0$

5.2 BA-PID controller Performance and robustness

In this section, the performance of BA-PID controller is examined at first. In second, we have examined the robustness of this controller to the load uncertainties.

5.2.1 Performance of BA-PID controller

First, we consider the terminal voltage step response of the AVR system without BA-PID. The result is shown in Fig. 4. In this case the system presents an undesirable oscillatory behaviour with large overshoot, long settling time.

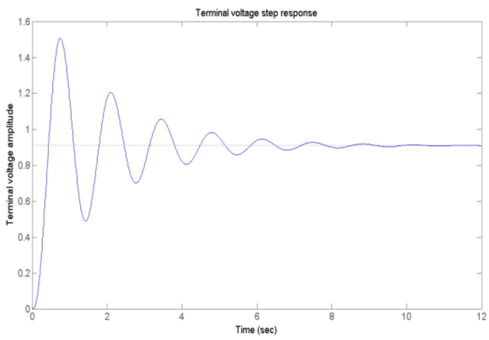

Fig. 4. Terminal Voltage Step Response of AVR System without PID Controller.

Secondary, AVR system with BA-PID is considered for fitness weighting factor 1.5. The corresponding step response is shown in Fig. 5. It can be seen from this figure, that the system response has small overshoot, short settling time and no oscillatory behaviour.

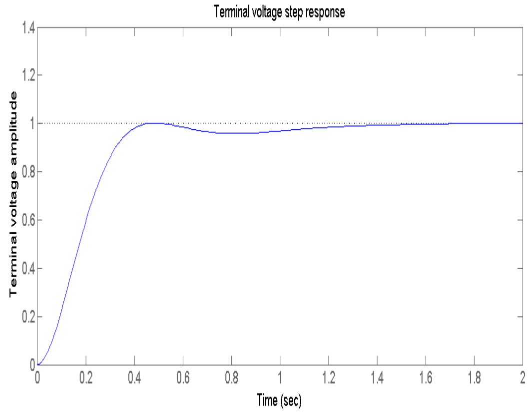

Fig. 5. Terminal Voltage Step Response of AVR System With BA-PID Controller

For the considered weighting factor, the BA-PID parameters searching process and the convergence characteristics graphs are given in Fig. 6. and Fig. 7. respectively.

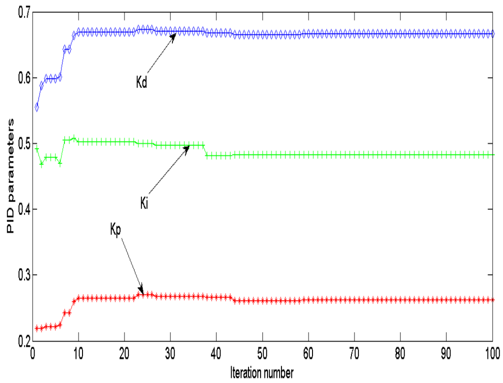

Fig. 6. BA-PID Parameters Searching Process Over Iterations.

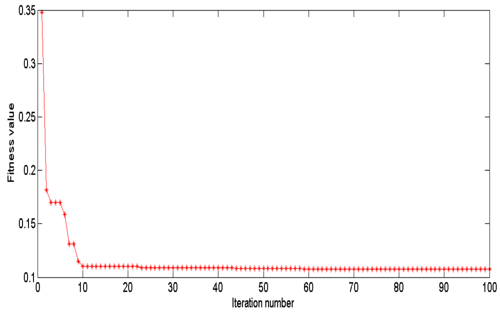

Fig. 7. Convergence Characteristic of BA-PID Controller.

As we can see from these characteristics, the approach reaches the best solutions without much fluctuation after a few iterations.

5.2.2 Robustness test

To show the robustness of the BA-PID controller, it is assumed that the generator model gain change from 0.7 to 1.0 with step 0.1 due to the change in load condition. The step response with previously designed CFA-PID controller is shown in Fig. 8. It can be seen from this figure, that the designed controller is robust to the uncertainties.

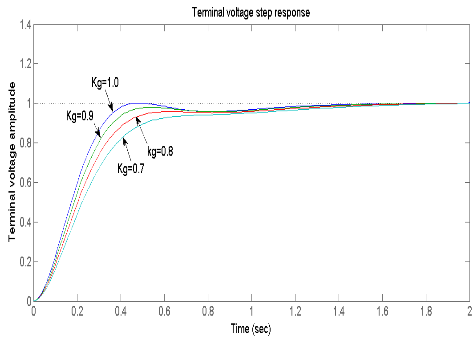

Fig. 8. Terminal Voltage Step Response With Load Uncertainties.

5.2 Comparison with PSO-PID and BA-PID controllers

For the purpose of comparison, the PSO-PID controller parameters are the same as in [6].The terminal voltage step responses of the AVR system controlled by

PSO-PID and BA-PID controllers are shown in Fig.9. The controller's parameters and performance indices are listed in Table 2.

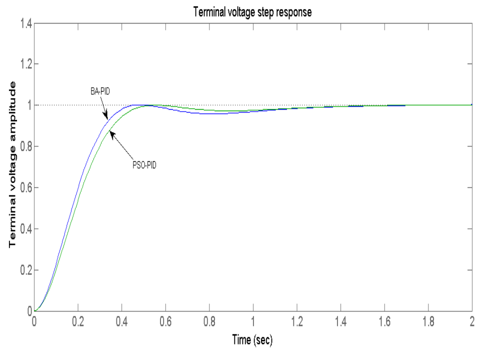

Fig. 9. Terminal Voltage Step Response of AVR System With BA-PID and PSO-PID Controllers.

Table 2. Best solutions using BA-PID and PSO-PID controllers.

Type of controller	K_P	K_I	K_D	$Mp\%$	E_{ss}	t_s	t_r	$F^{-1}(k)$
PSO-PID [6]	0.6300	0.4538	0.2276	0	0	0.4300	0.3000	8.9322
BA -PID	0.6668	0.4825	0.2262	0	0	0.3650	0.2629	9.2851

It is observed from Fig. 9. , that the BA-PID controller has better set point tracking compared to PSO-PID controller. From Table 2, it can be stated, that the terminal voltage step response of the AVR system controlled by BA-PID controller has smaller rising time and settling time.

6 Conclusion

This paper introduced a novel approach based on bat algorithm for tuning the PID controller parameters in an AVR system. The obtained results through simulation experiments on a practical high order AVR system shows that the proposed method can perform an efficient search for the optimal tuning of PID controller parameters. Furthermore, the new tuning approach can improve the control system performance in terms of time domain specifications and set point tracking compared with particle swarm optimization base technique.

The efficiency of the presented approach will depend on the selection of the control parameters (loudness and pulse rate), so it will be useful, and as further work, to analyse the effect of dynamic adaptation of theses parameters. This may result in getting more efficient outputs than the achieved ones.

Appendix

Pseudo code of the BA algorithm

```
Procedure of the BA Algorithm
Begin;
Define the objective function of f(x) ,
Generate initial population of bats;
Initialize pulse rate r, loudness A;
Define pulse frequency
While (t<ng)
    Generate new solution using equations (6) to (8)
if (rand> r_i )then
     Select a solution amoung the best solutions
     Generate a solution around the selected best solu-
tion;
end if
  Generate a new solution by flying randomly;
if (rand < A_i )and(f(x_i)< f( x_cgbest )then
Accept the new solutions
end if
    Rank the bats and find the current best;
End while;
   Post process results and visualisation;
End procedure;
```

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