Optimal Tuning of PID Controller in Automatic Voltage Regulator System using Improved Harmony Search Algorithm

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Abstract. This paper presents a new tuning approach based on an Improved Harmony Search algorithm (IHSA) to obtain the proportional-integral-derivative (PID) controller parameters in Automatic Voltage Regulator (AVR) system. In the tuning processes the IHSA is iterated to reach the optimal or the near optimal of PID controller parameters when the main goal is to improve the AVR step response characteristics. Conducted simulations show the effectiveness and the efficiency of the proposed approach. Furthermore it can improve the dynamic of the AVR system. The results analysis reveals that the new approach is able to find better control system performances compared with that of the particle swarm optimization (PSO).

Keywords: Automatic Voltage Regulator (AVR); Improved Harmony Search algorithm (IHSA); PID controller; Power System Security

1. INTRODUCTION

In modern secure power system, damping of generator terminal voltage oscillation following disturbances is of great concern because it can seriously affect the security of the entire power system. 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 (AVR) [1]. Hence, with the advancement in the design of fast acting AVR's as well as the increasing complexity of large interconnected power systems, oscillations may continue for an extended period and even instability may occur following some system disturbances.

Despite the potential of the modern control techniques with different structure, Proportional Integral Derivative (PID) type controller is still widely used for AVR system [2]. Industrial implementations of PID controllers in AVR systems show that the appropriate selection of PID controller parameters results in satisfactory performance during system upsets. Thus, the optimal tuning of a PID gains is required to get the desired level of robust performance. Since 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.

Recently, metaheuristic approaches, have received increased attention from researchers dealing with AVR's control problems. In 2004, a PSO based PID type controller for AVR system was presented By Giang [3] to find the optimal parameters of the PID controller so that the desired system specifications are satisfied. 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 (GA) [5]. Ching-Chang suggested a real-valued genetic algorithm (RGA) and a particle swarm optimization (PSO) to design PID controller for AVR system [6].

More recently, Shayeghi and Dadashpour presented an anarchic society optimization based PID control of an Automatic voltage regulator system [7]. In this paper, an efficient tuning approach is proposed to find the optimal PID parameters, and a practical high order AVR system with a PID controller is adopted to investigate the performance of the proposed IHSA-PID controller.

The approach is based on one of the recent stochastic optimization algorithms which imitate the music improvisation process, namely the harmony search algorithm. The idea of employing the music improvisation process to solve optimization problems was introduced by GEEM ZW et al in [8,9] it has developed rapidly and has shown significant potential in solving various hard optimisation problems. Such as pipe- network design [10], structural optimization [11], combined heat and power economic dispatch problem [12], scheduling of multiple dam system [13], and clustering of text document [14]. Recently, Mahdavi et al. proposed an improved harmony search [15] that employs a novel method generating new solution vectors with enhanced accuracy and convergence speed.

The paper is organised as follows. Section II presents the linearized model of an AVR system with PID controller. In section III we describe the basics of the IHSA. The proposed IHSA-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 derivative controller adds a finite zero to the open-loop plant transfer function and improves the transient response. The integral controller adds a pole at the origin and increases the system order by one and reduces the steady-state error due to a step function to zero. The PID controller transfer function is done by:

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

2.2 Linearized model of an AVR

The terminal voltage is kept constant in a synchronous generator, at various levels by using an AVR. The AVR system contained of four major parts, namely amplifier, exciter, generator and sensor. Thus, the real model of such system is depicted in Figure. 1 [1].

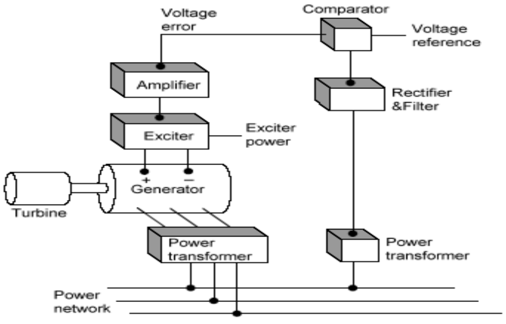


FIGURE.1 Real model of an AVR system [1]

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].

- Amplifier Model

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

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

- 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.

