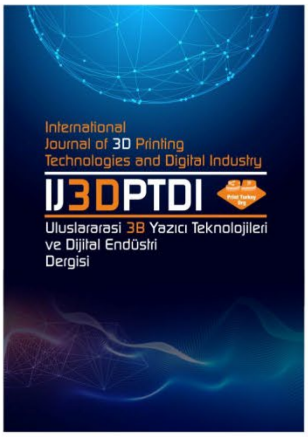

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HYBRID PARTICLE SWARM OPTIMIZATION AND GREY WOLF OPTIMIZER FOR SETTING PID PARAMETERS OF BLDC MOTORS

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ABSTRACT
BLDC (Brushless DC) motors have advantages over asynchronous motors and dc motors in various aspects. Particularly in electric bicycles and flying cars, BLDC motors are utilized widely. Electric bicycles and flying cars are becoming increasingly popular, and as a result, the significance of BLDC motors and their cost-effective and efficient utilization has been growing rapidly. PID (Proportional Integral Derivative) controllers are generally used in motor control because they are cheap and perform well. Many methods have been used to adjust PID parameters. Although methods such as Ziegler-Nichols, Cohen-Coon etc. are widely used, there are also new methods such as optimization algorithms PSO (Particle Swarm Optimization), Whale Optimization Technique, Gray Wolf Optimization technique etc. The hybrid method: HPSOGWO (Hybrid Algorithm of Particle Swarm Optimization and Grey Wolf Optimizer) is a combination of PSO and GWO (Grey Wolf Optimizer) techniques, and it can be used for tuning PID parameters. As associated with this, the aim of this study is to show the superiority of HPSOGWO algorithm in optimizing the PID parameters. In the content of this study, the essentials regarding the optimization background, and details of the BLDC motor modeling was explained first. After that, the methodology of the hybrid solution was expressed and then the application phase was explained in detail, by including the results generally. In the context of the intelligent optimization approach of this study, the results were obtained in the MATLAB Simulink environment. The application of the used solution method revealed its superiority over the study conducted solely with GWO in various parameters.

Keywords: BLDC Motors, Particle Swarm Optimization, Grey Wolf Optimizer, Hybrid Algorithm of Particle Swarm Optimization and Grey Wolf Optimizer, Intelligent Optimization.

1. INTRODUCTION
BLDC (Brushless DC) motors has a remarkable role in industrial applications. Although there are many motors used in various fields of industry, BLDC motors ensure many advantages when compared with other motors having no commutator-brush part. BLDC motors have also a popularity since they are connected with electrical devices. For example, use of BLDC motors in electric bicycles has been increasing day by day nowadays [1]. In the industry, 90% of the BLDC motors are controlled using PID controllers [2]. The main reasons for this are their simplicity, reliability, and robustness [1]. The adjustment of the PID controller values to optimal values is very important for increasing energy efficiency, faster motor response, etc. As moving from the explanations so far, the main objective of this study is associated with improving the energy efficiency by using more optimal PID parameters. There are classical tuning methods such as Ziegler-Nichol and Cohen-Coon for adjusting the PID parameters. While these methods yield favorable outcomes, there are optimization techniques that provide even superior results.

As a result of constraints and practical difficulties associated with current approaches, optimization-dependent techniques have been widely developed in the intelligent optimization literature [3]. Some of the techniques used are known as PSO (Particle Swarm Optimization), GA (Genetic Algorithms), WOA (Whale Optimization Algorithm), and the ACO (Ant Colony Optimization). GA has been used in PID tuning of DC motors and has been shown to be more successful than classical methods [4]. WOA has been used in PID tuning for trajectory tracking [5]. ACO has been used for PID tuning [6]. Recently, it has been shown that the GWO (grey wolf optimization) technique is more successful in PID tuning and has produced better results than the PSO algorithm in some aspects [2]. Finally, the number of hybrid algorithms has increased and, in particular, a successful algorithm has been obtained by hybridizing the PSO and GWO algorithms. It has been shown that such hybrid algorithm (HPSOGWO) has faster convergence in many aspects [7]. The aim of this study is to show that the HPSOGWO algorithm, which is a hybrid algorithm, gives better results than the PSO and GWO algorithms. One advantage of employing a hybrid approach is analyzing the outcomes by the combination of the optimization mechanisms by two different optimization algorithms. The motivation for utilizing the hybrid method in our study has been its superior performance in test functions.

