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# CHAOTIC-BASED PARTICLE SWARM OPTIMIZATION ALGORITHM FOR OPTIMAL PID TUNING IN AUTOMATIC VOLTAGE REGULATOR SYSTEMS

***Introduction.*** *In an electrical power system, the output of the synchronous generators varies due to disturbances or sudden load changes. These variations in output severely affect power system stability and power quality. The synchronous generator is equipped with an automatic voltage regulator to maintain its terminal voltage at rated voltage. Several control techniques utilized to improve the response of the automatic voltage regulator system, however, proportional integral derivative (PID) controller is the most frequently used controller but its parameters require optimization.* ***Novelty.*** *In this paper, the chaotic sequence based on the logistic map is hybridized with particle swarm optimization to find the optimal parameters of the PID for the automatic voltage regulator system. The logistic map chaotic sequence-based initialization and global best selection enable the algorithm to escape from local minima stagnation and improve its convergence rate resulting in best optimal parameters.* ***Purpose.*** *The main objective of the proposed approach is to improve the transient response of the automatic voltage regulator system by minimizing the maximum overshoot, settling time, rise time, and peak time values of the terminal voltage, and eliminating the steady-state error.* ***Methods.*** *In the process of parameter tuning, the Chaotic particle swarm optimization technique was run several times through the proposed hybrid objective function, which accommodates the advantages of the two most commonly used objective functions with a minimum number of iterations, and an optimal PID gain value was found. The proposed algorithm is compared with current metaheuristic algorithms including conventional particle swarm optimization, improved kidney algorithm, and others.* ***Results.*** *For performance evaluation, the characteristics of the integral of time multiplied squared error and Zwe-Lee Gaing objective functions are combined. Furthermore, the time-domain analysis, frequency-domain analysis, and robustness analysis are carried out to show the better performance of the proposed algorithm. The result shows that automatic voltage regulator tuned with the chaotic particle swarm optimization based PID yield improvement in overshoot, settling time, and function value of 14.41 %, 37.91 %, 1.73 % over recently proposed IKA, and 43.55 %, 44.5 %, 16.67 % over conventional particle swarm optimization algorithms. The improvement in transient response further improves the automatic voltage regulator system stability for electrical power systems.* References 44, tables 4, figures 6.

*Key words*: **proportional integral derivative (PID) tuning, chaotic particle swarm optimization (CPSO), robustness analysis, automatic voltage regulator (AVR), transient response.**

***Вступ.*** *В електроенергетичній системі потужність синхронних генераторів змінюється внаслідок збурень або різких змін навантаження. Ці зміни в потужності серйозно впливають на стабільність енергетичної системи та якість електроенергії. Синхронний генератор оснащений автоматичним регулятором напруги для підтримання напруги на його клемах на рівні номінальної напруги. Декілька методів управління використовуються для поліпшення реакції системи автоматичного регулятора напруги, однак пропорційний інтегральний похідний контролер (PID-контролер) є найбільш часто використовуваним контролером, але його параметри вимагають оптимізації.* ***Новизна.*** *У цій роботі хаотична послідовність, заснована на логістичній схемі, гібридизується за допомогою оптимізації рою частинок, щоб знайти оптимальні параметри PID для системи автоматичного регулятора напруги. Ініціалізація на основі хаотичної послідовності логістичної схеми та найкращий глобальний вибір дозволяють алгоритму вийти із локальної мінімальної стагнації та покращити швидкість збіжності, що дає найкращі оптимальні параметри.* ***Мета.*** *Основною метою запропонованого підходу є поліпшення перехідної реакції системи автоматичного регулятора напруги шляхом мінімізації максимального перевищення, часу встановлення, часу наростання та пікових значень напруги на клемах і усунення помилки у стаціонарного стані.* ***Методи.*** *У процесі настройки параметрів техніку оптимізації рою хаотичних частинок кілька разів пропускали через запропоновану гібридну цільову функцію, яка враховує переваги двох найбільш часто використовуваних цільових функцій з мінімальною кількістю ітерацій,і знайдено оптимальне значення коефіцієнту підсилення PID. Запропонований алгоритм порівнюється з сучасними метаевристичними алгоритмами, включаючи звичайну оптимізацію рою частинок, вдосконалений алгоритм нирок та інші.* ***Результати.*** *Для оцінки ефективності об'єднуються характеристики інтеграла у часі, помноженого на похибки у квадраті, та цільових функцій Цве-Лі Гейнга. Крім того, проводяться аналіз у часовій області, аналіз у частотної області та аналіз стійкості, щоб показати кращу ефективність запропонованого алгоритму. Результат показує, що автоматичний регулятор напруги, налаштований на хаотичну оптимізацію рою частинок, заснований на поліпшенні виходу PID в перевищеннях,часі налаштування та значенні функції перевищує на 14,41 %, 37,91 %, 1,73 % нещодавно запропонований нирковий алгоритм та на 43,55 %, 44,5 %, 16,67 % перевищує звичайні алгоритми оптимізації рою частинок. Поліпшення перехідної реакції ще більше покращує стабільність автоматичного регулятора напруги для систем електроенергетики.* Бібл. 44, табл. 4, рис. 6.

*Ключові слова:* **пропорційне регулювання інтегральної похідної, оптимізація хаотичного рою частинок, аналіз стійкості, автоматичний регулятор напруги, перехідна реакція.**

**Introduction.** The disturbances such as change in transmission line parameters, sudden load changes, fluctuation in the turbine output, etc., causes the synchronous generator to show an oscillatory performance around the equilibrium state [1]. Under such oscillations, the power system stability is greatly affected. To assure the power quality and to enhance the power network stability, excitation of synchronous generator is equipped with automatic voltage regulator (AVR) and power system stabilizer. AVR keeps the output voltage of synchronous generator at rated value. The transient response of AVR system extremely affects the stability of the power system [2].

