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Research article

A new control design strategy for automatic voltage regulator in power system

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ABSTRACT

This paper presents a new design technique to determine the optimal values of proportional–integral–derivative controller gains of an automatic voltage regulator, using the evolutionary algorithm namely ‘Cuckoo Search’. The dynamic performance of the proposed controller is evaluated by estimating its transient response characteristics, such as, rise time, settling time, maximum peak overshoot, and steady-state error. In addition, a thorough comparison of the time response characteristics, obtained with proposed controller and other existing evolutionary algorithm based controllers is made to demonstrate its external attributes and adeptness. Comparative analysis illustrates that the proposed controller can be considered as a significant device in the subject area of the power systems as it offers, more energy efficient, robust, and fast convergence characteristics than the controllers, considered here for the discussions. Furthermore, robustness of proposed controller has also been investigated by allowing 50% uncertainty in the automatic voltage regulator system. Finally, the stability of an automatic voltage regulator system with proposed controller is investigated through root-locus and bode plots. It is revealed that the proposed controller not only capable to provide good dynamic response, but also exhibits stable performance for wide range of open loop gains.

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1. Introduction

Nowadays, PID controller is being successfully implemented for the designing of efficient, stable, and robust controller of the automatic voltage regulator (AVR) due to their exceptional performance in wide range of operating conditions and easy implementations [1–8]. Typically, the AVR plays vital role in power system operation and control to retain the terminal voltages of an alternator at specified level even at the varying load conditions. Also, it plays pivotal role in monitoring the reactive power sharing between the parallel connected generators [9,10]. The working of AVR should be so proficient that the precise control over reactive power, reduction in active power loss, and fixed terminal voltages of the alternator could be achieved to avoid any mal-functioning or tripping of the equipment connected to the alternator.

Unfortunately, the presence of large inductance in the field winding and frequent change in the load demand degrade its dynamic performance and stability [10]. As a result, the use of PID controller in the AVR loop has been recommended to improve its dynamic performance, robustness, and stability. [6–8].

It is noteworthy that, the desired step response of an AVR system, with PID controller in the loop, depends essentially on the accurate tuning of the controller gains, such as, proportional (K_P), integral (K_I), and derivative (K_D) [11–15]. Hence, the precision of control and preferred step response characteristics of AVR can be realized by appropriate tuning of controller gains [11,12]. Nevertheless, high order, time delays, and nonlinear characteristics of power systems make difficult to tune controller gains, appropriately [13–15]. Therefore, the need of proper tuning techniques to obtain optimal gain parameters of the PID controller has received utmost attention by the researchers and industrial engineers.

Myriad of tuning techniques were reported in the research in order to acquire optimal values of controller gains. The first tuning technique was developed by Ziegler and Nichols [1]. Though, being most celebrated tuning rules and working quite well with wide range of industrial control process, determination of optimal or near optimal PID parameters is found harder with this tuning technique [16]. The other limitations of this tuning technique were explained in [2,17], also. These limitations result in retuning of the controller parameters before application to real application [2,5,16,17]. Subsequently, several others analytical tuning techniques, viz., model matching approach [8], frequency domain design method [18], internal model control [19], direct synthesis design [20], gain/phase-margin based design [21], etc., were suggested. However, these techniques give better performance under

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wide range of operating conditions but found computationally complex and time consuming [22,23]. Also, these tuning techniques were found inapt to provide good dynamic performance because of intricacy in power systems, such as, high level of non-linearities and stochastic behaviour [5,22,23].

Afterwards, evolutionary algorithm (EA) based PID controllers of AVR, such as, genetic algorithm (GA)-PID, hybrid GA-PID [6, 14], particle swarm optimization (PSO)-PID [6,13,22], chaotic ant swarm (CAS)-PID [7], ant bee colony (ABC)-PID [23], differential evolution (DE)-PID [23], etc., were recommended to overcome the limitations of classical PID controllers. Also, the performance of the various EA based PID controllers of AVR were compared with each other to reveal the most proficient PID controllers of the AVR system due to better computational efficiency and fast convergence [10–15]. In these aforementioned studies, EA based PID controllers of AVR were recommended as the best tools to handle with the systems, comprising with the complexities, in terms of high order, time delays and nonlinearities. Though, these numbers and the varieties of EA based tuning techniques have great potential to solve many optimization problems, none of them capable to reduce peak overshoot to zero. The other limitations of these EA based PID controllers of AVR, as discussed in several researches, can be highlighted in the following points [7,10,24–26]:

- (i) Premature and slow speed convergence usually degrades the performance and reduces the search capability of GA-PID controller.
- (ii) The use of three algorithm control parameters, such as, crossover value, the scale factor, and the size of population in DE reduces its search capability. The CAS algorithm has the same limitation.
- (iii) The success of PSO-PID controller is directly dependent on the PSO parameters, such as, the initial values of the control parameters, the size of swarm value, and the maximum iteration number. Dependency on large number of algorithm control parameters reduces its search capability and computational efficiency. Further, it is expensive to design PSO-PID controller of AVR system.
- (iv) The use of large numbers of objective function calculations and sequential processing in ABC algorithm reduces its computational efficiency.

Therefore, in line with the existing researches [6,8,10–15,22], in this paper an attempt has been made to design a new robust PID controller of AVR system which could provide more improved dynamic response without the loss of stability. Here, CS algorithm has been used to obtain optimal gains for PID controller of AVR. It is shown through comparative analysis of the results of the proposed controller, namely, CS-PID and existing controllers, such as PSO/GA/CAS-PID that, the proposed one offers exceptional dynamic performance with reduced computational efficiency. In addition, the use of CS algorithm, in optimization of PID controller gains offers the following advantages [26–28]:

- (i) The CS algorithm uses only one control parameter, i.e., the probability value, which is to be tuned to get optimal values of PID controller gains. Therefore, provides better computational efficiency and fast convergence.
- (ii) The success rate of finding global maxima in CS is 100%. Therefore, CS algorithm offers better tuning capability.
- (iii) Randomization is more efficient with CS Algorithm due to heavy tailed.

