

Design of PIDA Controller Using Bat Algorithm for AVR Power System

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Abstract In this article, a new proportional, integral, derivative, and acceleration (PIDA) controller for an automatic voltage regulator power system is presented. The controller parameters are designed by considering as an optimization with minimization of square error using bat algorithm. The response of the bat algorithm optimized PIDA (BA-PIDA) controller are observed and compared to the controllers in the literature. The superiority is validated in terms of performance indices (ITAE, IAE and ISE).

Keywords Proportional Integral Derivative Acceleration (PIDA), Bat Algorithm, Current Search Algorithm, Genetic Algorithm, Tabu Search

Initially, the design of PIDA controller parameters have been determined using analytical method. In this method two characteristic equations; one formed with desired root locations with specifications based on the design criterion, and another one with the nominal control structure were equated to deduce the parameters of PIDA. It have been considered to design PIDA controller for third order systems and extended for the control of an AC motor system [2]. The application of PIDA were considered for a servo motor driving a load through a long shaft or transmission system in [5]. Sambariya and Paliwal, 2016 have presented the optimal tuning of PIDA controller parameters using harmony search algorithm in [6].

Dal-Young et. al, 2001, highlighted the higher overshoot during the rise time while designed PIDA controller with analytical method. It were mitigated using pre-compensator to PIDA in ac motor control in [7]. The performance of PIDA controller for the third order system have been improved using Kitt's method and extended to discrete system [8, 9]. The design of PIDA for third order systems were presented using an algebraic design approach which also utilized the genetic algorithm (GA) to achieve design optimality in [10].

The recent current search algorithm have been proposed to determine the PIDA parameters for automatic voltage regulator (AVR) system in [4]. It have compared the system response with PIDA controller using genetic algorithm (GA) and tabu search (TS) algorithm and proved to be superior with current search algorithm. In this paper, the PIDA controller parameters are designed using bat algorithm.

The article is organized with five sections. The detail on the problem formulation is given in section 2. The bat algorithm is described in section 3. The response of the AVR system with bat algorithm based PIDA controller is compared to response that of with controllers in [4] in section 4. Finally, the article is concluded in section 5 and followed by references.

1 Introduction

The application of control system in the design of an efficient and economic controller is always a challenge to control engineers. The different controller structures and design methodologies are always the concerns of researchers. The proportional- integral-derivative (PID) controllers are generally preferred controllers in industrial applications [1]. In many cases, the systems are modeled as a third order. In fact, the traditional motion control system such as an Ac motor with position control is properly modeled as a third order plant without crude approximations [2]. The design of PID controllers is not always easy in some cases. It is the reason that a new structure of controller becomes necessity of such systems [3].

In 1996, Jung and Dorf proposed a new structure of controller and termed as proportional- integral-derivative and acceleration (PIDA) controller [2]. It consists of three numbers of zeros and poles but two poles may be neglected in the design process. It is addition of a zero in the standard PID structure to derive the PIDA structure of the controller. The introduction of an extra zero to the PID controller is to change the root locus of the third order plant in order to make dominant roots more dominant by eliminating the effects of non-dominant roots [4].

2 Problem formulation

2.1 AVR System

The application of an automatic voltage regulator (AVR) in the generator excitation system to control the reactive power flow and regulate the generator voltage was presented in [11, 12]. It holds the terminal voltage of a generator at a specified level. It critically affect the security of the power system [3].

The AVR consists of amplifier, exciter, generator, and sensor. A simplified AVR system controlled by the PIDA controller is represented by the block diagram in Fig. 1, where V_e is the error voltage between the reference input voltage $V_{ref}(s)$ and sensor voltage, while V_u , V_r , and V_f are the controlled, amplified, and excited voltage signals, and $V_t(s)$ is the output voltage. The detail on the linearized AVR system is mentioned as following [4]:

2.1.1 Amplifier model

The amplifier model in AVR system is expressed in Eqn. 1. The gain and time constants are presented by K_A and τ_A , respectively. The recommended values of K_A and τ_A are in the range of 10 to 400 and from 0.02 to 0.1 seconds, respectively [13]. The considered values of these parameters is as $K_A = 10$ and $\tau_A = 0.1$ seconds.

$$\frac{V_r(s)}{V_u(s)} = \frac{K_A}{\tau_A s + 1} \quad (1)$$

2.1.2 Exciter model

The exciter model transfer function is presented in Eqn. 2. The range of gain K_E and a time constant τ_e is 1 to 400 and 0.25 to 1.0 seconds, respectively [13, 11]. The selected values of these parameters are $K_E = 1$ and $\tau_e = 0.4$ seconds.