A number of control methods were studied, such as predictive controls, fuzzy controls, and neural controls for process controls system. Despite much effort, proportional integral derivative (PID) controllers are the main element of industrial controller systems and can be used in the form of embedded controller, distributed control system and programmable logic controller [3]. Overschee and Demoor stated 80 % of PID controllers are not tuned to optimal level in the industries. Furthermore, they reported that 30 % of the PID controllers operates in manual settings, whereas twenty 5 % work in the default settings [4]. Over the years, numerous techniques for tuning of PID parameters were proposed like traditional techniques including Ziegler/Nicole, Cohen/Kun, pole position and latest techniques (i.e., gains scheduling, minimum fluctuations and prediction) [5]. Some drawbacks of traditional control technique for PID controllers tuning are:

- inadequate dynamics of closed loop response;
- excessive rules for setting gains;
- mathematical complexity control design;
- difficulty in dealing with nonlinearities [6].

Therefore, in academia and industry, the tuning a PID controller is an interesting research topic.

Numerous techniques like artificial neural networks (ANN) and neural fuzzy systems were used for the tuning of PID-AVR parameters. However, these techniques require a quite large amount of data for training process [7]. On the other hand, metaheuristic optimization based tuning algorithms such as improve kidney-inspired algorithm (IKA) [8], particle swarm optimization (PSO) [9], biogeography-based optimization (BBO), local unimodal sampling algorithm (LUS) [10], artificial bee colony (ABC) algorithm [11], slap swarm algorithm (SSA) [12], artificial electric filed (AEF) [13], Harris hawks optimization (HHO) [14], sine cosine algorithm (SCA) [15], whale optimization algorithm (WOA) [16], etc., are applied for PID tuning in AVR system.

Many objective functions were proposed in literature as performance criteria for optimization of PID-AVR. The integral error is extensively used as an objective function, which is based on difference between reference and the system output. The frequently used integral functions include:

- integral absolute error (IAE);
- integral time absolute error (ITAE);
- integral squared error (ISE);
- integral time squared error (ITSE).

Minimizing the ISE and IAE provide relatively small overshoots with longer stabilization time. Alternatively, the ITSE and ITAE can overcome the limitations of the ISE and IAE, but they cannot guarantee the required stability [17]. In addition, Zwe-Lee Gaing (ZLG) defines the time step performance criterion by using a weighted factor with the parameters of time response [7].

A brief literature review of the tuning techniques applied on AVR systems over the past years is shown in Table 1, which encapsulates the performance indexes and analysis approaches used in the literature.

Genetic algorithm (GA), ABC, and PSO algorithms have tendency to solve numerous optimization problems, but affects with issues like memory capabilities, etc. Improved results might be obtained through other optimization methods, but they might have drawbacks such as initial convergence, local minimum congestion, difficulty in selecting control parameter, and increased computation time dependent on size of the studied system [18]. Also, there is no exact technique for finest parameters tuning of PID controller for AVR system. Therefore, studying novel heuristic optimization algorithms is an imperative and observable issue for researchers. Since metaheuristic algorithms have establish their place in efficiently solving numerous global optimization problem that can be applied to various scenarios, however the major problem faced by them is the premature convergence leads trapping in local optima [19]. Chaotic features diversify solution space, creating space to exploit and explore more space. Chaos phenomena can take place in a deterministic nonlinear dynamic system and is sensitive to initial conditions. Thus, chaotic movements within a certain range can travel all states without repetition. The easy implementation and its capability to escape from getting stuck in the local optima evolved in chaos based search algorithms [20]. Experimental studies argue for the benefit of using chaotic instead of random signals [21].

In this study, optimization of PID controller for AVR applications using the hybridization of chaotic initialization in particle swarm optimization (CPSO) is proposed. The combined ITSE and ZLG performance criterion is used. The ITSE-ZLG not only minimize the steps response characteristic that are settling time ($t_s$), peak time ($t_p$), rise time ($t_r$), overshoot (%MP), and steady state errors ($e_{ss}$), but also the average of time weighted absolute errors between the measured and rated voltage. The results obtained on the basis of the proposed technique are then compared with existing techniques algorithm in the literature. To show the supremacy of the proposed CPSO-PID approach, transient response analysis, frequency response analysis and pole-zero map under AVR system parameters changes are performed. At the end, the robustness analysis is performed.

**Mathematical model of AVR.** To maximize the power quality of system, AVR is crucial in maintaining the terminal output voltage of synchronous generator to predefined level through generator exciter control. Operation of AVR is dependent upon the difference between pre-defined voltage levels to variable terminal voltage level, which may arise due to disturbance in power network. Excitation mechanism serves the purpose to maintain the generator terminal voltages in case of system interruptions. Potential transformer measure's the voltage magnitude, afterwards rectified and compared with the reference. Error signal generated through this mechanism is amplified to control the field excitation, hence maintain the synchronous generator terminal voltage. Generation of reactive power increases/decreases to new stable equilibrium, maintaining the output voltage to defined rated value. Modelling of various parts of AVR system is given in the following equations:

$$G_{Amplifier}(s)=\frac{K_A}{1+s\cdot T_A}; \qquad (1)$$
$$0.02\le T_A\le 0.1,\quad 10\le K_A\le 40;$$

$$G_{Exciter}(s)=\frac{K_E}{1+s\cdot T_E}; \qquad (2)$$
$$0.4\le T_E\le 1,\quad 1\le K_E\le 10;$$