In addition, the robustness of CS-PID controller of AVR system has also been investigated by considering uncertainty in AVR system. It is shown that the CS-PID controller provides better result

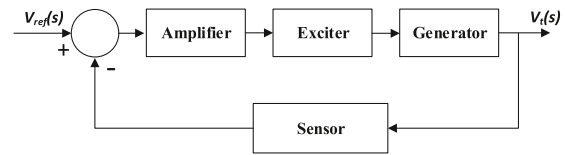


Fig. 1. Block diagram of AVR system.

Table 1

Transfer functions, gains and time constants of AVR system.

Components	Transfer function	Gain	Time constant
Amplifier	$G_a(s) = \frac{K_a}{1 + \tau_a s}$	$10 \leq K_a \leq 400$	$0.5 \text{ s} \leq \tau_a \leq 1 \text{ s}$
Exciter	$G_e(s) = \frac{K_e}{1 + \tau_e s}$	$0.5 \leq K_e \leq 10$	$0.3 \text{ s} \leq \tau_e \leq 1 \text{ s}$
Generator	$G_g(s) = \frac{K_g}{1 + \tau_g s}$	$0.7 \leq K_g \leq 1$	$1 \text{ s} \leq \tau_g \leq 2 \text{ s}$
Sensor	$H_f(s) = \frac{K_f}{1 + \tau_f s}$	$K_f \approx 1$	$0.001 \text{ s} \leq \tau_f \leq 0.06 \text{ s}$

under the condition of uncertainty, also. Finally, the stability of CS-PID controller has been evaluated through root locus and frequency response plots. It is revealed that the proposed controller offers better dynamic performance without loss of stability.

This paper is organized in six sections. Section 1 comprises introduction and the detailed literature review. Section 2 covers the description of AVR model and PID controller and in Section 3, the overview of proposed controller is explained in detail. The performance evaluation of the controller is given in Section 4. The stability analysis of AVR system is discussed in Section 5. Section 6 comprises the discussion and conclusion of the present work.

2. AVR model and PID controller

2.1. AVR model

Nowadays, widespread use of voltage sensitive equipment, such as, programmable logic controller, power electronics based equipment, adjustable speed drives, computer, LED lamps, etc., makes the voltage variations as one of the most pressing concern. These equipment are very subtle to the voltage variations and hence either mal-function or might be tripped due to slight changes in the voltages arising due to frequent change in load demands or faults in power systems [29]. Therefore, to reduce the cost of downtimes associated with these voltage variations, proper balance between the energy demand and generation and subsequently retaining of fixed terminal voltage at the alternator terminals have now become vital urgency of power system operation and control [9]. To accomplish this task the alternators are often connected with AVR. The AVR system is composed of four main components, namely, amplifier, exciter, generator, and the sensor, as shown in Fig. 1 [9]. In Fig. 1, $V_{ref}(t)$ and $V_t(t)$ represent reference and terminal voltage of AVR system, respectively. The transfer function of each component of AVR and their corresponding gain and time constant limits, as given in various researches [6–15], are summarized in Table 1.

The role of sensor, as shown in Fig. 1, is to sense terminal voltage variations, existing either due to change in load demand or power system faults, and feedback the same to the comparator after being rectified. This feedback signal is first compared with reference signal at the comparator to generate error signal and then amplified and given to the exciter. The major role in complete loop is played by the exciter which control the field current in such a way that the error is reduced to zero. Finally, the output of the exciter is given to alternator to achieve constant terminal voltages.

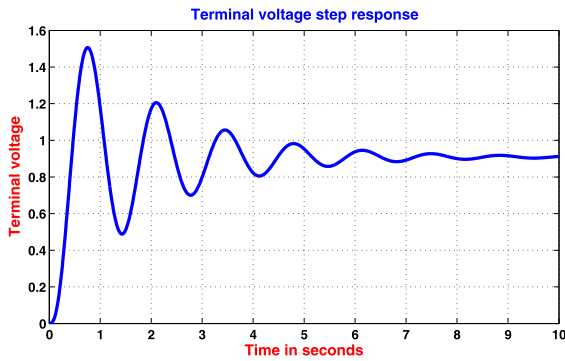


Fig. 2. Step response of AVR system.

The open and closed loop transfer functions of AVR model, i.e., $G_{OL}(s)$ and $G_{CL}(s)$, are determined as (1) and (2), respectively. Later, these two transfer functions are used, in this paper, to investigate the stability and dynamic performance of the AVR system.

$$G_{OL}(s) = \frac{K_T}{(1 + \tau_a s)(1 + \tau_e s)(1 + \tau_g s)} \quad (1)$$

$$G_{CL}(s) = \frac{K_T(1 + \tau_f s)}{(1 + \tau_a s)(1 + \tau_e s)(1 + \tau_g s) + K_T K_f} \quad (2)$$

where K_T is open loop gain of AVR and is given as

$$K_T = K_a K_e K_g \quad (3)$$

2.2. PID controller

The dynamic performance of the AVR system is evaluated by estimating its step response, using (2), and is shown in Fig. 2. The gains and time constants of the various components of AVR system, to obtain this step response, are considered as [6]: $K_a = 10$; $\tau_a = 0.1$ s; $K_e = 1$; $\tau_e = 0.4$ s; $K_g = 1$; $\tau_g = 1$ s; $K_f = 1$ and $\tau_f = 0.01$ s.

