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Dung-beetle-optimization algorithm-based P-I-D controller for a separately excited DC-motor

Kerrache Soumia[1], Haidas Mohammed[2]
[1]Department of Electrical Engineering, Faculty of Technology, Information Technology and Telecommunication Laboratory, University of Tahri Mohammed, Bechar, Algeria
[2]Department of Material Sciences, Faculty of Exact Sciences, Smart Grids and Renewable Energies Laboratory, University of Tahri Mohammed, Bechar, Algeria

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ABSTRACT

Understanding the proportional, integral, and derivative (P-I-D) control system is crucial for optimizing its parameters to achieve the desired system performance. The proportional gain determines how aggressively the system responds to the error, while the integral gain helps to eliminate any steady-state error. The derivative gain plays a role in stabilizing the system by damping out any oscillations caused by sudden changes in the error. P-I-D control is a widely used control technique in various engineering applications, including the control of DC-motors, which is refers to adjust the motor's input voltage, current, speed or position in order to achieve a desired output. One approach to tuning P-I-D parameters is the ziegler-nichols (ZN) methods, where the first one involves to plot the step response of the model's open loop with its tangent line. The other method conists systematically increasing the gains until the system becomes unstable, and then adjusting the gains to find the ultimate gain and ultimate period. One of the main advantages of metaheuristic algorithms is their ability to quickly converge to near-optimal solutions without getting stuck in local optima. This is achieved by using a combination of exploration and exploitation strategies to efficiently search through the solution space. Within our study, we seek to incorporate the Dung-Beetle based optimization algorithm (DBO) to adjust the P-I-D controller for a separately excited DC-motor's (SEDCM) speed control using MATLAB-software relies on the objective functions: the integral absolue error (IAE), the integral squared error (ISE) and the integral time absolue error (ITAE). The results obtained are compared in their best performances on rise time, settling time, overshoot, peak response and peak time.

Corresponding Author:

Kerrache Soumia
Department of Electrical Engineering, Faculty of Technology
Information Technology and Telecommunication Laboratory, University of Tahri Mohammed
Bechar, Algeria
Email: kerrach.soumia@gmail.com or kerrach.soumia@univ-bechar.dz

1. INTRODUCTION

Proportional, integral, and derivative (P-I-D) control [1], [2] is a popular control algorithm used in many automation systems, including DC-motors [3], [4]. In automation systems, P-I-D control is used to regulate the speed and position of DC-motors to achieve precise control over their movement [5], [6]. By adjusting the proportional, integral, and derivative terms of the P-I-D controller, engineers can tune the system to respond quickly to changes in input commands and maintain stability in the motor's operation.

P-I-D tuning is a crucial aspect of control systems design, as it directly affects the performance and stability of the system. Traditionally, P-I-D tuning has been done using methods such as ziegler-nichols (ZN) [7]. However, recent advancements in the field have led to the development of new methods that offer more efficient and effective ways of tuning P-I-D controllers, by using advanced algorithms and optimization techniques to automatically adjust DC-motor's P-I-D parameters based on system response, making the tuning process more efficient and accurate. The recent optimization technique, named equilibrium optimizer (EO) hase been proposed for optimal tuning of the parameters of P-I-D controller to provide accurate and robust control in DC-motors. According to [8], five metaheuristics have been compared in terms of performance: equlibrium optimizer (EO), particle swarm optimization (PSO), teaching-learning-based optimization (TLBO), differential evolution (DE), and genetic algorithm (GA), for finetuning the gains from a P-I-D for controlling DC-motor speed. The have implemented an optimization technique, which is flexible and quick tuning by using a GA to obtain the optimum P-I-D parameters for speed control of a SEDCM as a benchmark for performance analysis. Mohamed *et al.* [9], Jaya optimization algorithm supported by balloon effect (BE) is used to tune the parameters of the controller of the car position moved by a DC-motor, BE is introduced to improve response of the classical Jaya algorithm in face of the external disturbance and system parameters changes. The researchers have applied a new speed controlling technique that is based on PSO algorithm in the optimization process of the parameters for the fractional order proportional–integral–derivative (FO-P-I-D) controller.