2. MATERIAL AND METHOD

2.1 BLDC Motor Modeling

In order to model BLDC motors in the Simulink environment, the first step is to create their mathematical model. It can be stated that a BLDC motor has three phases, and these three phases facilitate the effective rotation in the motor. Assuming that there is an equal resistance in the context of all the phase windings regarding the BLDC motor, the equation used for the phase voltages is as follows:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & Lab & Lac \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

The equation above represents the equation providing the coil voltages of the BLDC motor. If we consider the scenario where the self-inductance of each phase winding is assumed to be the same, it implies that the phase inductances are equal as well:

$$L_{aa} = L_{bb} = L_{cc} = \mathrm{L} \quad (2)$$

In the equation 2, 'L' represents the inductance, which denotes the interaction degree between the magnetic fields of the windings. On the other hand, 'M' represents the mutual inductance, which signifies the magnetic coupling between two different windings.

$$L_{ab} = L_{ba} = L_{cb} = L_{bc} = L_{ca} = L_{ac} = M \quad (3)$$

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

If we assume that all the phase windings are equal to zero, we are able to construct the mathematical model:

$$\dot{I}_a = \dot{I}_b = \dot{I}_c = 0 \quad (5)$$

$$\mathrm{M}\dot{I}_a + M\dot{I}_c = -\mathrm{M}\dot{I}_a \quad (6)$$

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (7)$$

2.2 PID Controller Design

The PID controller is typically composed of the sum of past, future, and current error estimates. These effects can be observed in the equation below:

$$\mathrm{PID} = K_p + \frac{K_i}{s} + K_d s \quad (8)$$

Here, Kp represents the proportional gain, Ki is associated with the integral gain. On the other hand, the Kd is used for the derivative gain. The basic aim of a PID controller is to diminish the disparity between the desired value and the actual collected value. Some effects found here can be given a value of zero for some systems. Operating the PID controller with appropriate coefficients for the system has important benefits such as energy savings, fast convergence to the desired values, and increased work per unit time. There are various classical and advanced methods for finding the appropriate values. Successful results have been obtained using methods that use optimization techniques in these methods [2-3]. Better results can be obtained by using new optimization techniques.

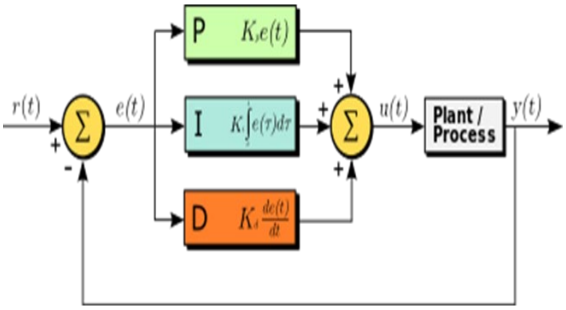

Figure 1. PID controller structure [8].

The image above shows the basic PID structure.

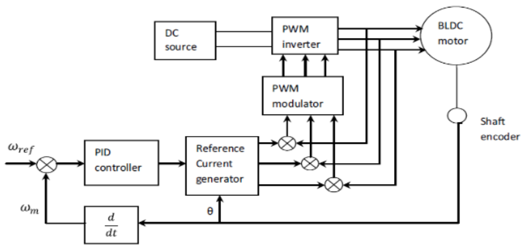

Figure 2. Complete diagram of PID controlled BLDC motor[2].

In the first figure shown above, we see the structure of a classical PID, and in the second figure, we see the structure of a PID-controlled BLDC motor.