It is obvious from the time response characteristics of the AVR systems, as shown in Fig. 2, the values of maximum peak overshoot (M_p) and settling time (t_s) are very large and obtained as 50.61% and 6.9865 s, respectively [6]. Further, it is noticeable that in the steady state condition, the system terminal voltage deviates from the nominal value by more than 9%. In power system, such type of response is completely undesirable, as the sophisticated equipment connected to the power system are highly sensitive to voltage variations and either starts mal-function or may trip when voltage variations retain for more than a second. Further, such amount of large overshoot in power system networks may force the system in the verge of instability. Therefore, the settling time less than a second and overshoot nearly equal to zero are highly expected to reduce the cost of downtimes associated with equipment trip, specially, due to voltage sag [30].

Reduction and elimination of steady state error can be achieved through the addition of pole at the origin whereas improvement in dynamic response can be obtained by addition of zero in open loop transfer function. These requirements of the addition of poles and zeros result in the amalgamation of PID controller in AVR loop [6,10]. PID controller is composed with three control parameters or gains, i.e., K_p , K_i and K_d . The open loop transfer function of linear model of the PID controller is often given as [6]:

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d s \quad (4)$$

The gains, namely, K_p , K_i and K_d , of the PID controller play very important role to decide its dynamic performance. The functionalities of these gains can be summarized in the following points [2–8]:

- (i) The proportional gain, K_p , reduces the rise time of step response.
- (ii) The integral gain, K_i , reduces the value of steady state error by adding a pole at the origin.
- (iii) The derivative gain, K_d , increases the stability of the systems by adding a zero in open loop transfer functions of the AVR system.

Hence, in order to get robust, stable, efficient, and good dynamic response of the AVR system, the optimal values (i.e., neither high nor low) of these gains are inevitable. For example, the high value of K_p makes system unstable whereas its low value results in less sensitive controller. Likewise, high value of K_i makes overshoot large whereas its low value makes the system sluggish. Similarly, the high and low values of K_d result in unstable system and poor dynamic performance [5], respectively. In summarily, a proper tuning technique, to obtain optimal values of these gains, is significant to achieve efficient and stable performance of the system.

3. Cuckoo search (CS) algorithm and proposed CS-PID controller of AVR

3.1. Cuckoo search algorithm

Some species of cuckoo birds, such as, ‘Ani’ and ‘Guira’, often lay their eggs in communal nests and generally throw others eggs to increase the hatching probability of their own eggs. The cuckoo search (CS) algorithm, population based optimization technique, is inspired from this breeding behaviour of cuckoo birds. Normally, this brood parasitic behaviour of cuckoo birds combines with the Lévy flight behaviour of fruit flies to enhance search capability of CS algorithm [28]. In order to simplify the optimization problem, CS algorithm uses following three rules [27,28]:

- (i) It is assumed that the cuckoo lays one egg once only and keeps it safely in the communal nest.
- (ii) The nest, consisting high quality eggs, is considered as the best nests to carry forward for the next generation.
- (iii) Eggs, lay by cuckoo bird, are discovered from fixed host nests with a probability $p_a \in [0, 1]$.

Further, the general system-equation, used in optimization when generating new solutions $Y_i^{(t+1)}$ for a cuckoo i , a Lévy flight is performed using the following equation: [27,28,31,32].

$$Y_i^{(t+1)} = Y_i^{(t)} + a \otimes \text{Lévy}(\lambda) \quad (5)$$

where $a(a > 0)$ is a step size which is related to the level of the problems which is to be optimized, \otimes indicates entry-wise multiplications, and ‘ t ’ represents the number of the current generation. Lévy flight is described as random walk trajectories which are composed of self-similar jumps and given as [26–28]:

$$\text{Lévy } \tilde{u} = t^{-\lambda}; \quad (1 < \lambda \leq 3) \quad (6)$$

Here, λ represents Lévy distribution parameter [26–28,33]. Finally, the three rules, as discussed above, (5) and (6) have been used to define the “pseudo code” of CS algorithm, as shown in Fig. 3 [26], and further this code has been used to optimize the given problem.

Details about the terminologies used in CS algorithm have been properly explained in [26–28,34]. Here, three rules, “Lévy flight trajectory, i.e., (6)”, “random walk algorithm, i.e., (5)”, and “pseudo code” are discussed in brief for the better understanding of the proposed controller design. Furthermore, there are various fields in which this algorithm perform well including steel structure design [35], structural optimization problem [36], applications to business optimization [37], model order reduction [34, 38,39] etc.

```

begin
Objective function  $Z(x), x = (x_1, x_2, \dots, x_d)^T$ ;
Generate Initial population of  $n$  host nests  $x_i (i = 1, 2, \dots, n)$ ;
while( $t < \text{Maximum Generation}$ ) or ( $\text{stop criterion}$ );
    Get a cuckoo (say  $\alpha$ ) randomly
    and generate a new solution by Le'vy flights;
    Evaluate its quality / fitness  $Z_\alpha$ ;
    Choose a nest among  $n$  (say  $\beta$ ) randomly;
        if ( $Z_\alpha > Z_\beta$ ),
            Re place  $\beta$  by the new solution;
        end
    Abandon a fraction ( $P_a$ ) of worse nests
    [and build new ones at new location via Le'vy flights];
    Keep the best solutions (or nests with quality solutions);
    Rank the solutions and find the current best;
end while
Post process results and visualization;
end
    
```

Fig. 3. Pseudo code of CS algorithm.