In this research, we focus on employing a new high-level problem-solving strategy based on a metaheuristic algorithm called the Dung-Beetle-optimizer (DBO) [10] to design the P-I-D's parameters to control the speed of an excited DC-motor through simulation with Matlab-Software.

2. METHOD

The initial stage of this work's research approach, "Dung-Beetle optimization algorithm-based P-I-D controller for a separately excited DC-motor (SEDCM)," is a mathematical modeling of the SEDCM, followed by the design of ZN P-I-D's parameters for the transfer function model of the aimed system. Finally, the Dung-Beetle optimization algorithm is described and employed to achieve optimal performances for this DC-motor's speed control.

2.1. Mathematical modeling of the SEDCM

A SEDCM is a type of direct current motor where the field winding is supplied with a separate source of excitation. This means that the field winding is not connected in series with the armature winding, allowing for independent control of the motor's speed and torque. One of the key advantages of it's their ability to provide precise speed control. By independently controlling the voltage applied to the field winding, the motor's speed can be adjusted to meet specific requirements. This makes them ideal for applications where precise speed regulation is necessary, such as in DC-motors are commonly used in a variety of applications due to their simplicity, reliability, and ease of control. There are several types of DC-motors, each with its own unique characteristics and advantages. One of the most common types of DC-motors is the SEDCM. In this type of motor, the field winding is supplied with a separate source of power, allowing for independent control of the motor speed and torque [11], [12]. In Figure 1, the equivalent electric circuit model of a SEDCM is shown.

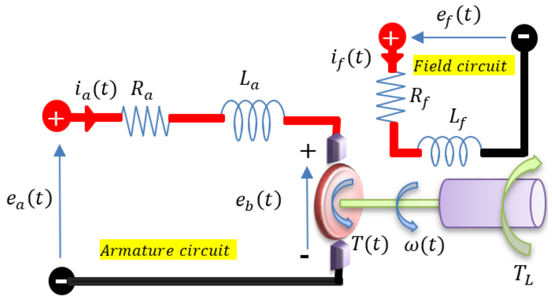

Figure 1. The equivalent electric circuit model of a SEDCM

The induced voltage $e_b(t)$, for a constant flux, is directly proportional to the angular velocity $\omega(t)$ of the rotor shaft, multiplied by the constant k_b [9], [13], [14].

$$e_b(t) = k_b \frac{d\theta(t)}{dt} = k_b \omega(t) \quad (1)$$

Applying Kirchhoff voltage law and newton second law of motion to the Figure 1, The DC-motor will reveal the armature voltage $e_a(t)$ [9], [13], [14].

$$e_a(t) = L_a \frac{di_a(t)}{dt} + R_a i_a(t) + e_b(t) \quad (2)$$

Assuming the load torque is zero and according to (3), the torque $T\ (t)$ generated by the DC-motor is directly proportional to the armature current $i_a(t)$ multiplied by the torque coefficient k_t [9], [13], [14].

$$T\ (t) = k_t i_a(t) \quad (3)$$

As part of energy conservation, the torque produced can also be derived from the equivalent sum of torques due to friction and inertia. Therefore [9], [13], [14].

$$T\ (t) = J \frac{d\omega(t)}{dt} + B\omega(t) = k_t i_a(t) \quad (4)$$

In (1) to (4) are transformed using the Laplace transform, seting zero initial conditions, will result in [9], [13], [14].

$$E_b(s) = K_b \Omega(s) \quad (5)$$

$$E_a(s) = (L_a s + R_a) I_a(s) + E_b(s) \quad (6)$$

$$T(s) = (Js + B)\Omega(s) = K_t I_a(s) \quad (7)$$

Based on (5) to (7), a relationship between the angular speed $\Omega(s)$ and the armature voltage $E_a(s)$ of the SEDCM can be established [9], [13], [14].

$$G_{E_a}(s) = \frac{\Omega(s)}{E_a(s)} = \frac{K_t}{(L_a s + R_a)(J_s + B) + K_b K_t} = \frac{K_t}{L_a J s^2 + (R_a J + L_a B)s + (R_a B + K_b K_t)}, for\ T_L = 0 \quad (8)$$