2.3 Particle Swarm optimization Technique

The concept of PSO was first put forwarded by Kennedy, J. and Eberhart, R.C in 1995 [9]. PSO imitates the behavior of birds hunting in a swarm and trying to find food sources while staying away from hunters. Each bird inside the PSO is called as particle, and the aim of each particle is to find the optimum paramter(s)for the objective function. In a typical PSO flow, the particles strive to discover the optimal solution within the search space. Each particle possesses two state variables, namely its current position and velocity, which are initially assigned randomly. After per iteration, the location and speed of each particle are adjusted on the basis of the equation provided below. Each step creates a temporary solution for the problem. In finding these solutions, each particle knows the previously found local best position and global best position [9]. In addition to this, a linearly decreasing weight also reduces the momentum of the particles as the iteration increases [10]. By adding various additions to the initial method, more new methods have been developed [11]. By using the self-adaptive weight method among these methods, more challenging problems can be overcome [11].

$$v_i(t+1) = w.v_i(t) + Q_1.\emptyset_1\big(p_i(t) - x_i(t)\big) + Q_2.\emptyset_2((g_i(t) - x_i(t)) \quad (9)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (10)$$

$$\mathrm{i} = N^+ \quad (11)$$

The velocity and positions of particles are updated as shown above. The new velocity v(t+1) and the new position x(t+1) of the particle are determined. The inertia weight "w" in equation 8 is referred to as the factor that signifies the extent of directional change. Q1 and Q2 are constants with positive values. Phi1 (Ø1) and Phi2 (Ø2) are haphazard numbers developed from a equal distribution between 0 and 1. The variables p(i) and g(i) represent, respectively, the local and global best positions of the particle. Equation 9 is utilized to determine the particle's latest position by incorporating these values. PSO is good for solving single-objective problems [10].

2.4 Grey Wolf Optimization Technique

The Grey Wolf Optimization (GWO) algorithm is known as a remarkable meta-heuristic optimization technique that draws inspiration from the behavior and hierarchical structure observed in grey wolves in their natural habitat. It was proposed firstly by Seyedali Mirjalili, Seyed Mohammad Mirjalili, and Andrew Lewis in 2014. GWO emulates the hunting mechanism and management hierarchy exhibited by grey wolves as a means to tackle optimization problems. In GWO, four solutions are generated, and best is the "alpha" solution. The other solutions are "beta", "delta", and "omega". GWO has been proven to be a competitive optimization technique when compared to other existing methods.

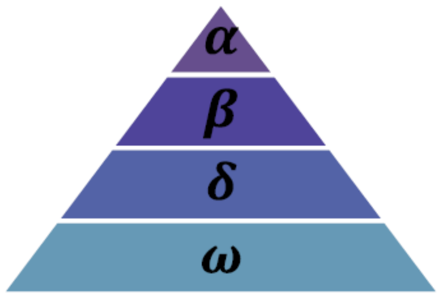

Figure 3. PID controller structure [12].

The picture above illustrates the positions of grey wolves in the social hierarchy.The hunting process of grey wolves comprises three fundamental steps:

1. Detecting, pursuing, and closing in on prey
2. Chasing, encircling, and pushing the prey up to it halts
3. Initiating an assault on the prey

2.5 Mathematical model
In order to develop an optimization technique by inspiring from the hunting behavior seen in grey wolf groups, it is generally necessary to understand how they hunt their prey. The hunting behavior of grey wolves when they attack their prey has been mathematically modeled. These fundamental steps are hunt containment, hunting, attacking the prey. These stages are described below.

2.5.1 Hunt Containment
The mathematical model that describes how grey wolves surround their prey during the exploration operations can be represented as follows:

$$\vec{D} = \left|\vec{F}.\vec{K}_p(t) - \vec{K}(t)\right| \tag{12}$$

$$\vec{K}(t+1) = \vec{K}_p(t) - \vec{Z}.\vec{D} \tag{13}$$

In the given equations, ‘t’ is for the current iteration value whereas ‘$\vec{Z}$’ and ‘$\vec{F}$’ are for the associated constant vectors. Additionally, the location vector of the prey is denoted as ‘$\vec{K}_p$’, and ‘$\vec{K}$’ is related to the position vector regarding the grey wolf. These equations are used to depict the hunting patterns of grey wolves and can help to understand and optimize the process of tracking, surrounding, and attacking prey.