3.2. Performance indices

It is noteworthy that, the optimal values of controller gains are dependent on suitable selection of objective function, also [6]. Generally, four different objective functions, namely, integral of time multiplied by absolute value of error (ITAE), integral of absolute value of error (IAE), integral of time multiplied by squared error (ITSE) and integral of squared error (ISE) were considered for optimization to get optimal values of gains [22,23]. Though, these objective functions provide good performance but suffers from several limitations [6]. For example, minimization of IAE and ISE results in enhancement of settling time whereas minimization of ITSE makes tuning process complex and time consuming [6]. In order to resolve these issues, new objective functions, as given by (7) and (8), were defined to improve the step response of the PID controllers of AVR system [6,7].

$$Z_1 = (1 - e^{-\gamma}).(M_p + e_{ss}) + e^{-\gamma}(t_s - t_r) \quad (7)$$

where, γ is the weighting factor such that $0.8 < \gamma < 1.5$. M_p , e_{ss} , t_s and t_r denotes maximum overshoot, steady state error, rise time and settling time, respectively.

$$Z_2 = (1 - \rho) \int_0^\infty t |V_{ref}(t) - V_t(t)| dt + \rho M_p \quad (8)$$

where ρ is the weighting factor ranging from 0 to 1.

Therefore, this paper considers the same objective functions, as defined in [6,7], to investigate the step response and stability of the proposed CS-PID controller of AVR system. The block diagram of the CS-PID controller of AVR is shown in Fig. 4 and the steps used for the design of CS-PID controller of AVR are discussed in Section 3.3.

3.3. Steps used for designing the proposed controller

The following steps are used in this paper to design proposed CS-PID controller:

- (1) Specify objective function and the parameter of CS i.e. the probability of the worst nest p_a .

Table 2
Gains and time constant of AVR systems.

Gain		Time constant	
AVR1	AVR2	AVR1	AVR2
$K_a = 10$	$K_a = 12$	$\tau_a = 0.1$	$\tau_a = 0.09$
$K_e = 1$	$K_e = 10$	$\tau_e = 0.4$	$\tau_e = 0.5$
$K_g = 1$	$K_g = 0.1$	$\tau_g = 1$	$\tau_g = 1.1$
$K_f = 1$	$K_f = 1$	$\tau_f = 0.01$	$\tau_f = 0.02$

- (2) Initialization of a population of p host nests then the problem is summarized as:

Minimize objectivefunction Z ,
subject to,

$$\begin{aligned}
 &K_{PL} < K_P < K_{PU}, \\
 &K_{IL} < K_I < K_{IU}, \\
 &K_{DL} < K_D < K_{DU}.
 \end{aligned}$$

where, K_{PL}, K_{IL}, K_{DL} and K_{PU}, K_{IU}, K_{DU} are the lowest and highest values of the chosen variables of the controller parameters respectively.

- (3) Obtain the value of Z_α for a randomly selected cuckoo (α). Select a nest (β) randomly among p and obtain the corresponding value of Z_β .
- (4) if ($Z_\alpha > Z_\beta$) then interchange β by the current obtained solution i.e. α .
- (5) Abandon a fraction of worse nests with optimal value of probability p_a and step size a .
- (6) The obtained solution must be updated by calculating $Y_i^{(t+1)}$, as given in Eq. (5) and repeat this algorithm, until the predefined condition is arrived or the maximum generation occurred.

4. Performance evaluation

In this section the dynamic performance of the CS-PID controller of AVR has been investigated. In [6], the performance of PSO-PID controller has been investigated with performance index Z_1 and AVR1. Similarly, in [7], the performance CAS-PID controller has been investigated with performance index Z_2 and AVR2. The better performance of PSO-PID than GA-PID has been revealed in [6] whereas CAS-PID has been investigated as better than GA in [7]. Therefore, in this paper, firstly, the performance of proposed CS-PID controller is investigated with Z_1 /AVR1 and Z_2 /AVR2. Then, the results of CS-PID with Z_1 /AVR1 are compared with PSO/GA-PID controllers whereas the results of CS-PID with Z_2 /AVR2 are compared with CAS/GA-PID. The gains and time constants of AVR1 and AVR2, as given in [6,7], are summarized in Table 2

Further, the parameters of the CS algorithm and range of search space for the controller gains, as used in this paper for simulation, are considered as:

- (i) number of nests (or different solutions) $n = 25$,
- (ii) discovery rate of alien eggs/solutions $p_a = 0.25$,
- (iii) total iteration $N_{IterTotal} = 50$.
- (iv) search space, i.e., $0.1 \leq K_P, K_I, K_D \leq 1$

4.1. Performance evaluation of CS-PID controller with (Z_1)/AVR1

Here, the performance of CS-PID controller has been evaluated with performance index and AVR, as suggested in [6], i.e., (Z_1)/AVR1. Further, the results of step response of CS-PID controller have been compared with GA-PID and PSO-PID controllers of AVR system to reveal its supremacies. The gains of CS-PID, GA-PID, and PSO-PID controllers of AVR are obtained by minimizing the performance index (Z_1), as given in (7), for two values of γ ,

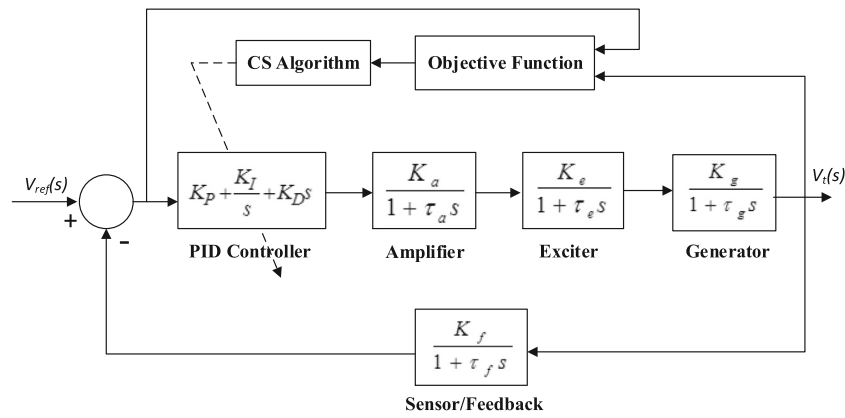


Fig. 4. Block diagram of CS-PID controller of AVR.