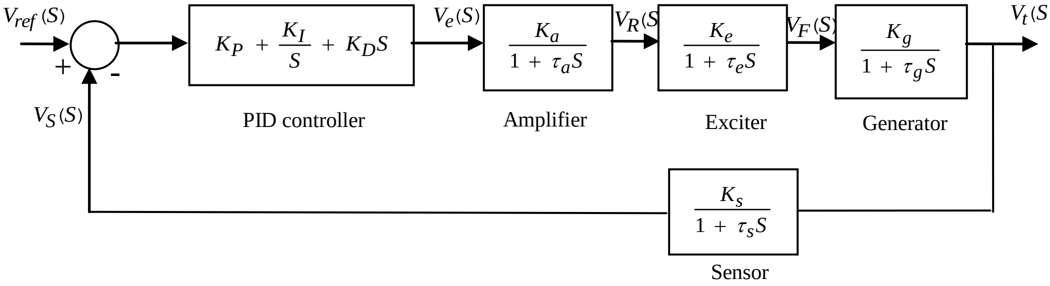


FIGURE 2. Block diagram of an AVR system

3. BASICS OF HARMONY SEARCH ALGORITHM

Harmony Search Algorithm (HSA) is a recently developed stochastic algorithm [8]. In fact, it has been developed in an analogy with music improvisation process where musicians in an ensemble continue to polish their pitches in order to obtain better harmony. In this process, the musicians seek to reach the perfect state of harmony similar to the optimum design process which seeks to achieve optimum solution. The pitch of each musical instrument determines the aesthetic quality, just as the objective function value is determined by the set of values assigned to each decision variable [8]. The standard HSA consists of the following five steps [8,9]:

Step 1 : Initialization of the optimization problem and algorithm parameters.

In this step, the optimization problem is specified as follows:

$$\begin{cases} Min\ (or\ Max)\ f(\vec{x}) \\ S.T\ : x_i^L \le X_i \le x_i^U \end{cases}, \ i = 1, \ldots, N \tag{6}$$

Where $f(.)$ is a scalar objective function to be optimized; $\vec{x}$ is a solution vector composed of continuous decision variables x_i; X_i is the set of possible range of values for each decision variable x_i, where x_i^L and x_i^U are the lower and upper bounds for each decision variable respectively, and N is the number of decision variables. In addition, the control parameters of HSA are also specified in this step. These parameters are the Harmony Memory Size (HMS) i.e. the number of solution vectors (population members) in the harmony memory (in each generation); Harmony Memory Considering Rate (HMCR); Pitch Adjusting Rate (PAR); and the Number of Improvisations (NI) or stopping criterion.

Step 2 : Harmony memory initialization.

In the second step each component of each vector in the parental Harmony Memory, which is of size HMS, is initialized with a uniformly distributed random number between the upper and lower bounds. This is done for the i-th component of the j-th solution vector using the following equation:

$$x_i^j = x_i^L + rand(0,1)\ .\ (x_i^U - x_i^L) \tag{7}$$

Where, $j = 1, \ldots, HMS$ and $rand(0,1)$ is a uniformly distributed random number between 0 and 1 and it is instantiated a new for each component of each vector.

Step 3 : New Harmony improvisation.

In this step, a new harmony vector $\bar{x}^{new} = \left(x_1^{new}, x_2^{new}, \ldots, x_N^{new}\right)$ is generated (or improvised) based on three rules: (1) memory consideration, (2) pitch adjustment, and (3) random selection. In the memory consideration, the value of the first decision variable x_1^{new} for the new vector is chosen from any of the values already existing in the current HM with a probability $HMCR$. Values of the other decision variables $\left(x_2^{new}, \ldots, x_N^{new}\right)$ are also chosen in the same manner. The $HMCR$, which varies between 0 and 1, is the rate of choosing one value from the previous values stored in the HM, while $(1 - HMCR)$ is the rate of randomly selecting a fresh value from the possible range of values. The improvisation operation is done by:

$$x_1^{new} = \begin{cases} x_i \in \left(x_i^1, x_i^2, \ldots, x_i^{HMS}\right) \\ \quad (\ with\ probability\ HMCR) \\ x_i \in X_i \\ \quad (with\ probability\ (1 - HMCR)) \end{cases} \tag{9}$$

Every component obtained by the memory consideration is further examined to determine whether it should be pitch-adjusted. This operation uses the parameter PAR (the rate of pitch adjustment) as follows:

$$x_1^{new} = \begin{cases} x_1^{new} \mp rand(0,1)\ .bw \\ (with\ probability\ PAR) \\ x_1^{new} \\ (with\ probability\ (1 - PAR)) \end{cases} \tag{10}$$

here bw is an arbitrary distance bandwidth (a scalar number) and $rand(0,1)$ is a uniformly distributed random number between 0 and 1.

Step 4 : Harmony memory update.

If the new harmony vector $\left(x_1^{new}, x_2^{new}, \ldots, x_N^{new}\right)$ is better than the worst harmony in the HM, judged in terms of the objective function value, then the new harmony is included in the HM and the existing worst harmony is excluded from the HM. This is actually the selection step of the algorithm where the objective function value is evaluated to determine if the new variation should be included in the population (Harmony Memory).

