Adaptive tuning of PID using chef-based optimization algorithm for improving automatic voltage regulator

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ABSTRACT

This article presents the proportional-integral-derivative (PID) parameter tuning on the automatic voltage regulator (AVR) using the chef-based optimization algorithm (CBOA). CBOA is modeling cooking training activities consisting of students and young chefs in an effort to mature cooking skills. This article uses other methods as a comparison in measuring the performance of the proposed method. The methods used are grasshopper optimization algorithm (GOA) and cooperation search algorithm (CSA). The simulation results show that the proposed method, namely CBOA, has a better ability in the peak value of overshoot, which is 0.232% compared to the CSA method and 12.99% compared to the GOA method.

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1. INTRODUCTION

Technology is developing rapidly and has a direct effect on the existing electrical system. The development of this power system is caused by varying load demands [1]. Power plants must maintain the continuity of energy needs [2]. Energy flows from the generator to the load requires reliable regulation despite frequent load changes in the distribution network [3]. Changes in load will have an impact on overall system performance. The stability of the magnitude and frequency of the voltage must be maintained and this is an important key in the control of the power system [4]. Oscillations caused by disturbances in the power system will indirectly reduce the capability and life of the equipment [5]–[7].

Basically, there are 2 parameters that must be kept in balance, namely the operating voltage level, and operating frequency. This is related to the rotor speed and the excitation of the synchronous generator. This is adjusted on the side of the power plant. At the generator terminal, the frequency and voltage levels are measured. Stability can be obtained with good and precise control. Operating frequency control can be maintained with a load frequency controller (LFC) [8]. On the other hand, the terminal voltage is maintained by an automatic voltage regulator (AVR) [9]–[11].

AVR controllers based on proportional-integral-derivative (PID) have been widely presented in the literature [11]. PID has a simple design and significant influence of each parameter on the controlled output. Many industrial applications have used PID control. On the other hand, PID has a weak point, namely conventional tuning. This has an impact on the less than optimal achievement of performance points [12]. The development of computing technology has an impact on the concept of metaheuristic-based optimization. Several metaheuristic techniques will be presented in 2022, including homonuclear molecules optimization (HMO) [13], gazelle optimization algorithm (GAOA) [14], five phases algorithm (FPA) [15], transit search optimization algorithm (TSOA) [16], and beluga whale optimization (BWO) [17]. Meanwhile, the development of optimization techniques that are integrated with controls such as PID has also increased significantly. Several optimization techniques have been presented based on PID on AVR using metaheuristic methods such as whale optimization algorithm [18], [19] slime mold algorithm [20], Archimedes optimizer [21], gradient-based optimization algorithm [22], equilibrium optimizer algorithm [23], atomic search optimization algorithm [24] and particle swarm optimization [25], [26].

The article presents the concept of tuning PID parameters on AVR using the latest metaheuristic method, namely chef-based optimization algorithm (CBOA). CBOA presented by Trojovská and Dehghani [27]. The CBOA method is effective for overcoming optimization problems. CBOA is able to maintain a balance between exploration and exploitation. In addition, it shows that CBOA is more efficient and competitive [27]. The contributions of this article are: i) Application of the latest metaheuristic method, namely CBOA, to optimize PID parameters on AVR with the aim of obtaining optimal AVR output. ii) To find out the performance of CBOA, this article validates it by comparing it with the grasshopper optimization algorithm (GOA) and cooperation search algorithm (CSA) methods. This article has the following structure: the 2nd presents the method applied and the complete study of the concepts of CBOA and AVR. The 3rd section reviews the results and performance analysis. The last part is to present the conclusions obtained.