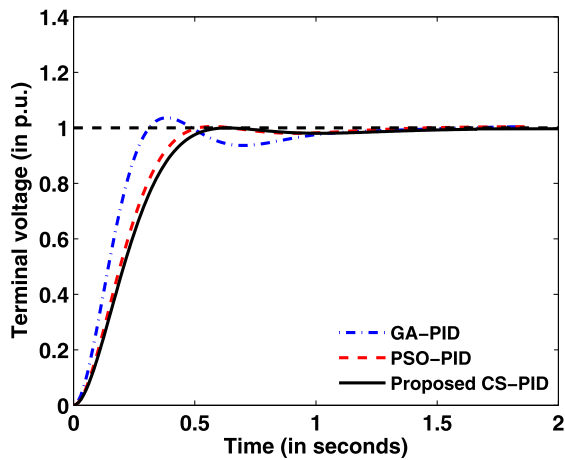


Fig. 5. Terminal voltage step response of AVR system ($\gamma = 1.5$).

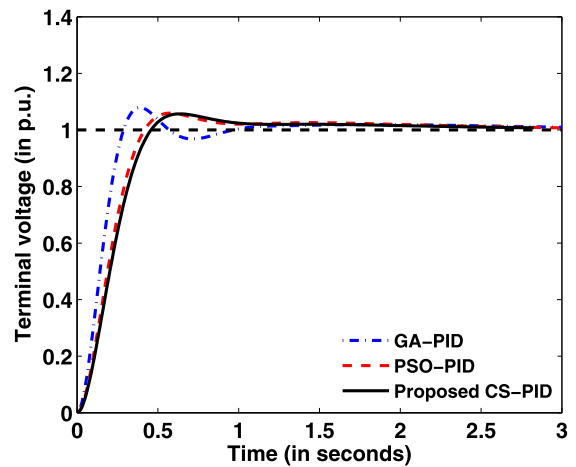


Fig. 6. Terminal voltage step response of AVR system ($\gamma = 1.5$) with +50% uncertainty.

i.e., 1 and 1.5. Ten trials are executed for each value of γ and best possible solutions of the controller gains are summarized in Table 3.

Using the values of the controller gains, as summarized in Table 3, the time response characteristics of CS-PID, PSO-PID and GA-PID have been estimated and shown in Fig. 5 for γ equals to 1.5 as for this value of γ the objective function, (Z_1) is found lowest.

The results of the time response characteristics, as summarized in Table 3, provide the following information:

- (i) The value of performance index, (Z_1), is found lowest for CS algorithm. The lowest value of Z_1 represents its more appropriate tuning capability than PSO and GA.
- (ii) The value of M_p for CS-PID controller is found as zero. The zero value of M_p represents that the proposed controller is more stable and less oscillatory in nature.
- (iii) The steady state values are same in all three controllers.
- (iv) The zero value of M_p of CS-PID controller is achieved at the cost of slightly larger value of t_s than the value obtained by PSO-PID controller. Nevertheless, the settling time of CS-PID controller is less than 1 s which is desirable for power system operation and control.
- (v) Settling time of CS-PID controller is less than GA-PID controller of AVR system.

Furthermore, +50% generator uncertainty has been considered in AVR system to check the robustness of CS-PID controller. The controller gains, using CS, GA, and PSO, under the condition of

uncertainty, are determined and summarized in Table 4. Subsequently, the step responses of the CS-PID, PSO-PID and GA-PID controllers of AVR system are estimated and shown in Fig. 6 for γ equals to 1.5 as for this value of γ the objective function, Z_1 is found lowest. It is noticeable from Fig. 6 that M_p and t_s are lesser for the CS-PID controller than the GA-PID and PSO-PID controllers. The lesser value of M_p and t_s indicate that the CS-PID controller is more stable and provide fast response than GA-PID and PSO-PID controllers of AVR.

4.2. Performance evaluation of CS-PID controller with (Z_2)/AVR2

Here, AVR2 and performance index, Z_2 , are considered to evaluate the performance of the CS-PID, GA-PID and CAS-PID controllers. CS algorithm has been used to get optimal values of these controller gains by minimizing performance index, Z_2 . The values of controller gains, as obtained by these algorithms, for $\rho = 0.3, 0.5$, and 0.7 , are summarized in Table 5.

It is clear from Table 5 that, each controller gives lowest value of Z_2 for $\rho = 0.7$. Therefore, the step responses of AVR2 with performance index, Z_2 , are shown in Fig. 7 for $\rho = 0.7$ only. However, the time response characteristics of AVR2 system, as summarized in Table 5, are obtained for $\rho = 0.3, \rho = 0.5$ and $\rho = 0.7$.

The time response characteristics, as shown in Fig. 7, and the results, as summarized in Table 5 for $\rho = 0.7$, reveal the following external attributes of the proposed controller.

Table 3
Comparative analysis of different controllers with $Z_1/AVR1$.

Case	γ	Controller	K_p	K_I	K_D	Z_1	M_p (%)	t_s	t_r	e_{ss}
1	1	Proposed CS-PID	0.5995	0.4126	0.2007	1.1916	0	0.5028	0.3234	0
		PSO-PID [6]	0.6568	0.5393	0.2458	1.4581	1.17	0.4027	0.2768	0
		GA-PID [6]	0.8861	0.7984	0.3158	1.2011	8.66	0.5980	0.2019	0
2	1.5	Proposed CS-PID	0.5937	0.4035	0.1966	0.9809	0	0.5127	0.3289	0
		PSO-PID [6]	0.6271	0.4652	0.2209	1.2297	0.45	0.4498	0.3025	0
		GA-PID [6]	0.7717	0.5930	0.3507	1.0051	3.62	1.0517	0.2003	0

Table 4
Comparative analysis of different controllers with $Z_1/AVR1$ and +50% generator uncertainty.