Step 5 : Check stopping criterion

If the stopping criterion (maximum number of improvisations) is satisfied, computation is terminated. Otherwise, steps 3 and 4 are repeated.

The main drawback of this method is that the number of iterations increases to find an optimal solution; this is due to the fixed values of the pitch adjustment rate and bandwidth at the beginning step. To improve the performance of the HSA and eliminate the drawbacks lies with fixed values of PAR and bw, M. Mahdavi [15] proposed a new variant of the HSA that is named under Improved Harmony Search algorithm (IHSA). Their proposed algorithm includes dynamic adaptation for both pitch adjustment rate (PAR) and bandwidth (bw) values. The PAR value is linearly increased over iteration of harmony search by using the following equation:

$$PAR(gn) = PAR_{MIN} + \frac{\left(PAR_{\max} - PAR_{\min}\right)}{NI} * gn \qquad (11)$$

Where $PAR(gn)$ is the PAR value for each generation, $PAR_{\min}$ and $PAR_{\max}$, are the minimum pitch adjusting rate and maximum pitch adjusting rate respectively. NI is the maximum number of iterations (improvisation) and gn is the generation number.

The bandwidth bw value is exponentially decreased in each iteration of harmony search by using the following equation:

$$bw(gn) = bw_{\max}.\exp(gn.c) \qquad (12)$$

With $c = \left[\ln\left({bw_{\min}} / {bw_{\max}} \right) / NI \right]$

4. IMPLEMENTATION IHSA-PID CONTROLLER

In this paper, a PID controller using improved harmony search algorithm was proposed to improve the dynamic of an AVR system. The block diagram of a practical AVR system using IHSA -PID is shown in Figure.3

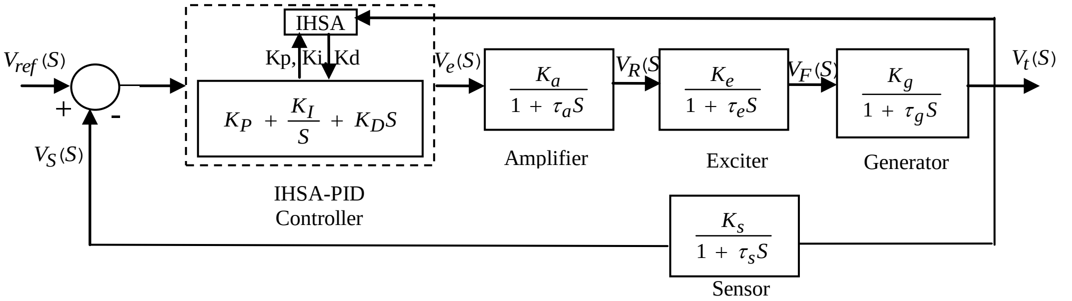


FIGURE 3. Block diagram of an AVR system with IHSA-PID controller.

To improve the step transient response of an AVR system, the main goal of the proposed IHSA-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 (objective function) can be formed by different performance specifications such as the integral of time multiplied by absolute-error value (ITAE), rise time, settling time, overshoot and steady state error. In this paper and for the purpose of comparison, the following performance function is used [6]:

$$F(K) = ITAE.\begin{pmatrix} (1 - e^{-\rho}) \,.\, (M_p + E_{ss}) + \\ e^{-\rho} \,.\, (T_s - T_r) \end{pmatrix} \qquad (13)$$

Where $K = \left[K_P, K_I, K_D\right]$ 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.

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 IHSA control parameters. The best obtained ones are presented in Table.1

TABLE 1. IHSA parameters values

Parameter	value
HMS	6
$HMCR$	0.95
$PAR_{\min}$	1
$PAR_{\max}$	0.95
$bw_{\min}$	0.0001
$bw_{\max}$	0.9

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: $0.0 \le K_P \le 1.5, 0.0 \le K_I, K_D \le 1.0$

In this section, we represent the terminal voltage of the AVR system with and without IHSA -PID controller at first. In second, to emphasize the advantage of the proposed IHSA -PID method in terms of performance, we have compared the results with the PSO-PID literature existing approach [6] for two different values of the fitness weighting factor.