The vectors $\vec{Z}$ and $\vec{F}$ are the following.

$$\vec{Z} = 2.\vec{a}.\vec{\iota_1} - \vec{a} \tag{14}$$

$$\vec{F} = 2.\vec{\iota}_2 \tag{15}$$

$\vec{\iota_1}$ and $\vec{\iota}_2$ represent stochastic vectors, while $\vec{a}$ progressively diminishes from 2 to 0 over the iterations. This technique is shown in 2D and 3D below.

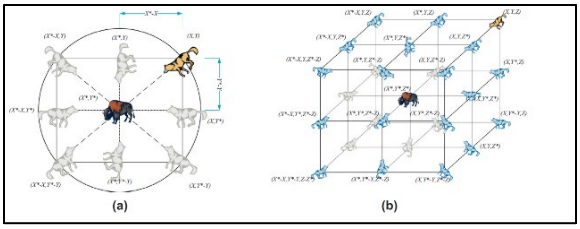

Figure 4. 2D and 3D vectors [12].

2.5.2 Hunting
Within the realm of grey wolves, the pursuit of prey hinges upon the alpha wolf, with the belief that the alpha, beta, and delta members possess superior knowledge regarding the prey's whereabouts. The other wolves refresh their locations accordingly. The alpha holds the highest rank, followed by beta and delta.

$$D_\alpha = \left|\vec{F}_1.\vec{X}_\alpha - \vec{X}\right|, D_\beta = \left|\vec{F}_2.\vec{X}_\beta - \vec{X}\right|, D_\delta = \left|\vec{F}_3.\vec{X}_\delta - \vec{X}\right| \tag{16}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.(\vec{D}_\alpha), \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.(\vec{D}_\beta), \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.(\vec{D}_\delta) \tag{17}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1+\vec{X}_2+\vec{X}_3}{3} \tag{18}$$

In the given equations, "t" signifies the current iteration, "$\vec{X}$" represents the position vector of the grey wolf. A, β, δ represent the positions of wolves in the hierarchy.

2.5.3 Attacking the prey
Finally, grey wolves stop moving in order to attack the prey. As can be seen in the figure below, they attack the prey when$\left|\vec{A}\right|$<1. One drawback of the GWO algorithm is that it can get stuck in local solutions.

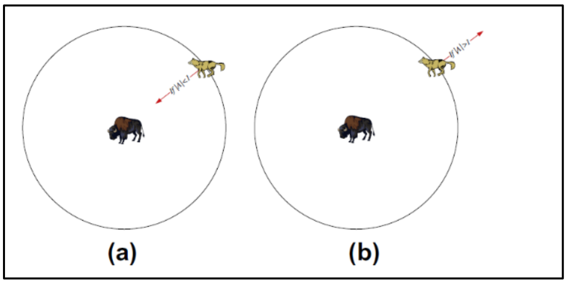

Figure 5. Attacking the prey [12].

Presented below is the pseudo-code that outlines the algorithm's logic and operations:

```
Initialize the grey wolf population Xi (i = 1, 2, ..., n)
Initialize a, A, and C
Calculate the fitness of each search agent
Xα=the best search agent
Xβ=the second best search agent
Xδ=the third best search agent
while (t < Max number of iterations)
   for each search agent
         Update the position of the current search agent by equation (3.7)
   end for
   Update a, A, and C
   Calculate the fitness of all search agents
   Update Xα, Xβ, and Xδ
   t=t+1
end while
return Xα
```