Case	γ	Controller	K_p	K_I	K_D	Z_1	M_p (%)	t_s	t_r	e_{ss}
1	1	Proposed CS-PID	0.5995	0.4126	0.2007	1.1916	5.6936	1.6437	0.2948	0
		PSO-PID [6]	0.6568	0.5393	0.2458	1.4581	6.3488	2.1969	0.2524	0
		GA-PID [6]	0.8861	0.7984	0.3158	1.2011	13.3432	1.8378	0.1948	0
2	1.5	Proposed CS-PID	0.5937	0.4035	0.1966	0.9809	5.6840	1.4986	0.2993	0
		PSO-PID [6]	0.6271	0.4652	0.2209	1.2297	5.9265	1.9641	0.2741	0
		GA-PID [6]	0.7717	0.5930	0.3507	1.0051	7.9521	1.8351	0.1916	0

Table 5
Comparison of different controllers for AVR system with (Z_2)/AVR2.

Case	ρ	Controller	K_p	K_I	K_D	Z_2	M_p (%)	t_s	t_r	e_{ss}
1	0.3	Proposed CS-PID	0.5278	0.3222	0.2039	0.0359	0	0.5312	0.3398	0
		CAS-PID [7]	0.6568	0.4821	0.3210	0.0385	3.4319	0.3166	0.2244	0
		GA-PID [7]	0.7905	0.6923	0.4338	0.0620	10.1143	0.7761	0.1679	0
2	0.5	Proposed CS-PID	0.5171	0.3144	0.1967	0.0251	0	0.5517	0.3512	0
		CAS-PID [7]	0.5942	0.5135	0.3520	0.0350	2.1365	0.8624	0.2174	0
		GA-PID [7]	0.4520	0.6322	0.4889	0.0655	4.9329	0.9858	0.1845	0
3	0.7	Proposed CS-PID	0.4910	0.3138	0.1864	0.0144	0	0.5987	0.3745	0
		CAS-PID [7]	0.5613	0.3670	0.2326	0.0146	0.4491	1.0062	0.3028	0
		GA-PID [7]	0.3850	0.5308	0.4829	0.0402	5.1852	3.4408	0.1727	0

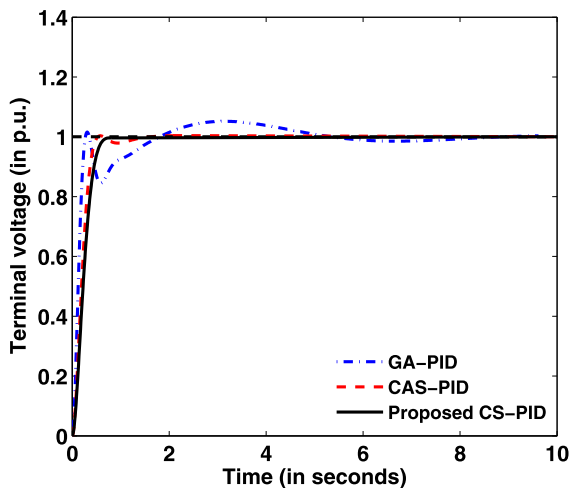


Fig. 7. Terminal voltage step response of $Z_2/AVR2$ system with different controllers ($\rho = 0.7$).

- The value of Z_2 , as obtained with CS algorithm, is lesser than the value obtained with CAS and GA algorithms. The lesser value of Z_2 with CS algorithm represents its more accurate tuning capability than the CAS and GA algorithms.
- The value of M_p is smaller with CS-PID than the GA-PID and CAS-PID controller. The smaller value of M_p with CS-PID controller indicate its less oscillatory and more stable characteristics than GA and CAS-PID controller.
- The settling time of CS-PID controller is less than the settling time of GA-PID and CAS-PID controllers. Therefore, the CS-PID controller of AVR offers faster response than GA/CAS-PID controllers.

Table 6
Comparison of different controllers with $Z_2/AVR2$ and +50% generator uncertainty.

Controller	K_p	K_I	K_D	M_p (%)	t_s	t_r	e_{ss}
Proposed CS-PID	0.4910	0.3138	0.1864	5.4725	2.1451	0.3370	0
CAS-PID [7]	0.5613	0.3670	0.2326	5.6386	2.0603	0.2782	0
GA-PID [7]	0.3850	0.5308	0.4829	5.6904	4.2819	0.1648	0

- The steady state error offers by these three controllers are zero.

Further, the robustness of the CS-PID controller is analysed, allowing +50% generator uncertainty in the AVR system. The respective values of performance specifications are summarized in Table 6 and the step responses of AVR system with different controllers under +50% generator uncertainty in the AVR system are shown in Fig. 8. It is obvious from the results, as summarized in Table 6, the CS-PID controller provides good terminal voltage step response.