2. METHOD

2.1. Chef-based optimization algorithm

The concept of chef-based optimization algorithm is to model cooking training activities consisting of students and young chefs in an effort to improve their skills. As with other metaheuristic concepts, CBOA also has candidate solutions that are always improved during the iteration process. In addition, CBOA is also population-based which has two types, namely cooking students and instructor chefs. Variables of the problem solved by the candidate solution. That parameter is represented as an agent. This concept is modeled as:

$$A = \begin{bmatrix} a_{1,j} \cdots & a_{1,j} & \cdots & a_{1,d} \\ \vdots \quad \ddots & \vdots & \ddots & \vdots \\ a_{nc,1} \cdots & a_{nc,j} & \cdots & a_{nc,d} \\ a_{nc+1,1} \cdots & a_{nc+1,j} & \cdots & a_{nc+1,d} \\ \vdots \quad \ddots & \vdots & \ddots & \vdots \\ a_{n,1} \quad \cdots & a_{n,j} & \cdots & a_{n,j} \end{bmatrix}_{nxd} \tag{1}$$

$$a_{i,j} = LB_j + rand(UB_j - LB_j) \tag{2}$$

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{Nxl} = \begin{bmatrix} F(A_1) \\ \vdots \\ F(A_i) \\ \vdots \\ F(A_N) \end{bmatrix}_{Nx1} \tag{3}$$

where N is the number of chefs, A is the sorted population matrix, and F is the vector of the objective function values. In (1), members from A_1 to A_N are represented by the group of chefs, and members from A_{N+1} to A_N are represented by groups of students. The vector F sequentially inserts the objective function values corresponding to A_1 to A_N. The metaheuristic method has the characteristics of exploration and exploitation phases. CBOA algorithm has 2 phases that describe these characteristics.

2.1.1. Phase 1: update for chef teacher

The phase is illustrated that the chef teacher has an obligation to improve the skills of students which has two steps. The first step, the best teacher is duplicated. This phase describes global search and exploration. This technique is an important step to raise students who trace to the best chefs. This step keeps the local optima away from it. In addition, the search space scanning becomes wide accurate and effective. This phase is modeled in the following mathematical (4)-(5).

$$act_{i,j}{}^{s1} = a_{i,j} + rand(B_j - C \times a_{i,j}) \tag{4}$$

$$A = \begin{cases} act_{i,j}{}^{s1}, Fct_i{}^{s1} < F_i \\ \quad A, else \end{cases} \tag{5}$$

Where $act_{i,j}^{s1}$ is the new state counted using the first step for renewing the chef teacher based on step one. B_j is the jth coordinate of the best chef instructor, $rand$ is a random number [0,1], and C is a digit selected at random through the processing of the set. CBOA will choose a new position if it has the ability to improve the objective function. In the second step, the skills of the chef teachers are improved based on individual activities and exercises. This second step concept describes local exploitation and search. Cooking skills are symbolized as problem variables. Chef teacher's ability is improved with the aim of achieving a good objective function value. Step two can be modeled mathematically as:

$$LB_j^{local} = \frac{LB_j}{t} \tag{6}$$

$$UB_j^{local} = \frac{UB_j}{t} \tag{7}$$

$$act_{i,j}^{s2} = a_{i,j} + LB_j^{local} + rand\left(UB_j^{local} - LB_j^{local}\right), i = 1,2, \dots .nc, j = 1,2, \dots .d. \tag{8}$$

$$A = \begin{cases} act_{i,j}^{s2}, Fct_i^{s2} < F_i \\ A, else \end{cases} \tag{9}$$

where LB_j^{local} and UB_j^{local} are the lower and upper local bound. The parameter t represents the iteration counter. $act_{i,j}^{s2}$ is the new state counted using the first step for renewing the chef teacher based on step two.

2.1.2. Phase 2: update for student

In phase 2, students learn to cook at a culinary school. This phase has 3 steps modeled on how students learn cooking skills. In the first step, students choose a class at random which is taught by the chef teacher. The first step is modeled mathematically as:

$$act_{i,j}^{s1} = a_{i,j} + rand(CT_{i,j} - C \times a_{i,j}) \tag{10}$$

$$A = \begin{cases} act_{i,j}^{s1}, Fct_i^{s1} < F_i \\ A, else \end{cases} \tag{11}$$

where $CT_{i,j}$ The elected chef teacher by the cooking student. In the second step, students will fully duplicate the skills of the cooking teacher. This step adds global search acceleration and search capabilities. The new position is calculated based on the student using (12).

$$act_{i,j}^{s2} = \begin{cases} CT_{i,j}, j = l \\ a_{i,j}, else \end{cases} \tag{12}$$

$$A = \begin{cases} act_{i,j}^{s2}, Fct_i^{s2} < F_i \\ A, else \end{cases} \tag{13}$$

