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Optimal tuning fractional order PID based on marine predator algorithm for DC motor

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ABSTRACT

DC motors are a popular topic because they are widely applied in various electronic equipment. So, this requires a control that is fast and reliable. The development of optimized control methods is growing rapidly with the discovery of several new methods. Marine predator algorithm (MPA) is an optimization method based on marine life between living things. This article discusses the application of the MPA method for optimizing fractional order PID (FOPID) control on DC motors. The implementation of the FOPID controller is also difficult because the fractional calculus operators of the FOPID controller cannot be directly implemented in numerical calculations. The method proposed in this article is the FOPID-MPA method. To get a performance test of the proposed method, this study uses several comparison methods, namely the seagull optimization algorithm (ASO), chimp optimization algorithm (ChOA), and sine tree seed algorithm (STSA). This study also uses a variation of the reference speed to get the performance of the proposed method. From the experiment it is known that the FOPID-MPA method gives the best performance. The FOPID-MPA method has an overshoot value of 4.34% compared to the PID-MPA method in case study 1 and has an integrated of time-weighted-squared-error (ITSE) value of 7.44% better than the PID-MPA method in case study 2.

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1. INTRODUCTION

The increase in the use of green technology for electricity generation is increasing and spreading [1]. The application of DC motors among industry or households has been so popular. DC motors are used to support electronic systems [2]–[5]. The advantages of DC motors have high torque, have no reactive power losses and do not cause harmonics in the electric power system that supplies them. PID controllers have been widely applied because of their simple structure, robustness and ease of adjustment under various operating conditions [6]–[8]. Along with the development of computing, control theory experienced a significant shift.

The fractional order controller described by a fractional order differential equation whose function is to extend the derivative and integral to a fractional order can adjust the frequency response of the control system directly and continuously. The fractional order proportional-integral-derivative controller (FOPID) has been widely applied and considerable attention in recent years from both an industrial and academic point of view. FOPID provides more flexibility in controller design compared to PID controllers [9]–[11]. FOPID has a structure of five parameters [12]. Indirectly, this implies that FOPID has a much more complex controller setup. However, the performance of the FOPID controller also depends on the appropriate design. This is the same as the PID controller design. A well-designed FOPID controller can respond to system uncertainty and disturbance effects by providing a good dynamic response.

Methods with highly effective tuning need to be applied to replace the classic, low-performance tuning methods which have the characteristic of being time-consuming. Metaheuristic algorithm is a very popular adaptive method because it has good performance. This method has the ability to perform a stochastic search in the solution space. Several variants of the metaheuristic algorithm applied to FOPID have been presented by several researchers such as: Cuckoo search [13], [14], Harris hawks optimization [15], grasshopper optimization algorithm [16], [17], Jaya optimization algorithm [18], Henry gas solubility [19], grey wolf optimization [20]–[22], and gradient-based optimization algorithm [23]. Improved control optimization by several methods provides better performance than classic controls. From the literature reviewed, there is still a lot of room that can be exported for DC motor control in the focus of transient response.

This article presents the application of the marine predator algorithm (MPA) as an optimization of the FOPID parameter in DC motors. the contribution of this research is:

– Application of the MPA method used to tune FOPID parameters that are difficult to approach with numerical calculations.
– Comparison of MPA performance with seagull optimization algorithm (ASO), chimp optimization algorithm (ChOA), and sine tree seed algorithm (STSA).

The article is organized into the following sections: section 2 describes the MPA, DC motor and FOPID methods. In section 3, the results and analysis are reviewed. Meanwhile, section 4 contains a summary of the articles.

2. METHOD

2.1. Marine predator algorithm (MPA)

The MPA is inspired by the life of the marine ecosystem. MPA has the character that it can store the optimization results [24]. This advantage is not owned by other methods. MPA is a metaheuristic method that has characters starting from random values.

$$Y_0 = L_b + rand(U_b - L_b) \tag{1}$$

Where L_b is the lower limit and U_b is the upper limit. $rand$ is a random number. Search agents in MPA are assumed to be prey and predators. The top predator called elite is found at the end of each iteration. Elite and Prey can be formulated in the following matrix:

$$Elite = \begin{bmatrix} A_{1.1}^I & A_{1,2}^I & \cdots & A_{1.d}^I \\ A_{2.1}^I & A_{2.2}^I & \cdots & A_{2.d}^I \\ \vdots & \vdots & \vdots & \vdots \\ A_{n.1}^I & A_{n.2}^I & \dots & A_{n.d}^I \end{bmatrix} \tag{2}$$

$$Prey = \begin{bmatrix} X_{1.1}^I & X_{1,2}^I & \cdots & X_{1.j}^I \\ X_{2.1}^I & X_{2.2}^I & \cdots & X_{2.j}^I \\ \vdots & \vdots & \vdots & \vdots \\ X_{i.1}^I & X_{n.2}^I & \dots & X_{i.j}^I \end{bmatrix} \tag{3}$$