5. Stability analysis of AVR system

In this section, the root locus and bode plots of both AVR systems, i.e., AVR1 and AVR2, as given in Table 2, are evaluated with and without controllers to check their stability. The performance index Z_1 and Z_2 are considered for AVR1 and AVR2, respectively, for the performance evaluation. The root locus plots of AVR1/ Z_1 and AVR2/ Z_2 are shown in Figs. 9 and 10. Likewise, Figs. 11 and 12 represent the bode plots of AVR1/ Z_1 and AVR2/ Z_2 , respectively. The stability assessment plots, as shown in Figs. 9–12, reveal the following information:

- Without any controller, the roots of characteristic equation are shifting towards right half of the s -plane, with change

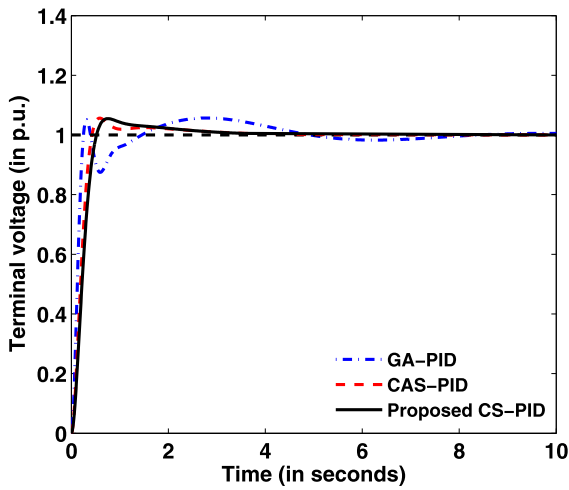


Fig. 8. Step response of $Z_2/AVR2$ system with different controllers with +50% uncertainty.

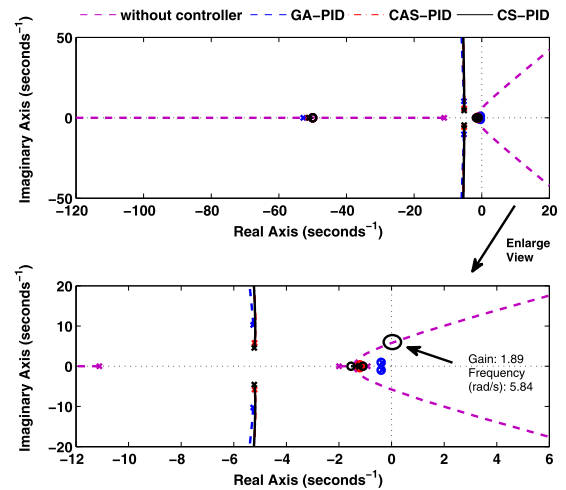


Fig. 10. Root Locus of $AVR2/Z_2$ system with and without controller.

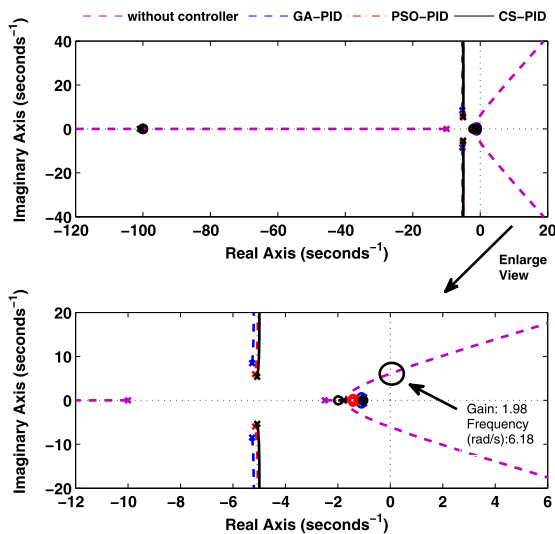


Fig. 9. Root Locus of $AVR1/Z_1$ system with and without controller.

in value of open loop gain (K), and hence may make system unstable for small change in K .

- (ii) The nature of AVR, without any controller, becomes oscillatory with slight change in value of K , i.e., at $K = 1.98$ for $AVR1/Z_1$ and $K = 1.89$ for $AVR2/Z_2$, as shown in Figs. 9 and 10, respectively.
- (iii) It is obvious from the root locus plots, as shown in Figs. 9 and 10, both the AVR, i.e., AVR1 and AVR2, exhibit stable performance with CS-PID, GA-PID, PSO-PID and CAS-PID controllers.

The pole-zero analysis for AVR1 and AVR2 are tabulated in Tables 7 and 8, respectively. Furthermore, the bode plots, as shown in Figs. 11 and 12 and the corresponding gain margin (GM) and phase margin (PM), as summarized in Tables 9 and 10 with and without controllers reveal the following information:

- (i) The GM and PM of AVR systems without any controller are very small. This indicates that the small variations in K can make system unstable.
- (ii) The GM and PM are infinity and -180 deg. for AVR with CS-PID, GA-PID, PSO-PID and CAS-PID controllers. These large

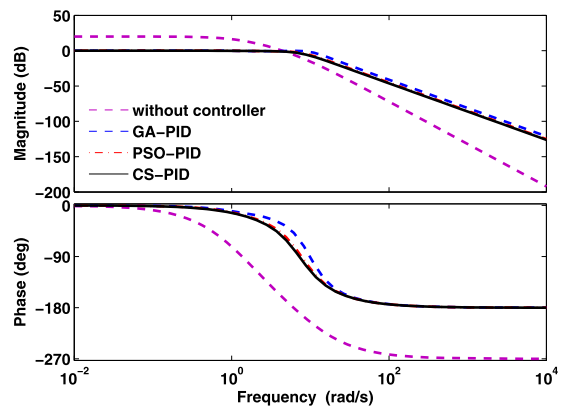


Fig. 11. Bode plot of $AVR1/Z_1$ with and without controller.