In the third step, students explore cooking skills based on their own practice and activities. Conceptually, this step describes local exploitation and search capabilities.

$$act_{i,j}^{s3} = \begin{cases} a_{i,j} + LB_j^{local} + rand\left(UB_j^{local} - LB_j^{local}\right), j = q \\ a_{i,j}, else \end{cases} \tag{14}$$

$$A = \begin{cases} act_{i,j}^{s3}, Fct_i^{s3} < F_i \\ A, else \end{cases} \tag{15}$$

Where $act_{i,j}^{s3}$ is the new state counted using the second step for renewing the chef teacher based on third step. Fct_i^{s3} is the grade of the objective function of $act_{i,j}^{s3}$.

2.2. Automatic voltage regulator system (AVR)

Synchronous alternator excitation control is the key to maintaining power system stability and electrical power quality. The AVR has a function to preserve the level of the synchronous alternator terminal voltage at its nominal value [28]. A simple AVR system consists of four main components, namely sensors, amplifiers, exciters and generators. The generator terminal voltage is precisely sensed by the voltage sensor [29]. This signal is corrected, delicated and opposed with the reference signal in the comparator. The transfer function of the four components illustrated in Figure 1 is assumed to be linear which takes into account the time constant and ignores saturation or other nonlinearities.

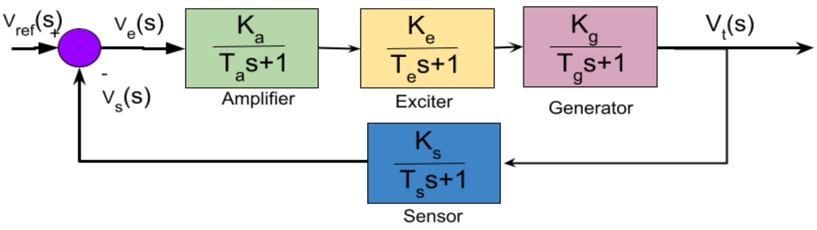


Figure 1. Transfer function design of the AVR without control [30]

2.3. The proposed CBOA controller in AVR system

In this section, a proposed CBOA-tuned PID controller, called PID-CBOA controller, is presented to enhance the transient response of the AVR system better. The block diagram of the PID-CBOA-based AVR system is shown in Figure 2. The performance of the PID-CBOA is measured by a performance index. This article uses integral total weighted absolute value error (ITAE) to analyze and design controls. ITAE mathematical equations are presented in (16).