$$\frac{V_f(s)}{V_r(s)} = \frac{K_E}{\tau_e s + 1} \quad (2)$$

2.1.3 Generator model

The transfer function representation of generator model in AVR system is given in Eqn. 3. It consists with a gain K_G and the time constant τ_G . The range may vary between 0.7 to 1.0, and 1.0 to 2.0 seconds, respectively [13]. The considered values are 1 and 1 second, respectively.

$$\frac{V_t(s)}{V_f(s)} = \frac{K_G}{\tau_G s + 1} \quad (3)$$

2.1.4 Sensor model

The sensor model is considered as a simple first-order transfer function as stated in Eqn.4. The gain K_R , and the time constant τ_G in the range from 1 to 10 and 0.001 to 0.06 second, respectively [13]. In this work, $K_R = 1$ and $\tau_G = 0.01$ second are considered.

$$\frac{V_s(s)}{V_t(s)} = \frac{K_R}{\tau_R s + 1} \quad (4)$$

2.2 PIDA Controller

The transfer function representation of the PIDA controller is expressed in Eqn. 5. The terms K_p , K_i , K_d , and K_a in this controller are the proportional, integral, derivative, and accelerated gains, respectively, while d , and e are filter parameters. The transfer function in Eqn. 5, is alternative presented in a polynomial form in Eqn. 6 with the parameters K_p , K_i , K_d , K_a , α , and β , respectively [4].

$$G_c(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{s + d} + \frac{K_a s^2}{(s + d)(s + e)} \quad (5)$$

$$G_c(s) = \frac{K_a s^3 + K_d s^2 + K_p s + K_i}{s^3 + \alpha s^2 + \beta s} \quad (6)$$

2.3 Objective function

In this article, the design of PIDA controller is carried out considering the problem as optimization. The objective function during optimization is considered as in Eqn. 7 with parameter bounds as in Eqn. 8. The optimization is considered with minimization of error signal as in Eqn. 7.

Minimize:

$$J = \int_{t=0}^{T_{sim}} |V_{ref}(t) - V_t(t)|^2 dt \quad (7)$$

Subjected:

$$\begin{aligned} K_a^{\min} &\leq K_a \leq K_a^{\max} \\ K_d^{\min} &\leq K_d \leq K_d^{\max} \\ K_p^{\min} &\leq K_p \leq K_p^{\max} \\ K_i^{\min} &\leq K_i \leq K_i^{\max} \\ \alpha^{\min} &\leq \alpha \leq \alpha^{\max} \\ \beta^{\min} &\leq \beta \leq \beta^{\max} \end{aligned} \quad (8)$$

3 Proposed Bat Algorithms

The bat algorithm is based on the echolocation behaviour of Micro bats [14]. In echolocation, each pulse generated by a micro bat may last only for 8 to 10 milliseconds with a frequency ranging from 25 kHz to 150 kHz, which corresponds to the wavelengths of 2 mm to 14 mm [15]. In BA, the echolocation characteristics of Micro bats can be idealized with the following assumptions.

- It is assumed that the bats are able to detect distance of prey, background obstacles and difference in the available prey/food in the search path in some magical way using echolocation property [16].
- An k^{th} Bat may randomly fly with location as x_k , velocity as v_k , frequency as f_{min} but with varying wavelength as λ_k and loudness of echo as A^0 to search food/prey. The Micro bats have an ability to adjust frequency (wavelength) of the emitted pulses of echo and rate of pulse emission out of $r \in [0, 1]$ according to the distance of their prey/food [17].
- The loudness of the echo pulse should be varied as reducing with decreased distance of the food, i.e. from large A^0 to a minimum value A_{min} (at target/prey location) [18].

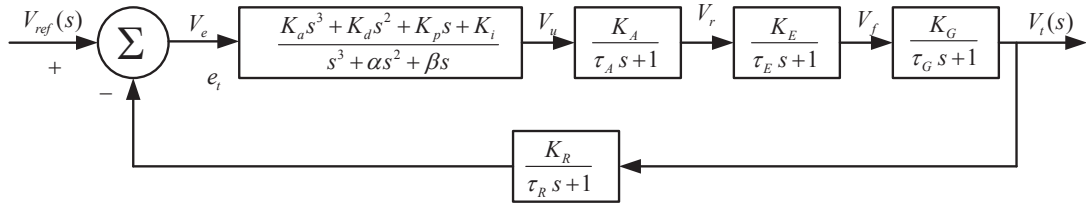


Figure 1. Representation of closed loop AVR system with PIDA controller

3.1 Procedural Steps

Let in an optimization problem; the objective function be represented by Minimization of $F(x)$ which is subjected to $x_k \in X_k, k = 1, 2, 3, \dots, N$ [19].