The position of the prey is updated using the MPA's three stages. These three stages are related to the ratio of the speed of the prey to the predator.

i) Step 1: High speed

At this stage, prey and predators move in the same area, and this movement simulates the process of searching for prey. In this phase, the prey is looking for food and the predator is watching the movement of the prey. When $< \frac{1}{3} \times \max\_iter$, this movement can be formulated in (4) and (5).

$$\overrightarrow{Sh_i} = \overrightarrow{R_b} \otimes \left(\overrightarrow{Elite_i} - \overrightarrow{R_b} \overrightarrow{\otimes Prey_i}\right) \; i = 1,2 \dots . n \tag{4}$$

$$\overrightarrow{Prey_i} = \overrightarrow{Prey_i} + P \times \vec{R} \otimes \overrightarrow{Sh_i} \tag{5}$$

The $\otimes$ is operation of element-wise multiplication. $\overrightarrow{R_b}$ is a random value. It is based on Brownian motion with normal distribution. $\vec{R} \in [0.1]$. P is uniform random value equal to 0.5.

ii) Stage 2: Equal speed

In this phase, exploration is turned into exploitation. predators and prey have the same speed. When $\frac{1}{3} \times \max\_iter < iter < \frac{2}{3} \times \max\_iter$.

$$\overrightarrow{Sh_i} = \overrightarrow{R_L} \otimes \left(\overrightarrow{Elite_i} - \overrightarrow{R_L} \otimes \overrightarrow{Prey_i}\right) \quad i = 1,2 \ldots . n/2 \tag{6}$$

$$\overrightarrow{Prey_i} = \overrightarrow{Prey_i} + P \times \vec{R} \otimes \overrightarrow{Sh_i} \tag{7}$$

In the first population, $\overrightarrow{R_L}$ denotes random numbers based on the distribution. Prey movement is simulated by $\overrightarrow{R_L}$ multiplication. While the second half of the population, the mathematical equation is as follows:

$$\overrightarrow{Sh_i} = \overrightarrow{R_b} \otimes \left(\overrightarrow{R_b} \otimes \overrightarrow{Elite_i} - \overrightarrow{Prey_i}\right) \; i = n/2, \ldots . n \tag{8}$$

$$\overrightarrow{Prey_i} = \overrightarrow{Prey_i} + P \times CF \otimes \overrightarrow{Ss_i} \tag{9}$$

$$CF = \left(1 - \frac{Iter}{max\_iter}\right)^{\left(2\frac{Iter}{max\_iter}\right)} \tag{10}$$

Predatory movements are controlled by adaptive parameters, namely CF.

iii) Stage 3: Low-speed

In this last phase, the prey has a speed below the predator. When $iter > \frac{2}{3} \times \max\_iter$, the mathematical equation is as follows:

$$\overrightarrow{Sh_i} = \overrightarrow{R_L} \otimes \left(\overrightarrow{R_L} \otimes \overrightarrow{Elite_i} - \otimes \overrightarrow{Prey_i}\right) \quad i = 1 \ldots . n \tag{11}$$

$$\overrightarrow{Prey_i} = \overrightarrow{Prey_i} + P \times CF \otimes \overrightarrow{Sh_i} \tag{12}$$

One of the environmental problems that affect the behavior of marine ecosystems is fish aggregating devices (FADs). This is one of the equations calculated in the MPA. The FADs equation modeling is as follows:

$$\overrightarrow{Prey_i} = \begin{cases} \overrightarrow{Prey_i} + CF \times [Z_0 = Z_{min} + \vec{R} \otimes (Z_{max} - Z_{min})] \otimes A \\ \quad if\ r \leq FADs \\ \overrightarrow{Prey_i} + [FADs\,(1 - r) + r](\overrightarrow{Prey_{r1}} - \overrightarrow{Prey_{r2}}) \\ \quad if\ r > FADs \end{cases} \tag{13}$$

where r is a uniform random variable. x_{max} is the upper limit and x_{min} is the lower limit. the optimization process is affected when the $FADs$ is 0.2. A is a binary vector.