In (8) describes the DC-motor's transfer function in the open loop [9], [13], [14]. A list of the separately excited type of DC-motor parameters is presented in Table 1 [9], [13]–[15]. Its block diagram is shown in Figure 2. The open-loop transfer function for the separately excited is given by (9) [9], [13]–[15]. A unit step function graph represents the motor under consideration's open-loop response, as seen in Figure 3.

$$G_{E_a}(s) = \frac{\Omega(s)}{E_a(s)} = \frac{15}{1.08s^2 + 6.1s + 1.63}, for\ T_L = 0 \quad (9)$$

Table 1. SEDCM parameters

Parameters	Values
B	0.0022 N m s rad^{-1}
J	0.0004 Kg m^2
K_b	0.05 V s rad^{-1}
K_t	0.015 Nm A^{-1}
L_a	2.7 H
R_a	0.4 Ω

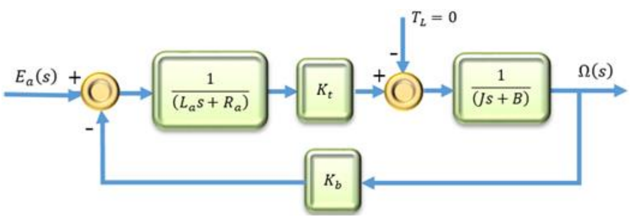

Figure 2. Separately DC-motor system block diagram

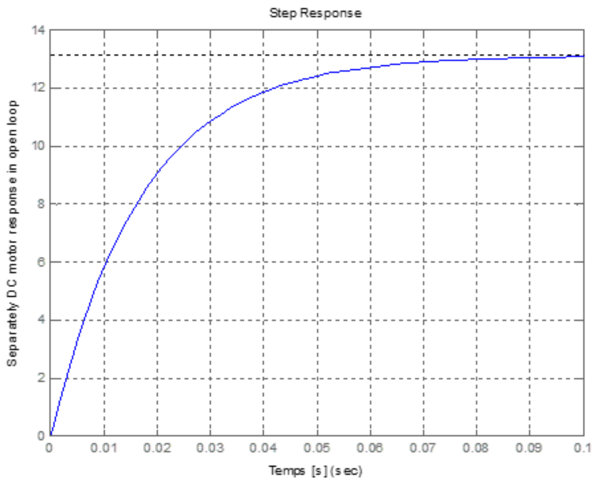

Figure 3. Separately DC-motor's unit step response on open loop

2.2. ZN P-I-D's parameters

P-I-D control is a feedback control system extensively utilized in numerous industrial applications to regulate processes and systems. The term P-I-D stands for proportional, integral, and derivative, which are the three components of the P-I-D controller. The proportional component K_p responds to the current error signal, the integral component K_i considers the accumulated error over time, and the derivative component K_d predicts the future error based on the rate of change of the error signal. By combining these three components, the P-I-D controller can effectively calibrate the control output to maintain the target setpoint.

ZN method is a specific approach used in the field of control systems engineering to adjust the parameters of a P-I-D controller. This method was developed by John G. Ziegler and Nathaniel B. Nichols in the 1940s, and has since become a widely used approach for optimizing the performance of control systems [16], [17]. Normally, in industrial applications, a first-order filter should replace the pure derivative term. The P-I-D controller with filter is mathematically expressed as in (10), where T_f is the filter time constant, which can be chosen as a fixed small positive value, for instance, T_f=0.001. The P-I-D controller with filter is mathematically defined by the transfer function as [18]:

$$G_{PID}(s) = K_p + \frac{K_i}{s} + \frac{K_d}{T_f s+1} s = = K_p\left(1 + \frac{1}{T_i s} + \frac{T_d}{(T_f s+1)} s\right) \quad (10)$$

An experimental procedure used to record the plant's open-loop step response and plot the tangent at the response curve's inflection point, is proposed by ZN for extracting the parameters *k*, *L*, and *T* (or *a*, where *a* = *k***L/T*), which are illustrated in Figure 4 [19], [20]. Table 2 shows the guidelines to determine the P-I-D controller's parameters (K_p, K_i and K_d).