$$ITAE = \int_0^{\infty} t.e(t).dt \quad (16)$$

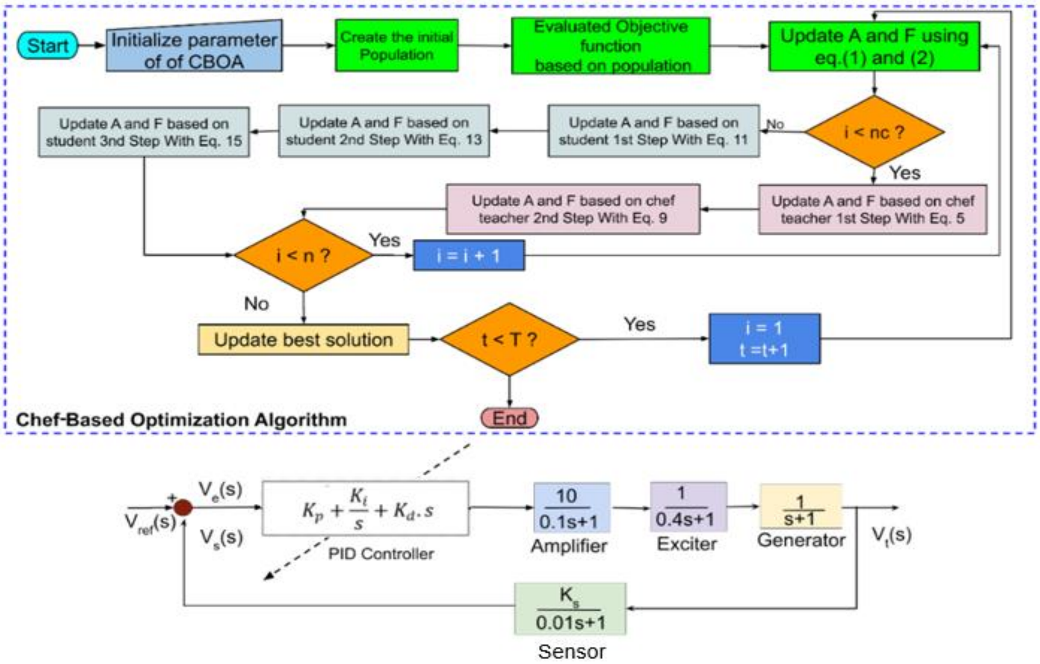


Figure 2. The AVR with PID and CBOA

3. RESULTS AND DISCUSSION

The CBOA program is coded in MATLAB/Simulink with Laptop hardware that has Intel I5 specifications (2.2 GHz) and 8 GB RAM. To review the performance of the CBOA method, this article uses 2 validations, namely the measurement of the convergence curve profile and the measurement on the AVR. It aims to obtain performance validation of the proposed method.

3.1. Convergence curve profile

The measurement of the convergence curve uses a benchmark function of 23 which consists of three categories, namely unimodal, multimodal and multimodal with fixed dimension functions. The benchmark functions in this article can be seen in Table 1 to Table 3. Unimodal functions from F1 to F7 can be seen in Table 1. Meanwhile, multimodal functions can be seen from F8 to F13 can be seen in Table 2. Functions F14 to F23 are multimodal functions with fixed dimensions can be seen in Table 3. Performance measurement with a convergence curve uses 2 comparison methods, namely GOA and CSA and is illustrated in Figure 3. Unimodal functions can be seen in Figure 3(a) to Figure 3(g), multimodal can be seen in Figure 3(h) to Figure 3(m) and multimodal with fixed dimensions is presented in Figure 3(n) to Figure 3(w). Basically, the quality of the solution is measured by assessing the degree of the minimum Fitness Function obtained in the end of iteration. The level of convergence is measured based on the speed of the convergence; namely how many iterations are achieved to achieve the most optimal value. The results of the minimization of the Fitness Function are considered for tuning the PID parameters on the AVR. The smaller the Fitness Function obtained; the quality of the resulting solution is getting more promising.

Table 1. Unimodal function

Test function	Range
$F_1(x) = \sum_{i=1}^{n} X_i^{\,2}$	$[-100,100]^n$
$F_2(x) = \sum_{i=1}^{n} \lvert X_i \rvert + \prod_{i=1}^{n} \lvert X_i \rvert$	$[-10,10]^n$
$F_3(x) = \sum_{i=1}^{n} (\sum_{j=1}^{n} \lvert X_i \rvert)^2$	$[-100,100]^n$
$F_4(x) = \max \{\lvert X_i \rvert, 1 \le i \le n\}$	$[-100,100]^n$
$F_5(x) = \sum_{i=1}^{i_{n-1}} [100(x_{i+1} - x_1^{\,2})^2 + (x_i - 1)^2]$	$[-30,30]^n$
$F_6(x) = \sum_{i=1}^{n} (\lvert X_i + 0.5 \rvert)^2$	$[-100,100]^n$
$F_7(x) = \sum_{i=1}^{n} i X_i^{\,4} + random(0,1)$	$[-1.28,1.28]^n$