Table 1

Tuning method for automatic voltage regulator system

| Reference | Proposed algorithm | Comparison | Performance indices | | | | | | Analysis methods | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | IAE | ISE | ITAE | ITSE | ZLG | Other | Transient response | Pole Zero Map | Frequency response | Robustness |
| Ekinci et al. [8] | IKA | PSO, DE, ABC, LUS, PSA, BBO, GOA | | | | + | + | | + | + | + | + |
| Ekinci et al. [14] | HHO | BBO | | | | + | | | + | | | + |
| Demirören et al. [13] | AEF | PSO, BBO | | | | + | | | + | | | |
| Mosaad et al. [16] | WOA | BA, CSA, FPA, PSO, SCA, WWO | | | + | | | | + | | | |
| Çelik et al. [22] | SOS | ABC, MOL, BBO | | | + | | | + | + | + | + | + |
| George et al. [23] | WCA | WOA, GA | | | | | | + | + | | | |
| Çelik et al. [24] | SFS | ABC, MOL, LUS, WCO, GSA, BBO | | | | + | | | + | + | + | + |
| Ekinci et al. [12] | SSA | ABC, ZN | | | | + | | | + | | + | |
| Odili et al. [25] | ABO | PSO, GA ACO, BFOA | + | | | | | | + | | | |
| Bingul et al. [26] | CS | PSO, MOL, ABC, BF-GA, LUS | | | + | + | | + | + | + | + | + |
| Hekimoglu et al. [15] | SCA | ZN, DE, ABC, BBO | | | | | + | | + | + | + | + |
| Kansit et al [27] | PSOGSA | ZN, PSO, MOL | | | + | | | | + | | | |
| Chatterjee et al. [28] | TLBO | GA, PSO, LUS, PSO, ABC | | | + | + | + | | + | + | + | + |
| Guvenc et al. [29] | BBO | ABC, DEA, PSO | | | | + | | | + | + | + | + |
| Sahib et al. [9] | PSO | ABC, DEA, GA, MOL, LUS | | | + | | | | + | + | + | + |
| Mohantya et al. [10] | LUS | ABC, PSO, DE | | | | + | | + | + | | + | + |
| Tang et al. [30] | CAS | PSO | | | | | + | | + | | | |
| Gozde et al. [31] | ABC | PSO, DEA | | | | + | | | + | + | + | + |

In Table 1 the following abbreviation is used: IKA –improved kidney-inspired algorithm, SSA – slap swarm algorithm, SOS – symbiotic organisms search, SFS – stochastic fractal search, CAS – Chaotic ant swarm, ABO – African buffalo optimization, WWO – water wave optimization, TLBO – teaching learning based optimization, CS – cuckoo search, water wave optimization, PSO – particle swarm optimization, DE – differential evolution, ABC – ant bee colony, LUS – local unimodal sampling, PSA – pattern search algorithm, BBO – bio-geography-based optimization, GOA – grasshopper optimization algorithm, GA – genetic algorithm, MOL – many optimizing liaisons, ZN – ziegler-nichols, WCO – world cup optimization, GSA – gravitational search algorithm, WCA – water cycle algorithm , WOA – whale optimization algorithm, ACO – ant colony optimization, BFOA – bacterial foraging optimization Algorithm, CSA – crow search algorithm, BA – bat algorithm, FPA – flower pollination algorithm, SCA – sine cosine algorithm, BF-GA – hybrid genetic algorithm and bacterial foraging.

$$G_{Generator}(s)=\frac{K_G}{1+s\cdot T_G};\quad 1\le T_G\le 2,\quad 0.7\le K_G\le 1; \tag{3}$$

$$G_{Sensor}(s)=\frac{K_S}{1+s\cdot T_S};\quad 0.001\le T_S\le 0.06,\quad 1\le K_S\le 2; \tag{4}$$

where $K_A$, $K_E$, $K_G$ and $K_S$ are the amplifier, exciter, generator and sensor gains respectively, $T_A$, $T_E$, $T_G$ and $T_S$ are the amplifier, exciter, generator and sensor time constant respectively.

The linearized AVR transfer function system without PID is given as follows:

$$\frac{\Delta U(s)}{\Delta U_{ref}(s)}=\frac{K_A\cdot K_E\cdot K_G\cdot(1+s\cdot T_S)}{(1+s\cdot T_A)\cdot(1+s\cdot T_E)\cdot(1+s\cdot T_G)\cdot(1+s\cdot T_S)+K_A\cdot K_E\cdot K_G\cdot K_S}. \tag{5}$$

**AVR system with PID controller.** The PID controller consists of 3 main control actions/gains with respect to the error signal:

1) proportional ($K_p$) control;
2) integral ($K_i$) control;
3) derivative ($K_d$) control.

In industrial control processes, a constant gain PID controller has been extensively used. PID controller transfer function is given as

$$U_c(t) = K_p \Delta U_e(t) + K_i \int_0^t \Delta U_e(t) dt + K_d (d\Delta U_e(t))/dt, \quad (6)$$

where $U_c$ is the control signal; $\Delta U_e(s)$ is the error signal among reference $\Delta U_{ref}(s)$ and measured signal $\Delta U(s)$, and $K_p$, $K_d$ and $K_i$ are the control gains of proportional, derivative and integral term, respectively.

The closed loop AVR transfer function with PID is derived as

$$\frac{\Delta U(s)}{\Delta U_{ref}(s)} = \frac{K_A \cdot K_E \cdot K_G \cdot (1 + s \cdot T_S) \cdot (s^2 \cdot K_d + s \cdot K_p + K_i)}{A}, \quad (7)$$

where

$$A = s \cdot (1 + s \cdot T_A) \cdot (1 + s \cdot T_E) \cdot (1 + s \cdot T_G) \cdot (1 + s \cdot T_S) + K_A \cdot K_E \cdot K_G \cdot K_S \cdot (s^2 \cdot K_d + s \cdot K_p + K_i).$$

The challenge in PID tuning is to determine the optimum parameters to reduce the time domain characteristics like $t_r$, $t_s$, $t_p$ and $\%M_p$. Therefore, optimization of PID tuning parameters is required using optimization methods.