Figure 6. Algorithmic representation of code

2.6 Hybrid PSO AND GWO Algorithms

It is important for an optimization technique to have equilibrium between exploration and exploitation capabilities [13]. The core concept behind the hybrid method is to enhance the exploitation capabilities of PSO by leveraging the exploration abilities of the GWO algorithm [7]. The goal of combining these abilities is to reach the global minimum faster. There are significant advantages over PSO and GWO in test function measurements. The hybrid method also performs significantly better than traditional techniques on real-world problems [14]. However, the PSO method has also been hybridized with other optimization techniques, and the main goal in these studies is to avoid the local optimum and approach the global optimum [15,16]. These techniques, tested on test functions, have shown significant differences [17]. The mathematical model of the modified technique is given below.

$$D_\alpha = \left|\vec{F}_1.\vec{X}_\alpha - w * \vec{X}\right|, D_\beta = \left|\vec{F}_2.\vec{X}_\beta - w * \vec{X}\right|, D_\delta = \left|\vec{F}_3.\vec{X}_\delta - w * \vec{X}\right| \quad (19)$$

$$V_i^{k+1} = w * (V_i^k + f1r1\left(X_1 - X_i^k\right) + f2r2\left(X_2 - X_i^k\right) + f3r3\left(X_3 - X_i^k\right)) \quad (20)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (21)$$

In the given equations, 't' is related to the current iteration value whereas the '$\vec{X}$' stands for the position vector regarding the grey wolf. Α, β, δ represent the positions of wolves in the hierarchy.

It has been shown that the HPSOGWO method has a significant result in fixed-dimension, unimodal, multimodal and test missions [7]. Outlined below is the pseudo-code that illustrates the operational steps of the hybrid method:

Table1. Algorithmic representation of technique [18].

1	Start
2	Set the related GWO as well as PSO parameters including population size value and iteration
3	Determine / model the cost function
4	Create starting populations (in a random way), and calculate accordingly the fitness alpha, beta, delta
6	Apply position update for each wolf
7	Pass to the PSO steps
8	Recall the updated positions
9	Update the values for a, A, and c. For each wolf, calculate the fitness value.
10	Update the values for alpha, beta, and delta positions regarding wolf
11	If the final iteration is not reached go back to the step 6
12	Ending of the algorithm

3. RESULTS

The motor parameters used in the simulation are given below, and the simulation photos of the circuit in the MATLAB environment are attached. ITAE was selected as the fitness function because it performs well [2].

$$ITAE = \int_0^\infty t * |e(t)|\, dt \quad (22)$$

Table 2. BLDC motor parameters

BLDC Motor Parameters	Values
RS	0.5 ohm
L	8 mH
J	0,0465 kg.m^2
K	0.55 kg.m/A
b	0.004 N.m.sec / rad
I_a	10 Amp.
V	12 V
P	84W
Ψ_m	65 mV/rad/sec
T_p	2.9 N.m
p	8

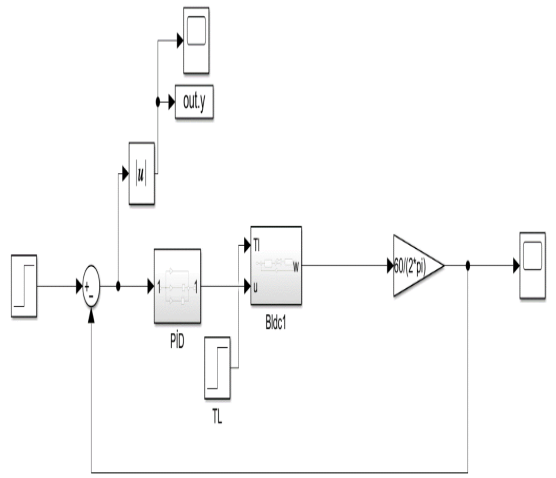

Figure 7. PID block diagram

The image above displays the model established in the Simulink environment.