Table 2. Multimodal function

Test function	Range
$F_8(x) = \sum_{i=1}^{n} -X_i \sin(\sqrt{\lvert X_i \rvert})$	$[-500,500]^n$
$F_9(x) = \sum_{i=1}^{n} [X_i^{\,2} - 10\cos(2\pi X_i) + 10]$	$[-5.12,5.12]^n$
$F_{10}(x) = -20\exp(-0.2\sqrt{\frac{1}{n}\sum_{j=1}^{n} X_i^{\,2}}) - \exp(\frac{1}{n}\sum_{i=1}^{n}\cos(2\pi X_i)) + 20 + e$	$[-32,32]^n$
$F_{11}(x) = \frac{1}{4000}\sum_{i=1}^{n} X_i^{\,2} + \prod_{i=1}^{n}\cos(\frac{X_i}{\sqrt{i}}) + 1$	$[-20,20]^n$
$F_{12}(x) = \frac{\pi}{n}\{10\sin(\pi y_1) + \sum_{i=1}^{n-1}(y_i - 1)^2[1 + 10\,sin^2(\pi y_{i+1}) + (y_i - 1)^2]\} + \sum_{i=1}^{n} u(x_i, 10,100,4)$ $y_i = 1 + \frac{x_i + 1}{4}$ $U(x_i, a, k, m) = \begin{cases} k(x_i - a)^m & x_i > a \\ 0 & -a < x_i < a \\ k(-x_i - a)^m & x_i < -a \end{cases}$	$[-50,50]^n$
$F_{13}(x) = 0.1\{\{\sin^2(3\pi x_i) + \sum_{i=1}^{n}(X_i - 1)^2[1 + \sin^2(3\pi x_i + 1)] + (X_i - 1)^2[1 + \sin^2(2\pi x_n)]\} + \sum_{i=1}^{n} u(X_i, 5,100,4)$	$[-50,50]^n$

Table 3. Multimodal function with fix dimension

Test function	Range
$F_{14}(x) = (\frac{1}{500} + \sum_{j=1}^{25}\frac{1}{j + \sum_{i=1}^{2}(x_i - a_{ij})^6})^{-1}$	$[-65.53,65.53]^2$
$F_{15}(x) = \sum_{j=1}^{11}\left[a_i - \frac{x_i(b_i^{\,2} + b_i x_2)}{b_i^{\,2} + b_i x_3 + x_4}\right]^2$	$[-5,5]^4$
$F_{16}(x) = 4x_i^{\,2} - 2.1x_1^{\,4} + \frac{1}{3}x_1^{\,6} + x_1 x_2 - 4x_2^{\,2} + 4x_2^{\,4}$	$[-5,5]^2$
$F_{17}(x) = \left(x_2 - \frac{5.1}{4\pi^2}x_1^{\,2} + \frac{5}{\pi}x_1 - 6\right)^2 + 10\left(1 - \frac{1}{8\pi}\right)\cos x_1 + 10$	$[-5,10] \times [0,15]$
$F_{18}(x) = [1 + (x_1 + x_2 + 1)^2(19 - 14x_1 + 3x_1^{\,2} - 14x_2 + 6x_1x_2 + 3x_2^{\,2})] \times [30 + (2x_1 - 3x_2)^2 \times (18 - 32x_1 + 12x_1^{\,2} + 48x_2 - 36x_1x_2 + 27x_2^{\,2})]$	$[-2,2]^2$
$F_{19}(x) = -\sum_{i=1}^{4} C_i \exp(-\sum_{i=1}^{3} a_{ij}(X_i - p_{ij})^2)$	$[0,1]^3$
$F_{20}(x) = -\sum_{i=1}^{4} C_i \exp(-\sum_{i=1}^{6} a_{ij}(X_i - p_{ij})^2)$	$[0,1]^6$
$F_{21}(x) = -\sum_{i=1}^{5}[(X - a_i)(X - a_i)^T + C_i]^{-1}$	$[0,10]^4$
$F_{22}(x) = -\sum_{i=1}^{7}[(X - a_i)(X - a_i)^T + C_i]^{-1}$	$[0,10]^4$
$F_{23}(x) = -\sum_{i=1}^{10}[(X - a_i)(X - a_i)^T + C_i]^{-1}$	$[0,10]^4$

3.2. Transient response measurement

The first step is to design a model of the AVR by integrating the PID. PID parameters are searched and optimized using the CBOA algorithm. The PID parameters obtained are shown in Table 4. The CBOA-based AVR system was analyzed for transient response with transfer function. The input source uses a unit step signal. In this article, transit responses using indicators such as overshoot, rise time (tr), and settling time (ts) are applied for analysis and comparison, and, as per Figure 4, the values for the proposed CBOA-PID System are 1.125, 0.198 s and 1.6 s, respectively. Comparative analysis with other methods as shown in Table 5 shows that the maximum overshoot value of the PID-CBOA method has a better value of 0.232% compared to the PID-CSA method, and 12.99% compared to the PID-GOA.