**PID parameters optimization for AVR system.**

**Particle Swarm Optimization (PSO)** is a population based optimization algorithm inspired from social behaviors of bird flocking [9]. In this algorithm, population (known as particle) is initialized. In $n$-dimension given problem, $N$ particles are travelling in the solution space. The $X_j(t) = (X_{j1}, X_{j2}, ..., X_{jm})$ denotes the location of the $j$-th particle at the $i$-th iteration and $X_{jm} \in [L_m, U_m]$, $1 \leq m \leq N$, where $L_m$ and $U_m$ represents the lower and upper bound having values [0.2 – 2] respectively. The $P_j = (P_{j1}, P_{j2}, ..., P_{jm})$ denotes the best position searched by the $j$-th particle known as $P_{best}$. Finally, the global best position achieved by the swarm is identified as global best $G_{best}$ and represented as $P_g = (P_{g1}, P_{g2}, ..., P_{gm})$. The velocity vector at the $i$-th iteration is $v_j(t) = (v_{j1}, v_{j2}, ..., v_{jm})$. Finally, the updated velocity and position variables of the particle for succeeding iteration are obtained as

$$\begin{aligned} V_j(t+1) &= W \cdot V_j(t) + \\ &+ r_1 \cdot C_1 \cdot (P_{best\,j}(t) - x_j(t)) + \\ &+ r_2 \cdot C_2 \cdot (G_{best\,j}(t) - x_j(t)); \end{aligned} \quad (8)$$

$$x_j(t+1) = x_j(t) + V_j(t), \quad (9)$$

where the parameter $C_1$ and $C_2$ are acceleration coefficient, $W$ is called inertia weight (i.e., set to 1 in the conventional PSO), $r_1$ and $r_2$ represents random number between [0, 1].

The PSO algorithm has several advantages including fast convergence, less complex computations unlike GA (e.g. coding/decoding, mutation and crossover), easy to compute and simple to implement [32]. But, PSO has drawbacks, such as easily stuck in local optima and decrease in the convergence rate in the later period of evolution [33].

**Chaotic Particle Swarm Optimization (CPSO).**

Generating random sequences with good uniformly is very important in the field of sampling, numerical analysis and metaheuristic optimization. The concept of using chaotic sequence instead of random sequence have been emerged in research fields using chaotic neural network (CNN) [34] and chaos optimization [35], etc. Chaos is a random movement of particles having characteristics of pseudo-randomness, ergodicity, and regularity determined through a deterministic equation [36]. A chaotic signal can cross every state in a certain search region in such a way that every state is visited only once. The diversity of random numbers generated by chaotic motion is better than the randomly generated values. Chaos search has a very special ability to improve the diversity of particle in search space that helps the optimization algorithm to escape from stucking in local optima [37]. Therefore, using chaotic sequences in evolutionary algorithms is a promising approach to obtain high quality solutions. Different kinds of chaos maps have been used in literature [38].

In this paper, to improve the searching performance and to escape from trapping into local minima, chaos dynamics is integrated into the PSO. The conventional PSO algorithm faces up to premature convergence because information can be exchanged between particles quickly and the particles are getting near to each other rapidly, especially in case of problems with multiple local optima. Thus, the dispersion of particles decreases in the search space and it is difficult to escape from local optima [39]. In order to increase a population's diversity in conventional PSO, chaos sequences were used to initialize the particles' population and velocity. In this paper, chaotic sequence is generated using the logistic equation [40]. The process of initializing using logistic chaotic map is defined through the subsequent equation [41]:

$$\begin{aligned} &Cx_j^{(i+1)} = 4 \cdot Cx_j^{(i)} \cdot \left(1 - Cx_j^{(i+1)}\right), \\ &j = 1, 2, ..., m, \end{aligned} \quad (10)$$

where $Cx_j$ is the $j$-th chaotic variable and $i$ denotes the number of iteration.

The procedure of chaotic search using logistic map is as follows [42].

**Step 1:** Setting $i = 0$ and maps the decision variables $x_j^i$ to chaotic variable $Cx_j^{(i)}$ positioned in the interval (0, 1) using below equation

$$\begin{aligned} &Cx_j^{(i)} = \frac{x_j^{(i)} - x_{\min,j}}{x_{\max,j} - x_{\min,j}}, \\ &j = 1, 2, 3, ..., n. \end{aligned} \quad (11)$$

**Step 2:** Calculating the chaotic variable $Cx_j^{(i+1)}$ for the succeeding iteration using logistic map equation according to $Cx_j^{(i)}$.

**Step 3:** Adapting the chaotic variable $Cx_j^{(i+1)}$ to decision variable $x_j^{(i+1)}$ using below equation

$$x_j^{(i+1)} = x_{\min,j} + Cx_j^{(i+1)} \cdot \left(x_{\max,j} - x_{\min,j}\right), \quad j = 1, 2, 3, \ldots, n. \tag{12}$$

**Step 4:** Calculating the new solution with decision variable $x_j^{(i+1)}$.

**Step 5:** If the new solution is superior to the previous decision variable or predefines maximum number of iterations is reached, take the new solution as the new result of chaos search else, let $i = i + 1$ and go back to Step 2.

Another improvement in conventional PSO lies in using the adaptive parameters ($W$, $C_1$, $C_2$) instead of constant values using the following equations

$$W = W_i - \frac{W_i - W_f}{MaxGen} \cdot Gen, \quad \left(W_i > W_f\right); \tag{13}$$

$$C_1 = C_{1i} - \frac{C_{1i} - C_{1f}}{MaxGen} \cdot Gen, \quad \left(C_{1i} > C_{1f}\right); \tag{14}$$

$$C_2 = C_{2i} - \frac{C_{2i} - C_{2f}}{MaxGen} \cdot Gen, \quad \left(C_{2i} > C_{2f}\right); \tag{15}$$

$C_{1i} = 2$, $C_{1f} = 1$, $C_{2i} = 2$, $C_{2f} = 1$, $W_i = 0.9$ and $W_f = 0.4$, where $Gen$ is the current generation of the swarm, $MaxGen$ is the maximum evolutionary generation, the indexes $i$ and $f$ denotes initial and final, respectively.