2.2. DC motor schematic

A DC motor is an electrical device that uses a DC input voltage as a managing parameter. Field control and armature control are controllers in DC motor. Schematically, the relationships between DC motors and armature control are shown in Figure 1.

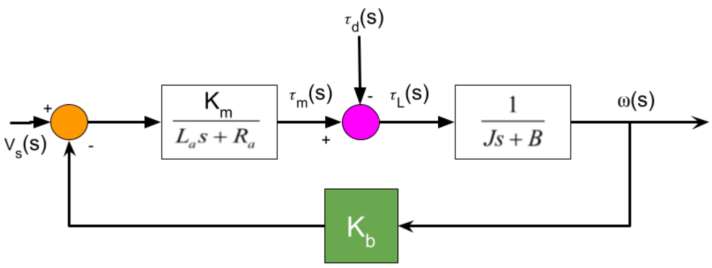

Figure 1. The DC motor schematic [25]

2.3. Fractional order PID

Fractional order is described by a fractional order differential which has derivatives and integrals of fractional order. The FOPID controller is a development of the PID controller model that has been around for a long time and is widely applied in industrial control systems. FOPID controls drive correction when errors between reference points and process variables occur [26]–[29]. This is done by calculating and responding with corrections that can adjust the process accordingly. The FOPID control model is as follows:

$$C_c(s) = k_p + k_i s^{-\lambda} + s^{\mu} k_d \tag{14}$$

The conventional frequency-domain method consists of three specifications, namely the crossover frequency gain (ω_c), phase boundary (φ_m), and phase slope at ω_c. Where G(s) is the plant and C(s) is the controller.

$$|C_c(j\omega_c)G_c(j\omega_c)| = 1 \tag{15}$$

$$Arg|C_c(j\omega_c)| + Arg|G_c(j\omega_c)| = -\pi + \varphi_m \tag{16}$$

$$\left.\frac{d|\text{Arg}\,|C_c(j\omega_c)G_c(j\omega_c)||}{d\omega}\right|_{\omega=\omega_c} = 0 \tag{17}$$

FOPID has five parameters to find. Where k_p is the proportional gain, k_i is the integral gain, k_d is the derivative gain, λ is the fractional order integral and μ is the fractional-order derivative. λ and μ are real numbers that have a range of $0 < \lambda < 2$ and $0 < \mu < 2$.

2.4. The proposed MPA for FOPID in DC motor

DC motor control is set using MPA-based FOPID or PID Parameters. A random value is used as the initialization of MPA. MPA is limited to a predetermined iteration. DC motor control using FOPID can be illustrated in Figure 2.