Table 4. The result PID value

Method	P	I	D
GOA	1.3825	1.4608	0.5462
CSA [31]	0.9265	0.645	0.2875
CBOA	0.9135	0.6366	0.2825

Table 5. Comparative analysis of the response transient

Controller	Overshoot	tr	ts	ITAE
PID-GOA	1.293	0.13	3.51	0.0745
PID-CSA	1.128	0.198	1.9	0.0399
PID-CBOA	1.125	0.198	1.6	0.0399

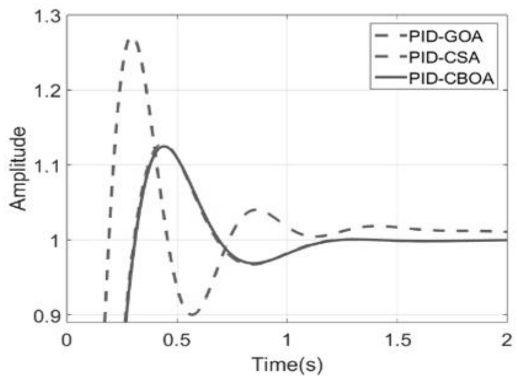


Figure 4. Comparative analysis of the proposed CBOA-based PID design

4. CONCLUSION

This article presents the latest PID parameter optimization method, namely CBOA. The CBOA algorithm adopts the learning activities of cooking students and teachers in culinary schools. Frequent load changes are a problem for generators. AVR is applied to keep the synchronous generator voltage balance and improve stability. Irregularities and less than optimal tuning of control parameters on the AVR can be overcome by optimization methods. To get the performance of the CBOA applied to the AVR control, a comparison with the GOA and CSA methods is used. The simulation results show that the CBOA method applied to PID in AVR has promising performance.