Fig. 1 shows the flow chart of CPSO.

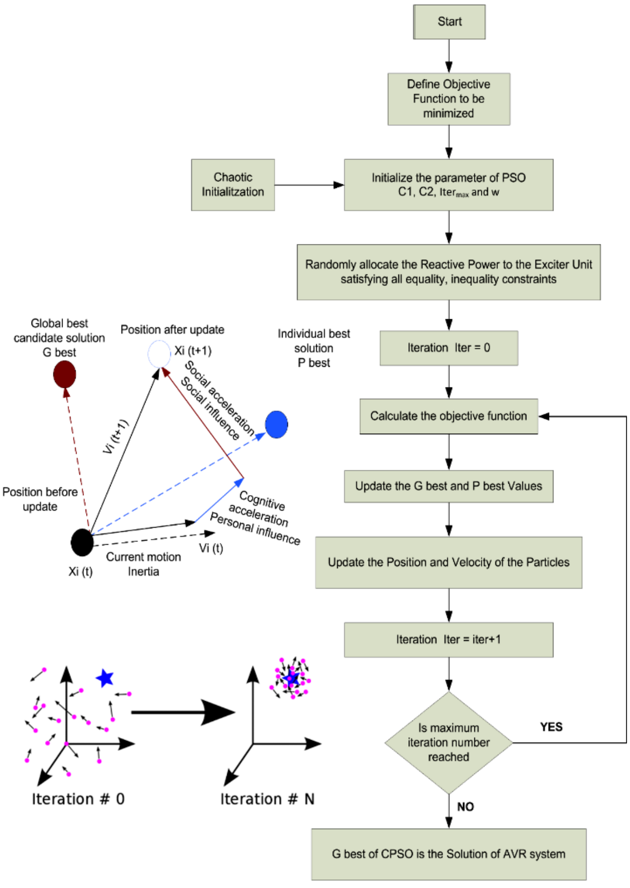


Fig. 1. Flow chart chaotic particle swarm optimization

**Performance evaluation criterion.** Several performance criterions were proposed in the literature to examine the performance of the AVR system [43]. The most of the criterions were associated with improvement in time domain parameters such as $\%M_p$, $e_{SS}$, $t_r$ and $t_S$ of the step response [44]. The frequently used criterions for the performance evaluation of AVR system are

1) Integral absolute error ($IAE$):

$$IAE = \int_0^{t_{sim}} \left|\Delta U_t(t)\right| dt; \tag{16}$$

2) Integral squared error ($ISE$):

$$ISE = \int_0^{t_{sim}} \left(\Delta U_t(t)\right)^2 dt; \tag{17}$$

3) Integral time weighted absolute error ($ITAE$):

$$ITAE = \int_0^{t_{sim}} t \cdot \left|\Delta U_t(t)\right| dt; \tag{18}$$

4) Integral time weighted squared error ($ITSE$)

$$ITSE = \int_0^{t_{sim}} t \cdot \left(\Delta U_t(t)\right)^2 dt; \tag{19}$$

5) Zwe-Lee Gaing (ZLG):

$$ZLG = \left(1 - e^{-\beta}\right) \cdot \left(M_p - e_{ss}\right) + e^{-\beta} \cdot \left(t_s - t_r\right), \tag{20}$$

where $\Delta U_t(t)$ is the difference between steady state value and its present terminal voltage; $t_{sim}$ is the simulation time duration; $\beta$ is the weighted factor and its values ranges between [0.5 – 1.5].

In the abovementioned criterions, ITSE and ZLG are frequently reported and resulted in improved results. ITSE resulted in high overshoot, whereas ZLG increase the rise and peak time. In this study, combined ITSE and ZLG are used [19]

$$J = ITSE + \alpha \cdot ZLG, \tag{21}$$

where $\alpha$ is the weighting factor to balance the $ITSE$ and $ZLG$ performance criterions and its values ranges between [30 – 50].

The above criterion can be changed in to optimization problem with constrained as

$$\min J\left\{ITSE, \%M_p, e_{ss}, t_s, t_r\right\};$$

$$\text{subject to} \begin{cases} 0.2 \le K_p \le 2; \\ 0.2 \le K_i \le 2; \\ 0.2 \le K_d \le 2. \end{cases} \tag{22}$$

The optimal values of free parameters ($ITSE^*$, $\%M_p^*$, $e_{SS}^*$, $t_s^*$ and $t_r^*$) are estimated using CPSO. Fig. 2 shows the complete implementation of CPSO for AVR.

**Simulation result and discussion.** The different analyses were performed including convergence, pole zero map, robustness etc. to show the improved performance of CPSO-AVR. Furthermore, the voltage response analysis is also carried out by considering different cases. All the analysis were done using MATLAB/Simulink (2018 Version) on an Intel i3, processor 1.90 GHz with a RAM 4.00 GB. The population size and maximum iteration for the analysis were chosen as 30. Subsequent sections show the important results after analysis.