3.1.1 Initialization

- As an initial step, the bat population is initiated as position and velocity as v_k with $k = 1, 2, 3, \dots, n$.
- Initial pulse frequency is defined as $f_k \in [f_{\min}, f_{\max}]$.
- The pulse rates r_k and the loudness A_k are also set as above
- Check number of iterations or $t < T_{max}$

3.1.2 Generation of new solutions

- New solutions may be generated by adjusting the pulse frequency and keeping wavelength as constant.
- For each bat (k), its position x_k and velocity v_k in a d -dimensional search space should be defined. x_k and v_k should be subsequently updated during the iterations [20, 21]. The new solutions x_k^t and velocities v_k^t at time step t can be calculated by:

$$f_k = f_{\min} + (f_{\max} - f_{\min})\beta \quad (9)$$

$$v_k^t = v_k^{t-1} + (x_k^{t-1} - x')f_k \quad (10)$$

$$x_k^t = x_k^{t-1} + v_k^t \quad (11)$$

where, β is defined for uniform distribution as a vector and selected as $\beta \in [0, 1]$. The x' stands as the best location in search space after comparing solutions of all the n bats [22]. The product of f_k and λ_k represents the velocity increment. The velocity increment can be adjusted by changing one and keeping fixed another according to a problem. The generally used range of frequency is $0 \leq f \leq 100$ and each bat at initialization step is selected from $f = [f_{\min}, f_{\max}]$ [23, 24].

3.1.3 Local Search

Once the best current solution is selected among the available solutions, then a new solution is generated by using local random walk and assigned to each bat as in Eqn. 12. If $\varepsilon \in [-1, 1]$ represents a random number range and $A^t = \langle A_k^t \rangle$ stands for average value of loudness of all initiated n bats at time t .

$$x_{new} = x_{old} + \varepsilon A^t \quad (12)$$

3.1.4 Bat flying and Generation of a new solutions

As the number of iteration increases, the loudness A_k and the rate r_k of pulse emission have to be updated. As a microbat reaches to its target/prey the rate of pulse emission increases while the loudness decreases. The loudness is generally selected from $[A^0, A_{min}] = [1, 0]$. The $A^0 = 1$ represents the maximum loudness of emitted pulse by microbat in search of prey, while $A_{min} = 0$ indicates that the microbat got the target/prey and not emitting any loudness. Thus, the loudness and the rate of pulse emission is updated as.

$$A_k^{t+1} = \alpha A_k^t \quad (13)$$

$$r_k^{t+1} = r_k^0 [1 - e^{-\gamma t}] \quad (14)$$

where, α and γ represent the constant values. Here, α is similar to the cooling factor of a cooling schedule in the simulated annealing [25] and the range of these constants is as $0 < \alpha < 1$ and $0 < \gamma$.

$$A_k^t \rightarrow 0 \quad (15)$$

$$r_k^t \rightarrow r_k^0 \quad (16)$$

To make optimization simpler, the value of α and γ should be selected as same, therefore, in this study $\alpha = \gamma = 0.9$. As in Eqns. 15 - 16, the initial loudness and emission rate may be represented by A_k^0 and r_k^0 , respectively. The value of emission rate at time t can be selected from $r_k^0 \in [0, 1]$.

3.1.5 Checking the stopping criterion

If the maximum count of iterations is reached as a stopping criterion is satisfied, then the process of computation is terminated. Otherwise, go to steps 3 and 4 to repeat the process.

4 Results and discussion

The PIDA controller for AVR system is designed using bat algorithm (BA). The performance of BA and the BA-PIDA controller is designed in the next sections.

4.1 Performance of bat algorithm

The scheme of optimization of PIDA controller using BA with an ISE based objective function is considered and shown in Fig. 3. The initializing parameters for bat algorithm are as mentioned following and the lower and upper bounds for PIDA parameters are considered as in Eqn. 17.