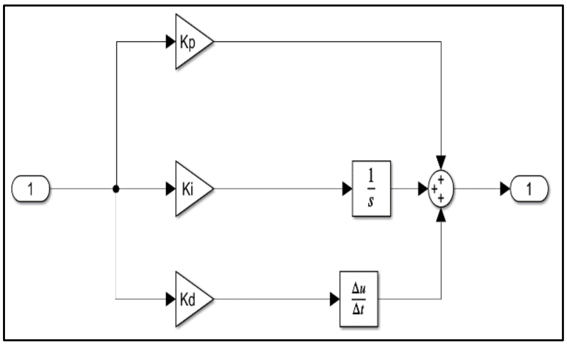

Figure 8. BLDC motor control circuit

The PID structure block can be observed above.

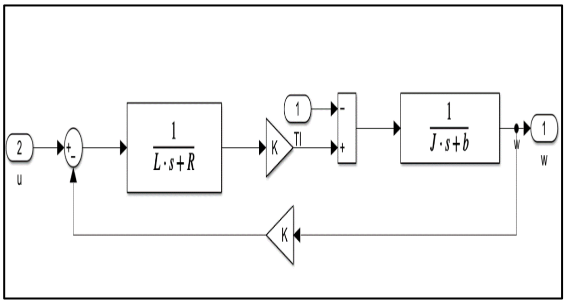

Figure 9. BLDC block diagram

The Simulink block for the BLDC motor is presented in Figure 11. In the simulation, certain parameters are assigned first. The error signal obtained from the BLDC control circuit is taken and the absolute value of this error signal is calculated. After that, the integral value is calculated to be evaluated as the objective function. Here, the objective for the function is minimization. In the simulation, 30 particles and 50 iterations were selected for GWO, PSO and the hybrid solution. Also, the boundary parameters were taken as lb = [-0.5 -0.5 0], up = [1 1 0.3]. After the initial parameters are assigned, each optimization technique is run separately to obtain results.

4. DISCUSSION

In previous studies, optimization-based methods have been observed to yield better results when compared with the related classical methods. In the comparison of the GWO and PSO methods, it was found that the GWO method is significantly superior in some values. It was found that the alpha score of the GWO method is 0.0167, while it is 0.0116 for the HPSOGWO method. There is already a research work, which is available on the superiority of the GWO and PSO algorithms [2]. In this study, the superiority of the HPSOGWO method over GWO and PSO is emphasized.

Table 3. PID results

	GWO	HPSOGWO
RiseTime	0,125	0,0889
SettlingTime	0,224	0,14
SettlingMin	0	0
SettlingMax	4,8982	2,7265
Overshoot	6,70E+06	1,11E+08
Undershoot	0	0
Peak	50	50

From the applications performed in this study, it was seen that the hybrid method gives better findings in terms of determining time and rise time. As provided in Figure 12, GWO and HPSOGWO optimization techniques were compared for the calculation of coefficients used in the control of a BLDC motor (under certain conditions). The superiority of the GWO technique over the PSO technique is demonstrated already in [2]. The greatest advantage of the hybrid method is that it incorporates characteristics from both techniques. The hybrid method has integrated exploration capabilities of both GWO and PSO. Therefore, the HPSOGWO technique yields better results in certain aspects, with lower values for determining time, overshoot, and rise time when the sum of these values is considered. From all of this, it can be seen that the proposed method yields significantly better results than the others. By combining this method with other techniques, better results can be achieved. One of the most crucial features that requires attention is that these techniques involve randomness, which can have both advantages and disadvantages. Additional studies can be conducted by modifying boundary parameters.

5. CONCLUSION AND FUTURE WORK

In this study, an optimization approach for PID adjustment of BLDC motors was introduced. In detail, the study employed PSO and GWO as the solution methods, and a hybrid solution way, which is called briefly as HPSOGWO was used for ensuring improved results. According to the results, the HPSOGWO was better according to single use of PSO or GWO. Eventually, the study showed that the widely used BLDC motors can be effectively optimized thanks to hybrid intelligent optimization. Also, it was seen that such use of optimization methods is always ensuring the potential of advancing the literature, which is requiring more accurate adjustments with the technological advancements.