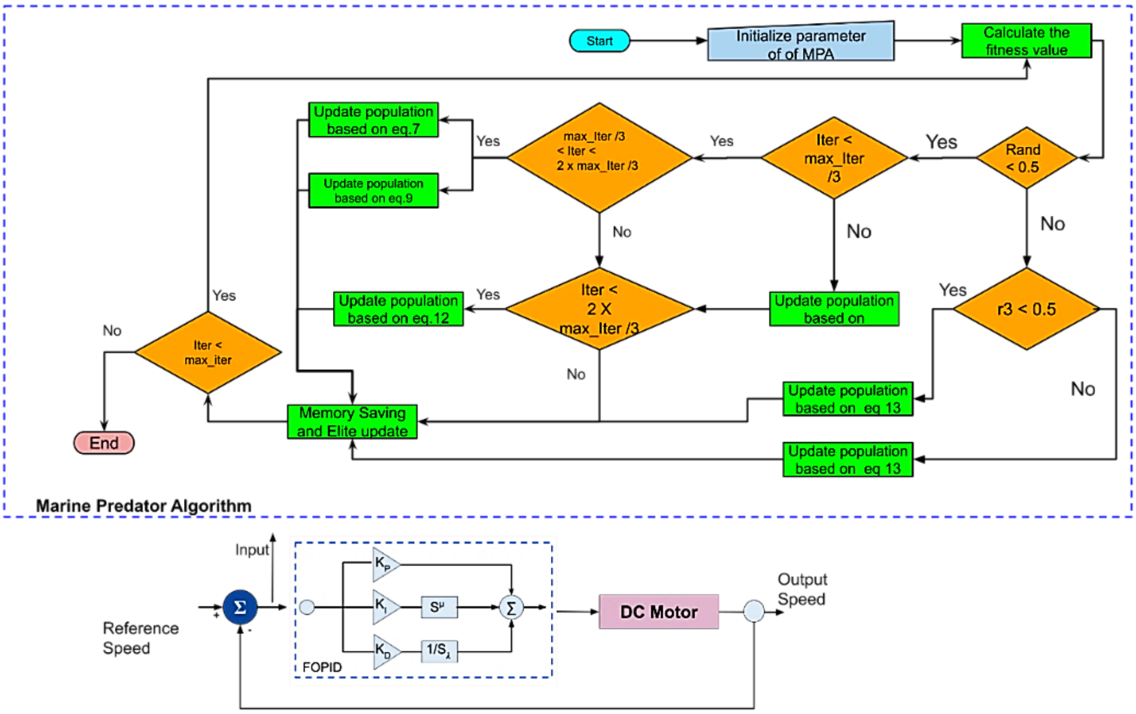

Figure 2. A FOPID based on MPA

3. RESULTS AND DISCUSSION

MATLAB/Simulink is used to model DC motor and implement MPA. In this paper, controller evaluation is carried out by measuring the transient response of a DC motor. FOPID parameters, namely P, I, D, λ and μ which are well regulated can produce step responses that can improve control performance. Table 1 display the MPA parameters used in this paper.

The optimal function is used to determine the performance of MPA. The convergence curve can be seen in Figure 3 (see Appendix). The unimodal function can be seen in Figures 3(a)-(g). while the multimodal function can be seen in Figures 3(h)-(m). Finally, the composite function can be seen in Figure 3(n)-(s). The optimization results of each algorithm can be seen in Table 2. Integrated of time-weighted-squared-error (ITSE) is popularly used for measuring control performance because they can perform good evaluations. The ITSE is used more as an objective function to set control gains. ITSE is most often applied to systems that require fast setup times. In this article ITSE is used as an evaluation. ITSE equation [30] is as follows:

$$ITSE = \int_0^{\infty} t.e^2(t).dt \quad (18)$$

Tabel 1. MPA Parameters

No.	Parameter	Value
1	Prey	50
2	$FADs$	0.2
3	Iterasi	50
4	P	0.2
5	Dim	4

Tabel 2. Optimized parameters

Method	K_P	K_I	K_d	λ	μ
PID – ChOA	3.2061	10	0.1699	-	-
PID – SOA	3.1251	10	0	-	-
PID – STSA	3.2522	10	0	-	-
PID - MPA	3.1837	10	2.4775	-	-
FOPID -MPA	3.7567	9.99	0.5422	1.0001	0.5

In this article, two case studies are used, namely study 1 with a reference speed of 1 and study 2 with variable reference speed. In case study 1, the FOPID-MPA method has the best ITSE value of 0.2779. FOPID-MPA method has an overshoot value of 1.0001. This value is close to the reference value, namely 1. In case study 1, the worst overshoot value is owned by the PID-ChOA method, which is 1.0022. The simulation results from study 1 can be seen in detail in Table 3 and Figure 4.

Table 3. DC motor output with reference speed of 1

Controller	Overshoot	Rise time	Settling time	ITSE
PID - SOA	1.0037	0.1759	0.2766	0.2939
PID-ChOA	1.0045	0.1826	0.2788	0.2958
PID-STSA	1.0027	0.1774	0.2841	0.2905
PID-MPA	1.0027	0.1774	0.2841	0.2905
FOPID-MPA	1.0019	0.1969	0.3163	0.2779

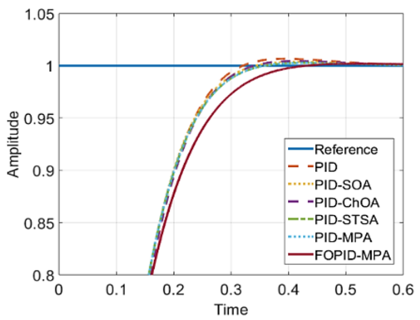

Figure 4. The result of DC motor in study 1

In case study 2, the reference speed was varied 3 times. First start, the reference speed is 0.5. Then it is increased until it reaches the reference speed of 1. Finally, the reference speed is lowered to 0.25. From the change in reference speed, the FOPID-MPA method has the best ITSE value of 0.4274. When the reference speed is 0.5, the overshoot value of the FOPID-MPA method is 0.5009. Then the reference speed is increased to 1, the FOPID-PID method has an overshoot of 1.0001. The decrease in reference speed to 0.25 was responded well by the FOPID-MPA method with an undershoot value of 0.2486. This value has an error of 0.8%. The simulation results from study 2 can be seen in detail in Table 4.