- Population size, typically 10 to 40 and considered as 20

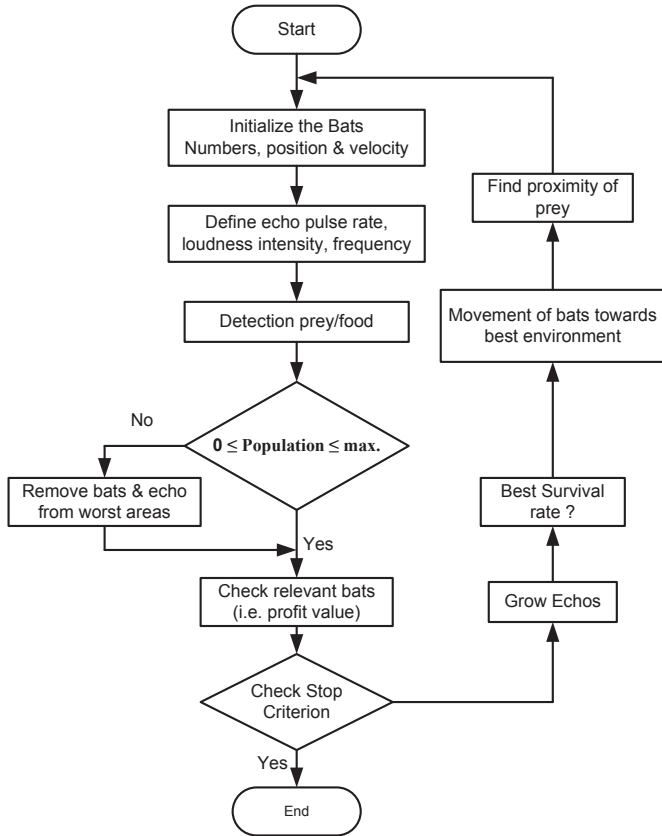


Figure 2. Working of bat Algorithm

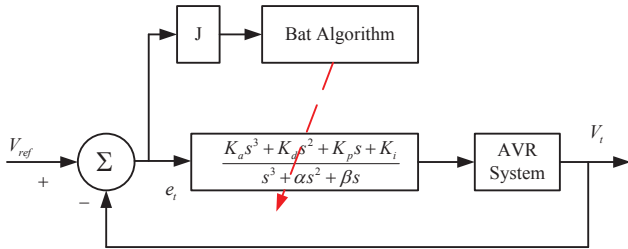


Figure 3. Representation of optimization scheme of the PIDA controller using bat algorithm

- Number of generations selected as 100
- Loudness (constant or decreasing) selected as 0.5
- Pulse rate (constant or decreasing) selected as 0.5
- Frequency minimum selected as 0.01
- Frequency maximum selected as 2
- Number of dimensions selected as 6

$$\begin{aligned}
 50 &\leq K_a \leq 150 \\
 450 &\leq K_d \leq 550 \\
 750 &\leq K_p \leq 850 \\
 350 &\leq K_i \leq 450 \\
 550 &\leq \alpha \leq 650 \\
 900 &\leq \beta \leq 1000
 \end{aligned} \tag{17}$$

The performance of bat algorithm in terms of fitness function and iterations is shown in Fig. 4. The unknown parameters of the PIDA controller are recorded at the end of

Table 2. Comparison of system response in terms of Performance indices

Controller	ITAE	IAE	ISE
PIDA-BA (Proposed)	199.79	19.724	19.585
PIDA-CS [4]	199.97	19.765	19.697
PIDA-GA [4]	199.90	19.743	19.650
PIDA-TS [4]	199.89	19.760	19.680

iteration 100, where, the process of optimization get terminated. These parameters are recorded in Table 1. It also enlist the parameters with genetic algorithm (GA), tabu search (TS) and current search (CS) as reported in [4].