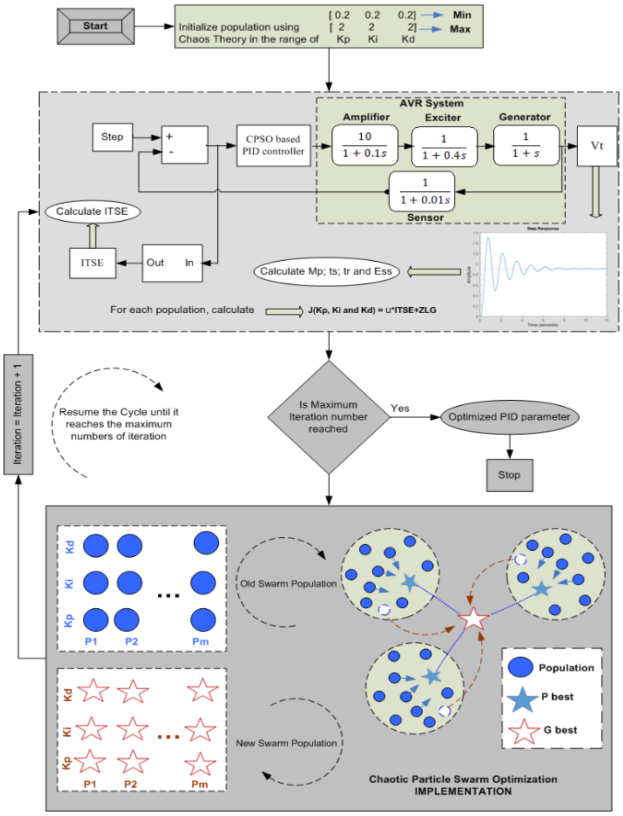


Fig. 2. Chaotic particle swarm optimization implementation

**Convergence profile.** The convergence curve of PSO and CPSO is shown in Fig. 3. The CPSO algorithm converges to optimized values only in 5 iterations as compared to PSO. Optimized value of PID gains obtained using CPSO were

$$K_p = 1.0535,\ K_i = 1.0112 \text{ and } K_d = 0.3752.$$

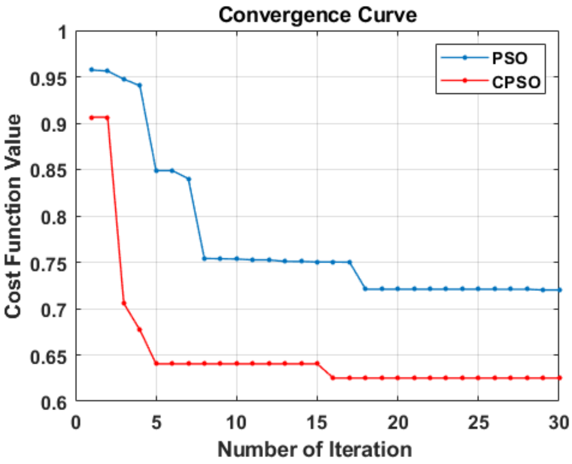


Fig. 3. Convergence curve

Equation (23) shows the overall transfer function of AVR system obtained with these optimized values

$$PID_{optim}=\frac{\Delta U_t(s)}{\Delta U_{ref}(s)}= \tag{23}$$

$$=\frac{0.0599s^3+6.103s^2+10.53s+10.09}{0.0004s^5+0.0454s^4+0.55s^3+7.509s^2+11.43\cdot s+10.09}$$

**Comparative analysis with different algorithms.** Comparison of obtained results using CPSO with other optimization algorithms were done to show the effectiveness and supremacy of the CPSO technique. The other algorithms used to optimize the PID parameter for AVR system include IKA, PSO, BBO, LUS, ABC, SSA, AEF and HHO. In order to evaluate the performance, the time domain characteristics $\%M_p$, $e_{SS}$, $t_r$ and $t_S$ of the transient response as well as value of the criterion were compared. The comparative analysis of CPSO-PID with other meta-heuristic techniques is tabulated in Table 2. The percentage improvement of CPSO over other optimization algorithms is also reported in Table 2. It is important to note here that PID controller tuned with CPSO algorithm using the cost function given in Eq. (21) for AVR system will result in less oscillatory and stable response. Fig. 4 shows the simulation result of step response of AVR terminal voltage obtained from different algorithms. It is noted that the CPSO yields better results as compared to other algorithm.

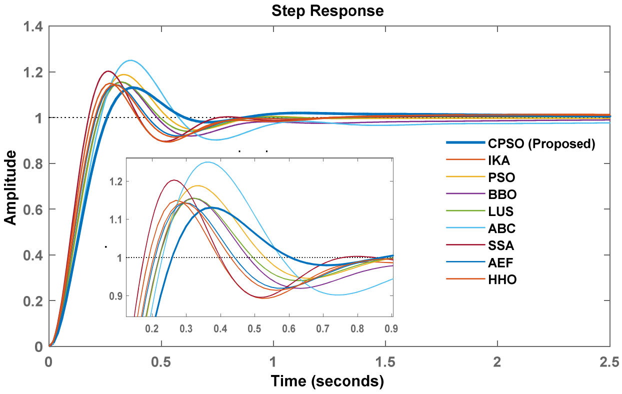


Fig. 4. Comparative analysis of step responses

**Pole-Zero and frequency response Analysis.** The pole-zero map helps to determine the system stability and provide the information about the position of closed-loop zeros, poles and their resultant damping ratio (DR). To check the stability of AVR, the analysis of pole-zeros and bode-plot were done with tuned controller parameters obtained using CPSO. From pole/zero analysis for CPSO-AVR, the closed loop poles are

$$s_1=-101,\quad s_{2,3}=-4.94\pm j8.65,\quad s_{4,5}=-1.3\pm j0.91$$

as shown in Fig. 5 and the corresponding DR values are 1.00, 0.49 and 0.81, respectively.