Table 4. DC motor output with variable reference speed

Controller	Overshoot step 1	Overshoot step 2	Undershoot step 3	Rise time	Settling time	ITSE
PID - SOA	0.5018	1.0018	0.2472	0.0621	1.276	0.4638
PID - ChOA	0.5022	1.0022	0.2467	0.0662	1.279	0.4565
PID - STSA	0.5014	1.0014	0.2481	0.06158	1.282	0.4592
PID - MPA	0.5013	1.0014	0.2480	0.06158	1.281	0.4592
FOPID - MPA	0.5009	1.0001	0.2486	0.0596	1.317	0.4274

4. CONCLUSION

The article review usage of the MPA to FOPID in DC motors. The MPA is inspired by marine ecosystem life and has the advantage of being able to store optimization results. This article uses several comparison methods, namely ASO, ChOA, and STSA. The comparison method is used for proportional-integral-derivative (PID) control. In this article, 2 case studies are used. In case study 1, the FOPID-MPA method has the best ITSE value of 0.2779. The ITSE value of FOPID-MPA is 4.34% better than the PID-MPA method. The overshoot value of the FOPID-MPA method is 1.0019. The overshoot value of FOPID-MPA is 4.34% better than the PID-MPA method. In case study 2, the ITSE of the FOPID-MPA method is 7.44% better than the PID-MPA. In this article, it is found that the application of the FOPID-MPA method shows better performance than the PID-MPA method.