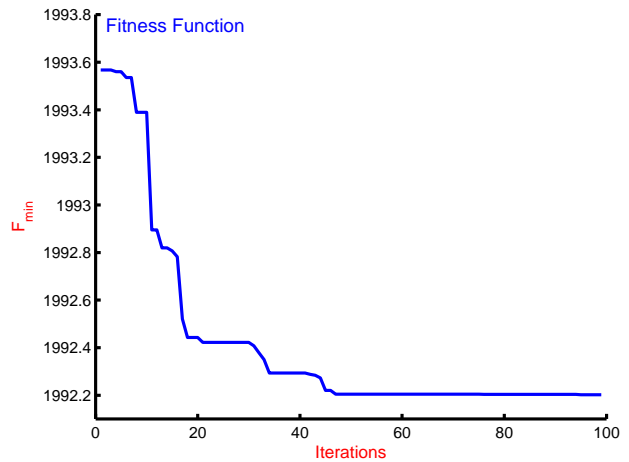


Figure 4. Representation of fitness function using bat algorithm

4.2 Simulation results

The simulation study of the AVR power system is carried out without controller and with PIDA controllers. Initially, the system without controller is simulated and the response is shown in Fig. 5. The AVR system is equipped with PIDA controller with parameters in Table 1. The responses are observed and compared as shown in Fig. 6. It is clear from the figure that the response with proposed BA-PIDA outperforms as presented in [4]. The critical analysis was carried out in terms of performance indices. These performance indices are integral time weighted error (ITAE), integral absolute error (IAE) and integral of squared error (ISE) as defined by Eqn. 18 - Eqn. 20, respectively. The detail on performance indices may be referred as in [26, 27, 28, 1, 29]. The observed performance indices are enlisted in Table 2. The ITAE value with proposed PIDA-BA controller is 199.82 which is lesser as compared to 199.97, 199.90 and 199.89 with controllers in [4]. It means that the proposed PIDA-BA outperforms the PIDA-CS, PIDA-GA and PIDA-TS.

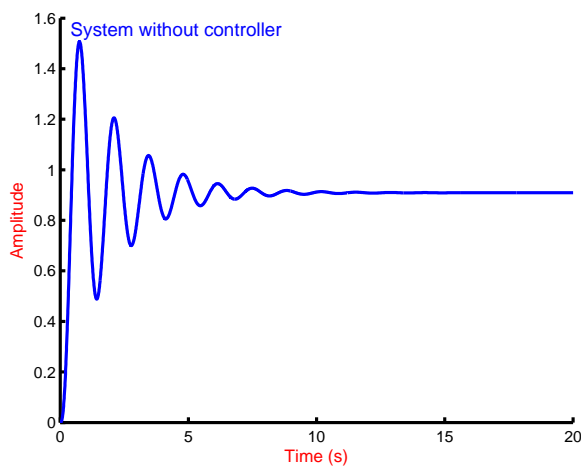
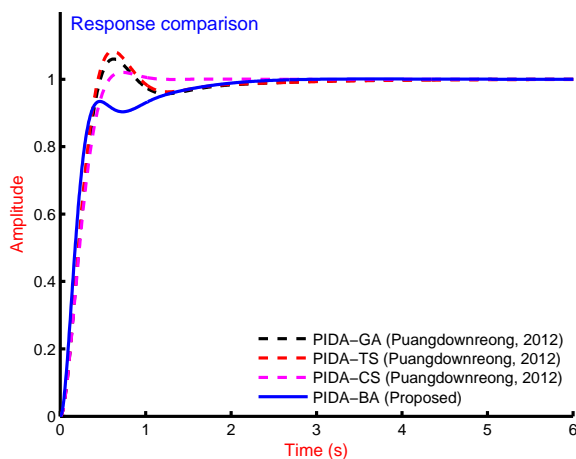
$$ITAE = \int_0^{T_{sim}} t |y_o(t) - y_r(t)| dt \tag{18}$$

$$IAE = \int_0^{T_{sim}} |y_o(t) - y_r(t)| dt \tag{19}$$

Table 1. Comparison of the PIDA parameters

Controller	K_a	K_d	K_p	K_i	α	β
PIDA-BA (Proposed)	149.9821	549.5267	755.1120	350.0000	550.2274	1000.000
PIDA-CS [4]	101.0102	498.9516	799.1201	394.0112	589.5411	965.0501
PIDA-GA [4]	99.1016	577.5625	784.0012	342.1474	592.9654	912.4471
PIDA-TS [4]	102.2365	592.3258	824.8747	341.6321	596.1974	854.1247

$$ISE = \int_0^{T_{sim}} |y_o(t) - y_r(t)|^2 dt \quad (20)$$

**Figure 5.** Step response of the AVR system without controller**Figure 6.** Step response of the AVR system with controllers

5 Conclusion

The optimum PIDA controller is obtained using bat algorithm. The performance of this controller is compared to that of with current search, genetic algorithm and tabu search algorithms and outperforms these. The effectiveness of the proposed BA-PIDA is presented graphically and in terms of performance indices (ITAE, IAE and ISE).

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