APPENDIX

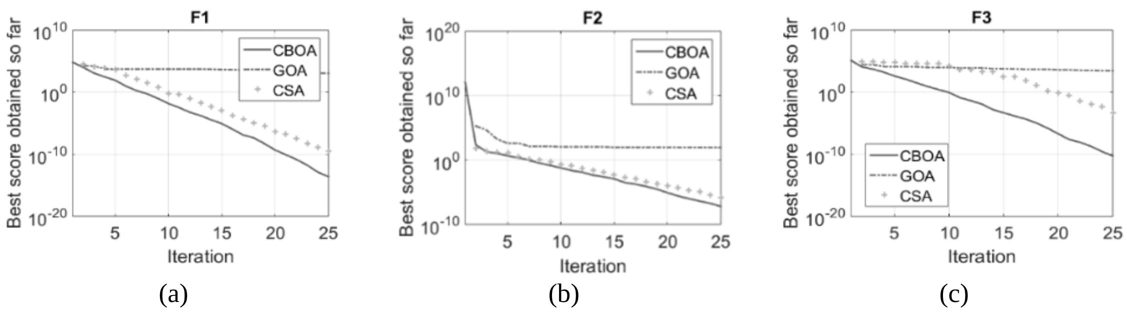


Figure 3. Convergence curve of benchmark function: (a) F1, (b) F2, and (c) F3

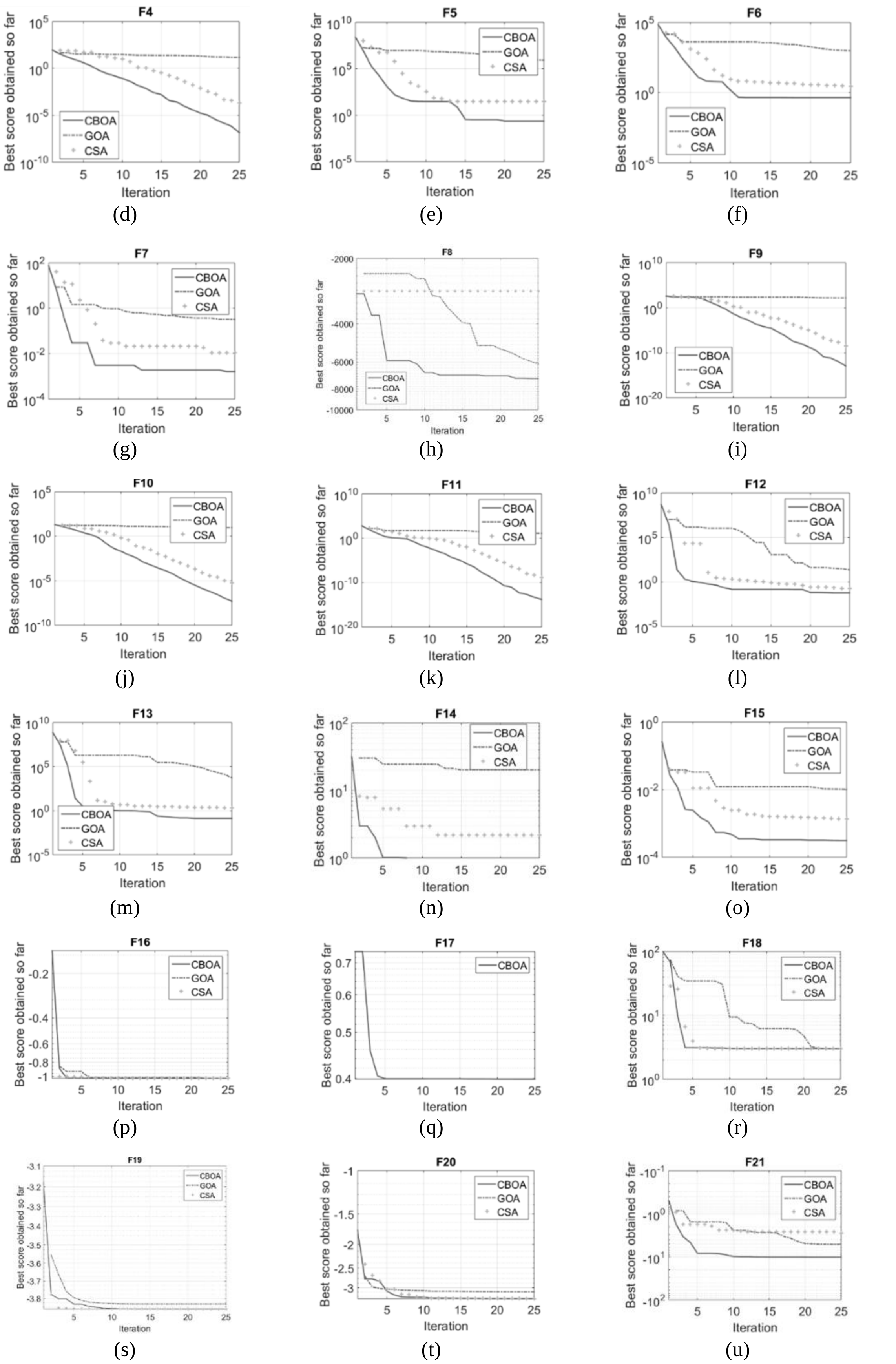
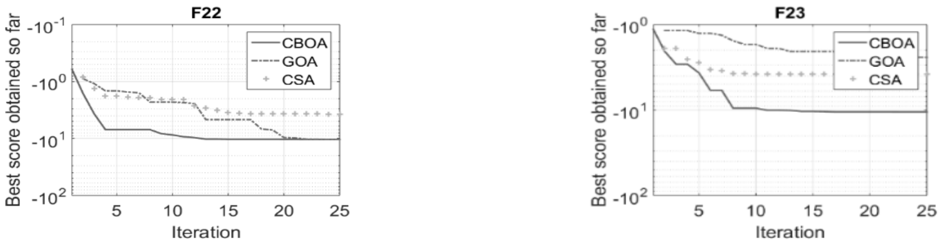


Figure 3. Convergence curve of benchmark function: (d) F4, (e) F5, (f) F6, (g) F7, (h) F8, (i) F9, (j) F10, (k) F11, (l) F12, (m) F13, (n) F14, (o) F15, (p) F16, (q) F17, (r) F18, (s) F19, (t) F20, and (u) F21 *(continue)*



(v) (w)

Figure 3. Convergence curve of benchmark function: (v) F22 and (w) F23 *(continue)*

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