APPENDIX

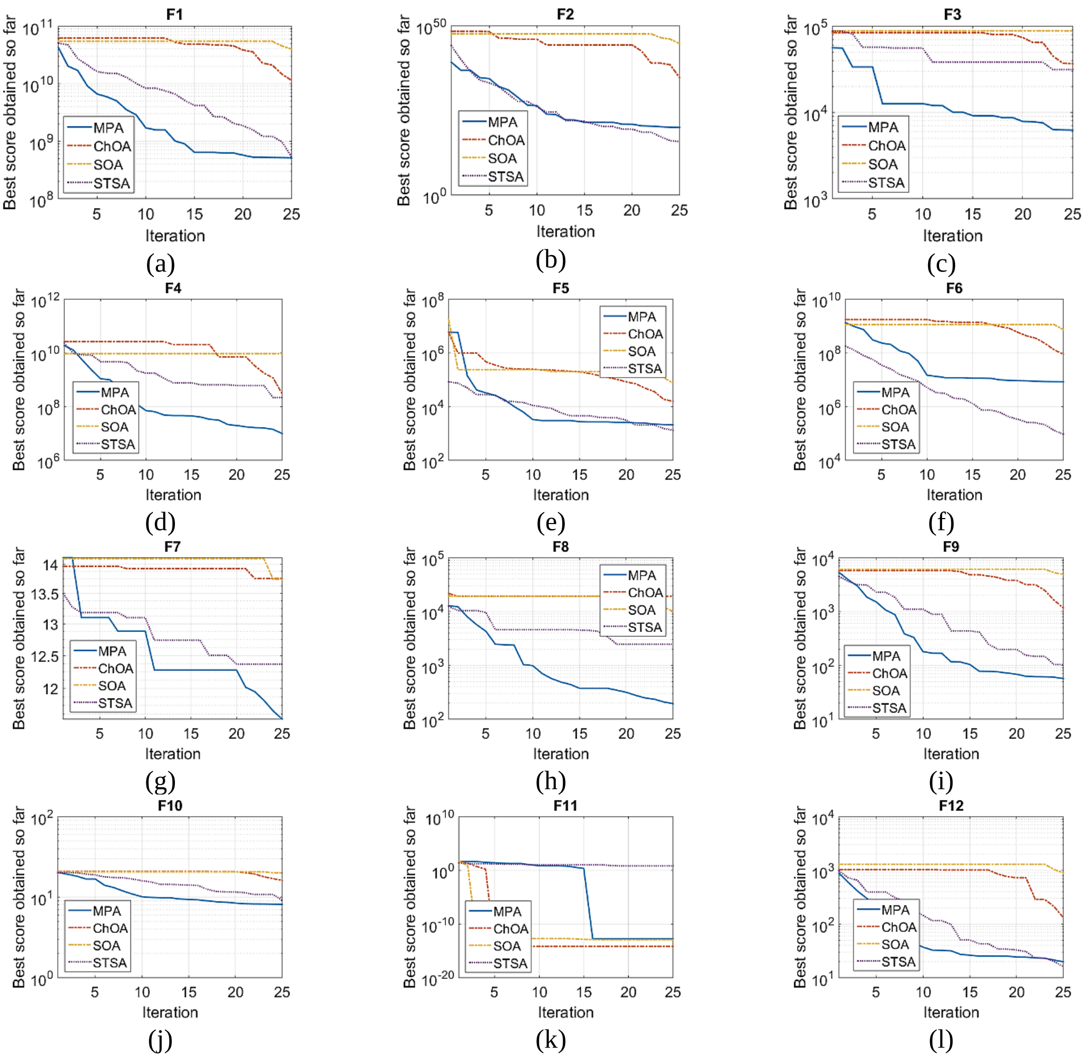

Figure 3. The convergence curve: (a) F1, (b) F2, (c) F3, (d) F4, (e) F5, (f) F6, (g) F7, (h) F8, (i) F9, (j) F10, (k) F11, and (l) F12

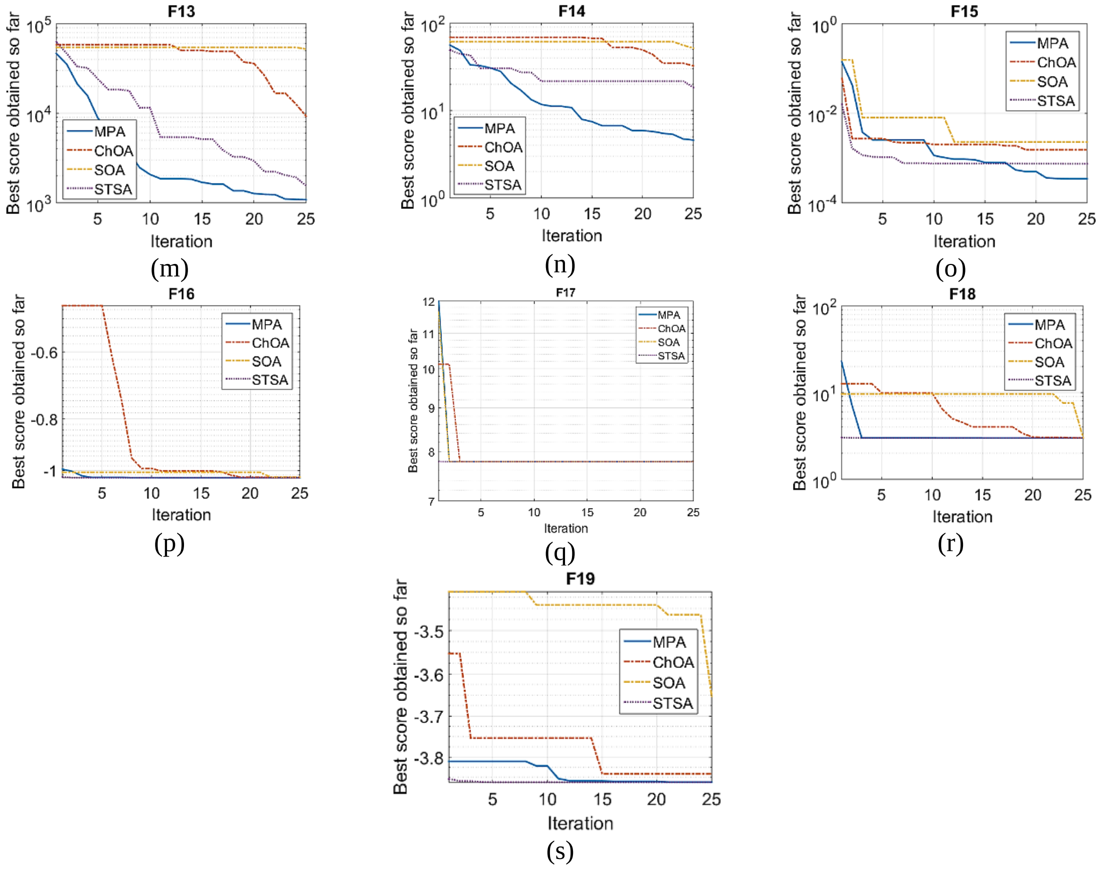

Figure 3. The convergence curve: (m) F13, (n) F14, (o) F15, (p) F16, (q) F17, (r) F18, and (s) F19 (continue)

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