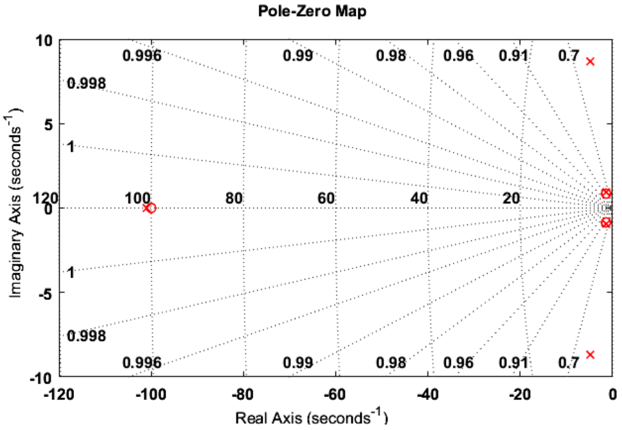


Fig. 5. Pole-zero analysis of chaotic particle swarm optimization based automatic voltage regulator

Table 2

Comparative analysis of chaotic particle swarm optimization-PID with other meta-heuristic algorithms

| Controller type | PID parameters | | | Transient response parameters | | | | Objective function | | | Improvement contributed by CPSO-PID | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $K_p$ | $K_i$ | $K_d$ | $\%M_p$ | $t_s$, s | $t_r$, s | $t_p$, s | *ITSE* | *ZLG* | *ITSE+ZLG* | $\%M_p$ | $t_s$, s | *ITSE+ZLG* |
| CPSO-PID (Proposed) | 1.0535 | 1.0112 | 0.3752 | 13.11 | 0.564 | 0.1743 | 0.3732 | 0.0078 | 0.2299 | 0.6214 | – | – | – |
| IKA-PID | 1.0426 | 1.0093 | 0.599 | 15.00 | 0.753 | 0.128 | 0.328 | 0.0062 | 0.3246 | 0.6322 | 14.41 | 37.91 | 1.73 |
| PSO-PID | 1.3541 | 0.9266 | 0.4378 | 18.82 | 0.815 | 0.149 | 0.328 | 0.0072 | 0.3668 | 0.7250 | 43.55 | 44.50 | 16.67 |
| BBO-PID | 1.2464 | 0.5893 | 0.4596 | 15.52 | 1.446 | 0.149 | 0.317 | 0.0078 | 0.5774 | 0.9656 | 18.38 | 156.38 | 55.39 |
| LUS-PID | 1.2012 | 0.9096 | 0.4593 | 15.56 | 0.800 | 0.149 | 0.322 | 0.0064 | 0.3378 | 0.6577 | 18.68 | 41.84 | 5.84 |
| ABC-PID | 1.6524 | 0.4083 | 0.3654 | 25.01 | 3.094 | 0.156 | 0.360 | 0.0177 | 1.2430 | 2.1295 | 90.77 | 448.58 | 242.69 |
| SSA-PID | 1.3381 | 1.1204 | 0.6361 | 20.30 | 0.690 | 0.119 | 0.263 | 0.0056 | 0.3407 | 0.6203 | 54.84 | 22.34 | 0.25 |
| AEF-PID | 1.1062 | 0.9543 | 0.5178 | 14.30 | 0.7760 | 0.140 | 0.291 | 0.0060 | 0.3300 | 0.6302 | 9.07 | 37.58 | 1.41 |
| HHO-PID | 1.0887 | 0.9882 | 0.5361 | 14.42 | 0.7657 | 0.137 | 0.290 | 0.0060 | 0.3223 | 0.6227 | 9.99 | 35.76 | 0.20 |

Table 3 shows the values of peak-gain, phase margin, delay margin, and bandwidth for different algorithms using Bode analysis. The peak gain for CPSO-AVR is found as 0.79 dB (7.11 rad/s), whereas phase margin and delay margin are 95.8 and 0.178s (9.38 rad/s), respectively. Finally, the bandwidth is 12.267 as shown in Table 3. From the aforementioned analysis, the CPSO-AVR yielded stable and good frequency response as all closed loop poles were in the left half s-plan.

**Robustness analysis.** To evaluate the robustness of CPSO-AVR, time constant of exciter, amplifier, sensor and generator were varied between –50 % to +50 % as shown in Fig. 6. The results of transient response after the variations in AVR parameters are listed in Table 4. It is observed in Table 4 that the total deviation range for different values of parameters of AVR time constants are in acceptable range showing the robustness of AVR system with CPSO algorithm.

Table 3

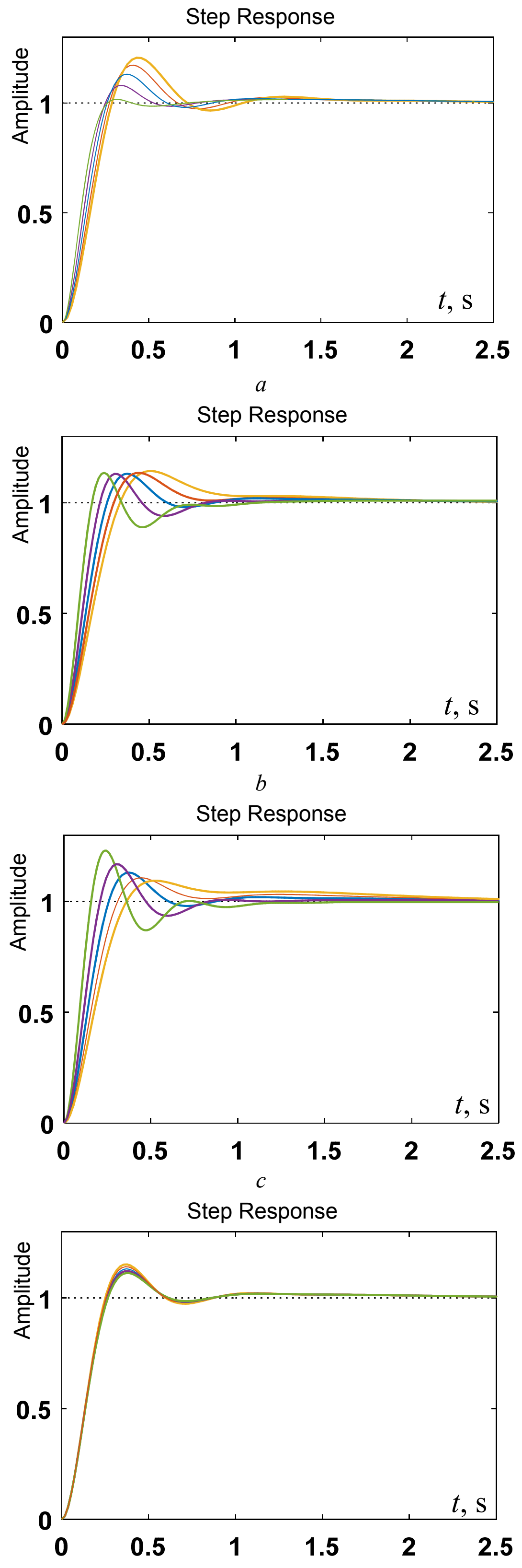
Peak-gain, phase-margin (deg.), delay-margin and bandwidth of automatic voltage regulator system