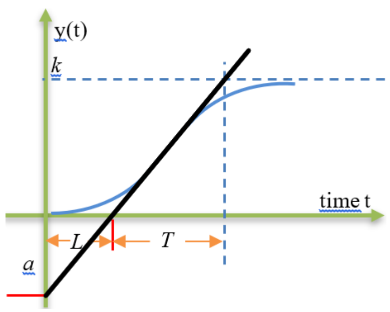

Figure 4. The graphic approach of ZN

Table 2. ZN formula for adjusting P-I-D parameters

Controller type	From step response K_p	T_i	T_d
P	$1/a$		
P-I	$0.9/a$	$3L$	
P-I-D	$1.2/a$	$2L$	$L/2$

A developed MATLAB-simulation is intended to identify the P-I-D controller's parameters based on ZNs first method, appplied to the SEDCM's transfer function, is presented in Figure 5. The simulation result has yielded these parameters: L = 0.1364, and a = 0.0326. Therefore, the P-I-D controller's parameters are K_p = 36.8066, K_i = 134.9474 and K_d = 2.5097, which are represented in the closed loop for speed's control of the SEDCM with reel parameters in Figure 6, and by plotting its unit step response in Figure 7.

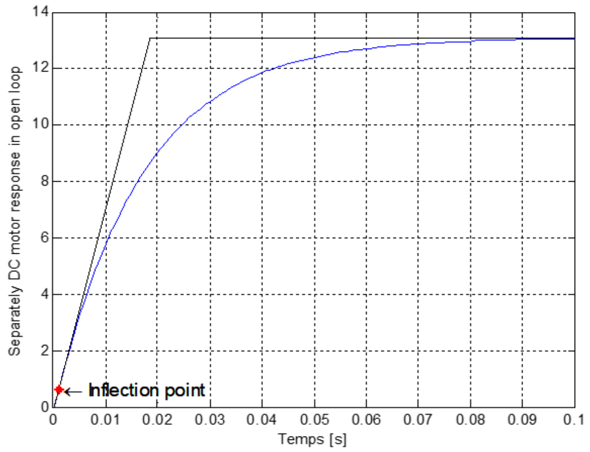

Figure 5. ZNs first method

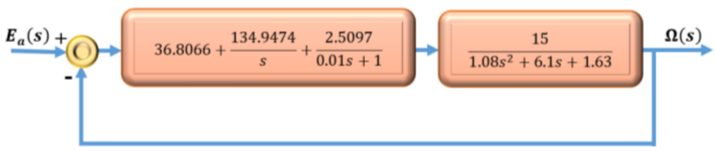

Figure 6. SEDCM-control with P-I-D

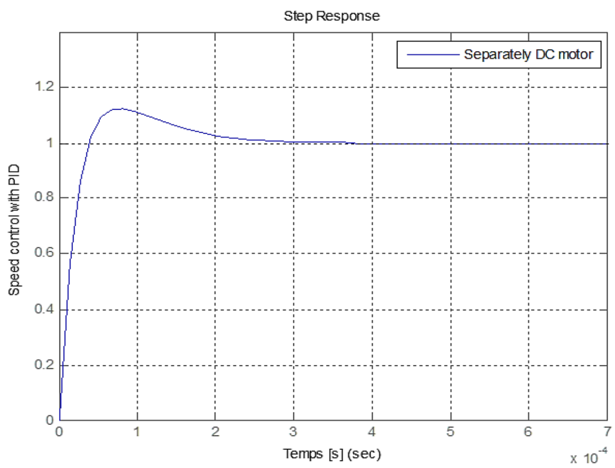

Figure 7. SEDCM's speed control with P-I-D based on ZN

2.3. P-I-D optimization by Dung-Beetle optimazer algorithm

The current research introduces the DBO algorithm [10], [21], a distinct population-based method that draws inspiration from the Dung-Beetle's ball-rolling, dancing, climbing, thieving, and reproducing behaviors. This algorithm considers both local exploitation and global exploration in order to achieve a high convergence rate and excellent solution correctness. We presume that the intensity of the light source also afects the Dung-Beetle's path. During the rolling process, the position of the ball-rolling Dung-Beetle is updated and can be expressed as [10], [21]:

$$\begin{cases} Z_i(t+1) = Z_i(t) + \alpha \times \kappa \times Z_i(t-1) + b \times \Delta z \\ \quad where\ \Delta z = |Z_i(t) - Z^{\omega}| \end{cases} \tag{11}$$

where b is a constant value in the range (0, 1), $\kappa \in (0, 0.2]$ indicates a constant number reflecting the deflection coefficient, and t indicates the current iteration number. $Z_i(t)$ is the location of the ith Dung-Beetle at the t^{th} iteration. The global worst position is represented by Z^{ω}, and variations in light intensity are simulated by Δz. The natural coefficient α, which can be either -1 or 1, illustrates how environmental factors such as wind or bumpy terrain can cause Dung-Beetles to stray from their intended track [10], [21].

The Dung-Beetle will climb to the top of the dung ball and dance to reposition itself if it encounters an obstacle that stops it from moving forward along its intended path. As a result, the following is the updated and defined location of BRDB [10], [21]:

$$Z_i(t+1) = Z_i(t) + \tan(\Theta) \times |Z_i(t) - Z_i(t-1)| \tag{12}$$

This defection angle Θ is located between $[0, \pi]$. Dung-Beetles conceal their dung balls in secure places to ensure the safety of their offspring. To mimic the preferred egg-laying habitats of female dung beetles, a boundary selection technique called [10], [21]:

$$\begin{cases} LB^s = \max\ (Z^* \times (1-F),\ LB) \\ UB^s = \min\ (Z^* \times (1+F),\ UB) \\ \quad where\ \ F = 1 - \frac{t}{max-iter} \end{cases} \tag{13}$$

LB and UB denotes the minimum and maximum limits of the optimization problem, respectively. Z^* represents the current local best position as shown in Figure 8 [10], [21].

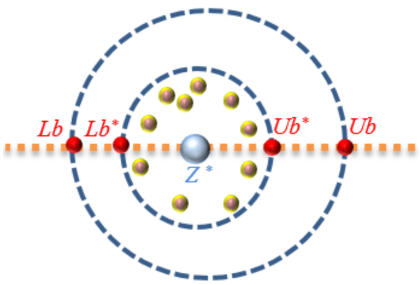

Figure 8. Boundary selection strategy conceptual model

Once the spawning area is identified, the female Dung-Beetles choose the brood balls in this area to lay their eggs. In each iteration of the DBO algorithm, each female Dung-Beetle produces one egg. In (13) shows that the boundary range of the spawning area changes dynamically, which is mainly determined by the F value. Accordingly, the position of the brood ball is also dynamic in the iteration process, which is determined by [10], [21]:

$$B_i(t+1) = Z^* + b_1 \times (B_i(t) - LB^8) + b_2 \times (B_i(t) - UB^8) \tag{14}$$

where b_1 and b_2 represent two independent random vectors of size 1 × D, D denotes the dimension of the optimization problem, and $B_i(t)$ is the location information of the ith brood ball at the t^{th} iteration [10], [21].

Once they are fully grown, small Dung-Beetles come out of the ground to find nourishment. For these Dung-Beetles, the ideal area for foraging is as follows [10], [21]:

$$\begin{cases} LB^b = \max(Z^b \times (1-F), LB) \\ UB^b = \min(Z^b \times (1+F), UB) \end{cases} \tag{15}$$

where LB^b and UB^b denote the minimum and maximum boundaries of the ideal foraging territory, respectively, and Z^b stands for the global optimum position. Consequently, the following is an update to the little Dung-Beetle's position [10], [21]:

$$Z_i(t+1) = Z_i(t) + C_1 \times (Z_i(t) - LB^b) + C_2 \times (Z_i(t) - UB^b) \tag{16}$$

where $Z_i(t)$ shows the position information of the i^{th} small Dung-Beetle at the t^{th} iteration, C_1 represents a random number that follows normally distributed, and C_2 signifies a random vector belonging to (0, 1).