5.1 AVR TERMINAL VOLTAGE STEP RESPONSE

The terminal voltage step response of the AVR system without IHSA -PID is shown in Figure.4 In this case; the system presents an undesirable oscillatory behaviour. For two fitness weighting factor, the best solutions of the AVR system with IHSA-PID are summarized in Table.2, and the corresponding step responses are shown in Figure.5

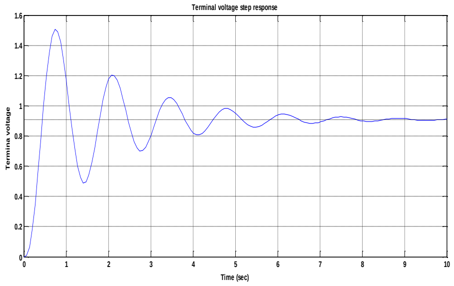
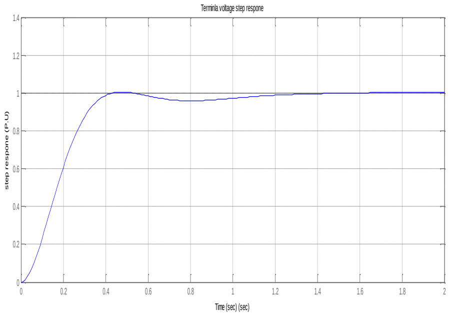


FIGURE.4 Terminal Voltage step response of AVR system without PID controller

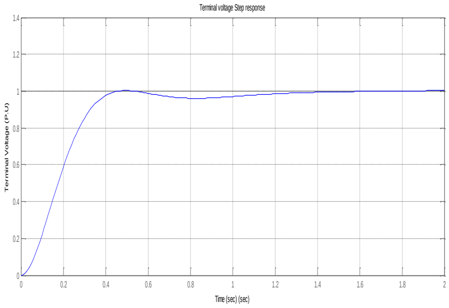
The curves indicate clearly that the system response is greatly improved by introducing the IHSA –PID

TABLE 2. Best solutions using IHSA-PID controller with different ρ

ρ	K_P	K_I	K_D	$Mp\%$	E_{ss}	t_s	t_r	$F^{-1}(k)$
1.0	0.6739	0.5076	0.2699	0	0.0054	0.3582	0.2578	5.9916
1.5	0.6636	0.4806	0.2575	0	0.0027	0.3701	0.2666	9.3110

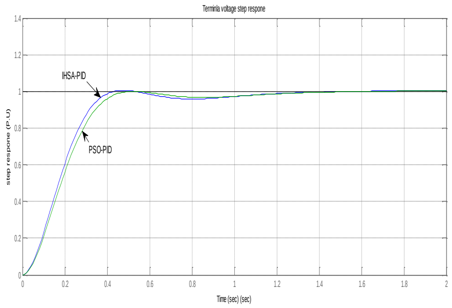


(a) $\rho = 1.0$

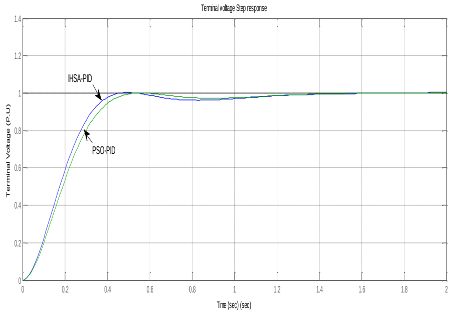


(b) $\rho = 1.5$

FIGURE.5 Terminal Voltage step response of AVR system with IHSA-PID controller



(a) $\rho = 1.0$



(b) $\rho = 1.5$

FIGURE.6 Terminal Voltage step response of AVR system with IHSA-PID and PSO-PID controllers

5.2 Comparison with PSO-PID Controller

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 controller and IHSA -PID controller are shown in Fig.6. The controller parameters and performance indices in the time domain are listed in Table.3.

It is observed from Figure.6 that the IHSA -PID controller has better set point tracking compared to PSO-PID controller. From Table.3, it can be stated, that the terminal voltage step response of the AVR system controlled by IHSA-PID controller has smaller rising time and settling time for both weighting factor.

TABLE 3. Best solutions using CFA-PID and PSO-PID controllers with different ρ

ρ	**Type of controller**	K_P	K_I	K_D	$Mp\%$	E_{ss}	t_s	t_r	$\frac{1}{F(k)}$
1	PSO-PID [6]	0.6443	0.4700	0.2423	0	0	0.4000	0.2800	5.3882
	IHSA -PID	0.6739	0.5076	0.2699	0	0.0054	0.3582	0.2578	5.9916
1.5	PSO-PID [6]	0.6300	0.4538	0.2276	0	0	0.4300	0.3000	8.9322
	IHSA -PID	0.6636	0.4806	0.2575	0	0.0027	0.3701	0.2666	9.3110

6. CONCLUSION

This paper introduced a novel approach based on IHSA for tuning the PID controller parameters in an AVR system. In the tuning process, the IHSA is iterated to reach the optimal parameters of the PID controllers based on a predetermined fitness function. 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 speicfications and setpoint tracking when compared with particle swarm optimization method. Finally, we suggest as future work to analyze the performance of the proposed approach in obtaining the optimal values of PID controller parameters under various load conditions.

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