| Controller | Peak-gain | Phase-margin (deg.) | Delay-margin | Bandwidth |
|---|---|---|---|---|
| CPSO-PID (Proposed) | 0.79 dB (7.11 rad/s) | 95.8 | 0.178 s (9.38 rad/s) | 12.267 |
| IKA-PID | 1.78 dB (10.6 rad/s) | 76.7 | 0.095 s (14.0 rad/s) | 16.785 |
| PSO-PID | 1.79 dB (8.29 rad/s) | 79.3 | 0.121 s (11.5 rad/s) | 13.915 |
| BBO-PID | 1.56 dB (8.65 rad/s) | 81.6 | 0.112 s (11.7 rad/s) | 14.284 |
| LUS-PID | 1.43 dB (8.59 rad/s) | 83.2 | 0.126 s (11.6 rad/s) | 14.208 |
| ABC-PID | 2.87 dB (7.52 rad/s) | 69.4 | 0.111 s (10.9 rad/s) | 12.880 |
| SSA-PID | 1.51 dB (9.7 rad/s) | 80.8 | 0.11 s (12.9 rad/s) | 15.624 |
| AEF-PID | 1.45 dB (9.45 rad/s) | 81.8 | 0.114 s (12.5 rad/s) | 15.286 |
| HHO-PID | 1.51 dB (9.7 rad/s) | 80.8 | 0.11 s (12.9 rad/s) | 15.624 |

Table 4

Robustness analysis of chaotic particle swarm optimization-PID for deviation in parameters of AVR system

| Model parameter | Performance parameter | Rate of change (%) | | | | Range of total deviation |
|---|---|---|---|---|---|---|
| | | –50 | –25 | +25 | +50 | |
| $T_A$ | Peak value (p.u.) | 1.168 | 1.799 | 1.172 | 1.206 | 0.066 |
| | $t_s$, s | 0.2402 | 0.4793 | 1.3530 | 1.4793 | 1.620 |
| | $t_r$, s | 0.1601 | 0.1652 | 0.1846 | 0.1943 | 0.114 |
| | $t_p$, s | 0.3157 | 0.3445 | 0.4104 | 0.4285 | 0.148 |
| $T_E$ | Peak value (p.u.) | 1.135 | 1.130 | 1.13 | 1.143 | 0.010 |
| | $t_s$, s | 0.6548 | 0.7419 | 1.5231 | 1.6749 | 1.969 |
| | $t_r$, s | 0.1155 | 0.1465 | 0.2006 | 0.2257 | 0.294 |
| | $t_p$, s | 0.2421 | 0.3011 | 0.4444 | 0.5156 | 0.381 |
| $T_G$ | Peak value (p.u.) | 1.230 | 1.168 | 1.107 | 1.943 | 0.717 |
| | $t_s$, s | 1.0112 | 0.7536 | 1.8619 | 2.1511 | 2.814 |
| | $t_r$, s | 0.1059 | 0.1409 | 0.2076 | 0.2414 | 0.384 |
| | $t_p$, s | 0.2356 | 0.3002 | 0.4451 | 0.5341 | 0.431 |
| $T_S$ | Peak value (p.u.) | 1.112 | 1.121 | 1.140 | 1.151 | 0.017 |
| | $t_s$, s | 0.5660 | 0.5652 | 1.1758 | 1.1977 | 1.123 |
| | $t_r$, s | 0.1791 | 0.1769 | 0.1724 | 0.1702 | 0.027 |
| | $t_p$, s | 0.3717 | 0.3813 | 0.3649 | 0.3760 | 0.021 |



*a*, *b*, *c*, *d*

Fig. 6. Step response for variation between +50 to –50 in $T_E$ (*a*), $T_A$ (*b*), $T_G$ (*c*), and $T_S$ (*d*)

**Conclusions.**

In this paper, chaotic particle swarm optimization based proportional integral derivative (PID) controller was used for the optimal tuning of automatic voltage regulator system. The logistic map chaotic sequence-based initialization and global best selection enables the algorithm to escape from local minima stagnation and improve its convergence rate and resulting precision. In the process of parameter tuning, the chaotic particle swarm optimization technique was run several times through the proposed objective function, which accommodates the advantages of the two most commonly used objective functions with a minimum number of iterations, and an optimal PID gain value was found. Automatic voltage regulator system with chaotic particle swarm optimization based PID controller minimizes the performance criterion value to obtained optimized parameters of PID. Performance comparisons were performed with 8 optimization algorithms (improved kidney algorithm, particle swarm optimization, bio-geography based optimization, local unimodal sampling, artificial bee colony, slap swarm algorithm, artificial electric filed, and Harris hawks optimization) to demonstrate the usefulness of the chaotic particle swarm optimization based PID for automatic voltage regulator system.

The comparative analysis of results revealed that the proposed chaotic particle swarm optimization based PID controller based system showed an excellent transient response in terms of $t_s$, $\%M_p$ and performance criterion value. In addition, bode analysis, pole-zero and robustness analysis were done to show the system stability optimized by the chaotic particle swarm optimization algorithm. The analyses depict that the stability of automatic voltage regulator system is good and the proposed controller is less affected the possible variations in the parameters of the system. The proposed chaotic particle swarm optimization technique can be implemented to tune the controllers for the swing-up and stabilization for a pendulum-cart system.

**Conflict of interests.** The authors declare no conflicts of interest.

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