As "dung thieves," certain Dung-Beetles steal dung balls from other Dung-Beetles. In (14) states that Z^b is the best place to eat. As a result, as will be explained below, the thief's position information is updated during the iteration process [10], [21].

$$Z_i(t+1) = Z^b + S \times g \times (|Z_i(t) - Z^8|) + |Z_i(t) - Z^b| \tag{17}$$

where S is a fixed value, g is a normal-distributed random vector of size 1 × dim, and $Z_i(t)$ reflects the ith thief's position at the t^{th} iteration [10], [21].

For more performance given to the control of the SEDCM's speed, an optimization with DBO algorithm is suggested and implemented to find the best P-I-D controller parameters. Three cases of objective function are used, which are respectively: the integral absolue error (IAE), the integral squared error (ISE) and the integral time absolue error (ITAE), as shown in (18)-(20).

$$\text{IAE} = \int |e(t)| dt \tag{18}$$

$$\text{ISE} = \int e(t)^2 dt \tag{19}$$

$$\text{ITAE} = \int t|e(t)| dt \tag{20}$$

Figure 9 presents the P-I-D controller optimization block using Dung-Beetle algorithm in order to find the best desired parameters (K_p, K_i, and K_d), which are injected to simulate the final transient response of SEDCM's speed control.

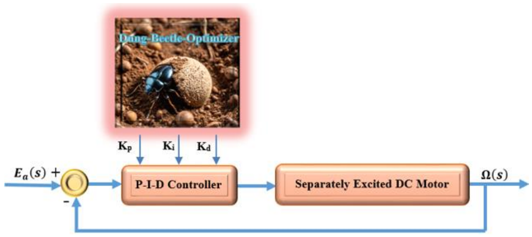

Figure 9. P-I-D controller optimization block using Dung-Beetle algorithm

3. RESULTS AND DISCUSSION

In light of the developed simulation, the DBOs parameters are displyed in Table 3, where we have concentrated our work on three fitness functions, and designing the count of search agents, the maximum allowed iterations and the P-I-D parameters's lower and upper bands. The Table 4 reveals the simulation results of the optimal gain values of P-I-D controller attained through using DBO for ISE, IAE and ITAE criteria, applied to the SEDCM. Figure 10 and Table 5 present a comparison of several transient responses and their attributes (rising time, settling time, overshoot, peak response, and peak time) for the study SEDCM model, obtained by ZN with first method and the DBO algorithm with the three suggested fitness functions.

A comparison of the convergence curves for the best score obtained using the different suggested strategies is shown in Figure 11.

Table 3. DBOs parameters

Fitness function	ISE, IAE, and ITAE	
Search agent count	30	
Maximum allowed iterations	20	
	P-I-D lower band	P-I-D upper band
K_p	0.01	120
K_i	0.01	120
K_d	0.01	120

Table 4. P-I-D controller gains adjusted by using DBO

Parameters	DBO-ISE	DBO-IAE	DBO-ITAE
K_p	90.6740	109.8846	120
K_i	32.7171	29.7931	32.0841
K_d	15.8948	18.8593	21.1472

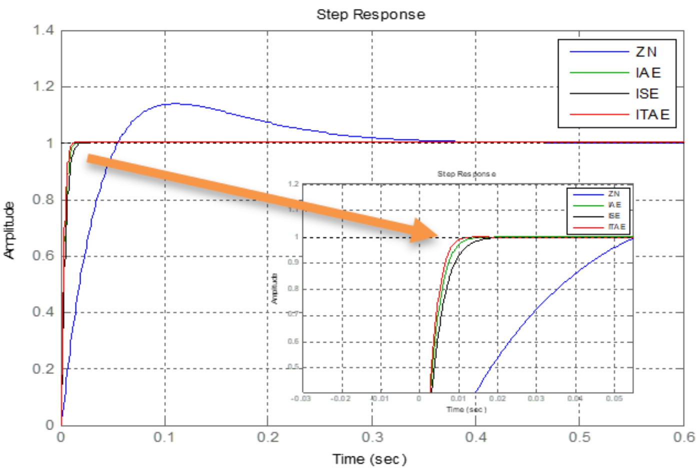

Figure 10. DBO-P-I-D step response for SEDCM system

Table 5. Time response charaRteristics

Parameters	ZN	DBO-ISE	DBO-IAE	DBO-ITAE
Rise time	0.397	0.00778	0.00629	0.00548
Settling time	0.295	0.01380	0.0107	0.00906
Overshoot	13.962%	0.0168%	0.0498%	0.0613%
Peak response	1.1396	1.00016	1.0004	1.0006
Peak time	0.111	0.041	0.0231	0.014