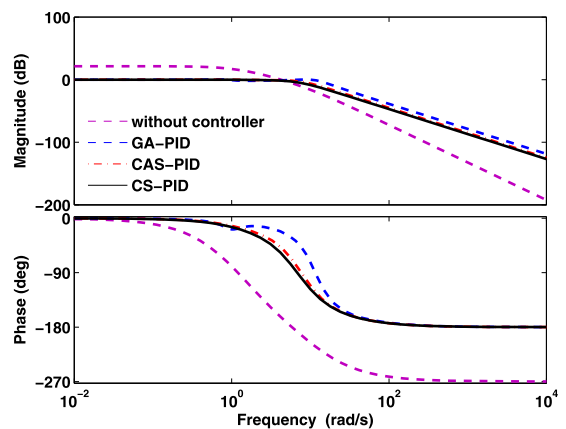


Fig. 12. Bode plot of $AVR2/Z_2$ with and without controller.

values of GM and PM indicate that the AVR system can acquire any values of K without the loss of stability.

6. Conclusion

In this paper, CS algorithm has been used to design a robust PID controller of AVR system. The optimal values of controller gains have been obtained by minimizing the performance indices

Table 7
Pole-zero analysis of AVR1.

Controller	Open loop		Closed loop	
	Pole	Zero	Pole	Zero
Proposed	0, -10.0, -2.50, -1.0	-1.9869, -1.0330	-1.0054, -0.0507 + 0.0535i, -0.0507 - 0.0535i, -0.0176, -0.0105	-100.0, -1.9869, -1.0330
GA-PID [6]	0, -10.0, -2.50, -1.0	-1.1002 + 0.6931i, -1.1002 - 0.6931i	-99.9712, -12.4892, -0.5198 + 4.6642i, -0.5198 - 4.6642i	-100, -1.1002 + 0.6931i, -1.1002 - 0.6931i
PSO-PID [6]	0, -10.0, -2.5, -1.0	-1.4194 + 0.3020i, -1.4194 - 0.3020i	-1.0061, -0.0516 + 0.0597i, -0.0516 - 0.0597i, -0.0129 + 0.0044i, -0.0129 - 0.0044i	-1, -0.0142 + 0.0030i, -0.0142 - 0.0030i
Without controller	-10.0, -2.50, -1.0	-	-1.0097, -0.0527 + 0.0848i, -0.0527 - 0.0848i, -0.0100 + 0.0069i, -0.0100 - 0.0069i	-100

Table 8
Pole-zero analysis of AVR2.

Controller	Open loop		Closed loop	
	Pole	Zero	Pole	Zero
Proposed	0, -11.11, -2.0, -0.9091	-1.5433, -1.0909	-51.1114, -5.2204 + 4.5600i, -5.2204 - 4.5600i, -1.2340 + 0.1618i, -1.2340 - 0.1618i	-50, -1.5433, -1.0909
GA-PID [7]	0, -11.11, -2.0, -0.9091	-0.3986 + 0.9697i, -0.3986 - 0.9697i	-52.7741, -5.2641 +10.2695i, -5.2641 -10.2695i, -0.3590 + 0.8869i, -0.3590 - 0.8869i	-50, -0.3986 + 0.9697i, -0.3986 - 0.9697i
CAS-PID [7]	0, -11.1, -2.0, -0.9091	-1.2066 + 0.3493i, -1.2066 - 0.3493i	-51.3767, -5.2098 + 5.8168i, -5.2098 - 5.8168i, -1.1119 + 0.4284i, -1.1119 - 0.4284i	-50, -1.2066 + 0.3493i, -1.2066 - 0.3493i
Without controller	-11.11, -2.0, -0.9091	-	-49.8665, -13.4278, -0.3629 + 4.4135i, -0.3629 4.4135i	-50

through CS algorithm. The two performance indices, directly dependent on time response characteristics and two AVR systems, have been considered to evaluate the effectiveness of the proposed CS-PID controller. Further, the results of the time response characteristics of AVR system with the CS-PID controller are compared with PSO-/GA-/CAS-PID controllers, for the same objective functions, to show its efficiency. The comparative results reveal the following attributes of the proposed CS-PID controller of AVR systems:

- (i) The CS-PID controller outperforms GA/CAS/PSO-PID in terms of stability and tuning capability because the values of M_p and performance indices, obtained with CS algorithm, are found lesser than the values obtained with GA/CAS/PSO algorithms.
- (ii) The AVR systems have smaller settling time with CS-PID controller than GA-PID and CAS-PID controllers. The smaller value of settling represents fast dynamic response of AVR systems with CS-PID controller.

Table 9
Frequency response specifications of AVR1/ Z_1 system.

AVR system	GM	GM frequency (Hz)	PM (Degree)	PM frequency (Hz)
Without controller	1.9250	6.1238	18.5936	4.4050
With GA-PID controller	∞	∞	-180	0.6342
With PSO-PID controller	∞	∞	-180	0.6278
With CS-PID controller	∞	∞	-180	0

- (iii) The settling times of AVR systems with CS-PID controller are little more than the PSO-PID controller. However, the settling times of AVR systems are found less than one second with CS-PID controller, which is desirable in power system operation and control.

In addition the robustness of AVR has also been investigated under the condition of uncertainty. It is shown that the CS-PID controller also provides good dynamic performance in case of

Table 10Frequency response specifications of AVR2/Z₂ System.

AVR system	GM	GM frequency (Hz)	PM (Degree)	PM frequency (Hz)
Without controller	1.8913	5.8433	16.3920	4.2461
With GA-PID controller	∞	∞	-180	0.8758
With CAS-PID controller	∞	∞	-180	0
With CS-PID controller	∞	∞	-180	0

uncertainty. Finally the stability of the CS-PID controller has been analysed with root locus and bode plots. It is shown that the proposed controller in AVR loop not only enhances the dynamic performance but also gives stable performance for wide range of open loop gain of AVR system. Therefore, considering these attributes of CS-PID controller of AVR system, it can be considered as one of the alternative in power system and control to achieve better dynamic response and stable performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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