As connected with the study, future works may be planned for contributing to the industrial applications. It may be planned to use the same HPSOGWO solution for alternative devices and components. Also, different optimization techniques may be recalled to create alternative hybrid solutions for the PID-based adjustment of BLDC motors. In more advanced applications, parameters of the BLDC motors may be evaluated deeply, by considering more challenging factors for working conditions.

REFERENCES

1. Izza, A., Jamaaluddin, U., I, R., W, W., “Identification and implementation hybrid fuzzy logic and PID controller for speed control of BLDC motor”, Journal of Physics: Conference Series 4th Annual Applied Science and Engineering Conference, Bali, 2019.

2. Pallav, D., Santanu, K, N., “Grey Wolf Optimizer Based PID Controller for Speed Control of BLDC Motor”, Journal of Electrical Engineering & Technology, Vol. 16, Pages 955-961, 2021.

3. Embiruçu, M., Neto, A, C., “Tuning of PID Controllers: An Optimization-Based Method”, IFAC Proceedings Volumes, Vol. 33, Pages 367-372, 2000.

4. Neenu, T., P, P., “Position Control of DC Motor Using Genetic Algorithm Based PID Controller”, Proceedings of the World Congress on Engineering, London, 2009.

5. Loucif, F., Kechida, S., Sebbagh, A., “Whale optimizer algorithm to tune PID controller for the trajectory tracking control of robot manipülatör”, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 42, 2019

6. Hsiao, Y., Chuang, C., Chien C., “Ant colony optimization for designing of PID controllers”, lnternational Symposium on Computer Aided Control Systems Design, Taiwan, 2004

7. Narinder, S., S, B, S., “Hybrid Algorithm of Particle Swarm Optimization and Grey Wolf Optimizer for Improving Convergence Performance”, Journal of Applied Mathematics, Vol 2017.

8. The Electronics and Robotics Club, “PID Controller”, https://erc-bpgc.github.io/handbook/automation/ControlTheory/PID_Controller/, April 20, 2023

9. Riccardo, P., James, K., Tim B., “Particle swarm optimization”, Springer Science + Business Media, Vol. 1, Pages 33-57, 2007.

10. Seyedali, M., Jin S, S., “Multi-Objective Optimization using Artificial Intelligence Techniques”, Springer, Germany, 2020.

11. Yuhui, S., Russell C, E., “Empirical study of particle swarm optimization”, Proceedings of the

1999 Congress on Evolutionary Computation-CEC99, Washington DC, 1999.

12. Seyedali, M., Seyed, M, M., Andrew, L., "Grey Wolf Optimizer", Advances in Engineering Software, Vol. 69, Pages 46-61, 2014.

13. Xin-She, Y., "Swarm intelligence based algorithms: a critical analysis", Evolutionary Intelligence, Vol. 7, Pages 17-28, 2014.

14. Fatih, A, Ş., Fatih, G., Asım, S, Y., Tunncay Y., "A novel hybrid PSO–GWO algorithm for optimization problems", Engineering with Computers, Vol. 35, Pages 1359–1373, 2019.

15. Duangjai, J., "A hybrid differential evolution with grey wolf optimizer for continuous global optimization", International Conference on Information Technology and Electrical Engineering, Chiang Mai, 2015.

16. Mohamed, A, T., A, F, A., "A Hybrid grey wolf optimizer and genetic algorithm for minimizing potential energy function", Memetic Computing, Vol. 9, Pages 347-359, 2017.

17. Narinder, S., Satya, B, S., "A novel hybrid GWO-SCA approach for optimization problems", Engineering Science and Technology, an International Journal, Vol. 20, Pages 1586-1601, 2017

18. Shaheen, A, M, M., Hasanien, M, H., Alkuhayli, A., "A novel hybrid GWO-PSO optimization technique for optimal reactive power dispatch problem solution", Ain Shams Engineering Journal, Vol. 12, Pages 621-630, 2021.