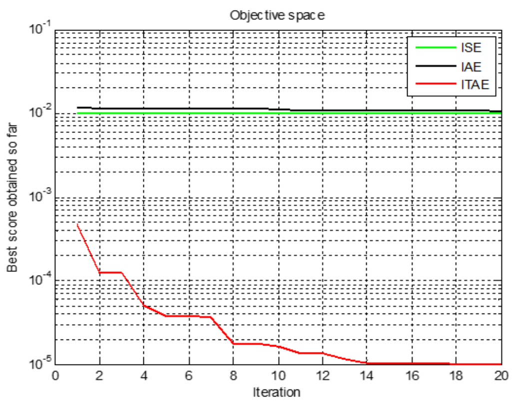

Figure 11. Controller's performance evaluation analysis

4. CONCLUSION

Within this research, the metaheuristic algorithm called DBO has been applied to extract the best P-I-D's speed controller parameters for a SEDCM. For the first stage, a detailed mathematical modeling with a transient response representation in open loop has been given to this DC-motor. In the second stage, the ZNs first method is applied to determine the P-I-D controller parameters (K_p= 36.8066, K_i = 134.9474 and K_d = 2.5097), which are injected in the closed loop model for the study system and given an acceptable performance for the speed control. In the last stage, an itemized model was assigned to the DBO algorithm, which is applied to adjust the objective function of the desired model that combines a P-I-D controller with filter and a SEDCM in closed loop. A three various fitness are chosen. The first one is the ISE, where it has given the P-I-D's parameters as follows: K_p= 90.6740, K_i = 32.7171 and K_d = 15.8948. Whereas their response chararateristics are rise time= 0.00778, settling time = 0.01380, overshoot = 0.0168%, peak response = 1.00016 and peak time = 0.041. For the second one, which is the IAE, has given the follow results: K_p= 109.8846, K_i = 29.7931, K_d = 18.8593, rise time = 0.00629, settling time = 0.0107, overshoot = 0.0498%, peak response = 1.0004 and peak time = 0.0231. The last one called the ITAE has given the best tuned P-I-D's parameters for control of the SEDCM, which are K_p= 120, K_i = 32.0841, and K_d = 21.1472. Hence, the higher transient response performances have been validated by the characteristics acquired (rise time = 0.00548, settling time = 0.00906, overshoot = 0.0613%, peak response = 1.0006 and peak time = 0.014).

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BIOGRAPHIES OF AUTHORS

Kerrache Soumia was born in Medea, Algeria, she received the dipl.El-Ing from the university of Medea ,Algeria in 2009, Master’s degree in Instrumentation and microelectronics from the university of Medea in 2014, and the Ph.D. degree in Electrical Engineering from the University of Tahri Mohammed -Bechar (Algeria), in 2021. She is currently a professor at University of Bechar in the department of Electrical Engineering, and does his research at SGRE Laboratory and Information Technology and Telecommunication Laboratory. Her main interests are automatic, embedded system, control, renewable energies, electrical network, artificial intelligent, computer science, image processing, microelectronics, Bechar 08000, Algeria. She can be contacted at email: Kerrach.soumia@univ-bechar.dz.

Haidas Mohammed was born in Bechar, Algeria; he is professor at Uiversity of Tahri mohhammed-Bechar. He is a member in Smart Grids and Renewable Energies Laboratory (SGRE). He received his Ph.D. degree in Electrical Engineering on 2019 from University of Tahri mohammed-Bechar, his domain research area are on electrical engineering, electrical networks, automatic, computer science, artificial intelligent, robotic, biostatistics, optimization, electro-mechanical system, embedded systems, renewable energies, smart grids, control systems, telecommunication, and wireless. Bechar 08000, Algeria. He can be contacted at email: haidasmed08@gmail.com or haidas.med@univ-bechar.dz.