Optimization of PID Controller with Metaheuristic Algorithms for DC Motor Drives: Review

Article *in* International Review of Electrical Engineering (IREE) · October 2020

DOI: 10.15866/iree.v15i5.18688

3 authors:


Stephen Oladipo
Tshwane University of Technology


Yanxia Sun
University of Johannesburg


Zenghui Wang
University of South Africa

International Review of Electrical Engineering (I.R.E.E.), Vol. 15, N. 5
ISSN 1827- 6660 September – October 2020

Optimization of PID Controller with Metaheuristic Algorithms for DC Motor Drives: Review

Stephen Oladipo[1], Yanxia Sun[1], Zenghui Wang[2]

Abstract – *Direct Current (DC) motors are broadly used in various industrial applications such as robotics, automobiles, toys and for many other motoring purposes. This is attributable to their extraordinary flexibility, durability and low implementation cost. It is essential to control the speed, position, torque and other variables of the DC motor to achieve the needed performance depending on the area of application. Many classical techniques have been used in the past to control the DC motor, however, such methods typically take a long time, particularly when used for complex nonlinear systems. The application of metaheuristic algorithms as a means of implementing Artificial Intelligence (AI) in this area has proven to be highly effective in overcoming these shortcomings. In recent decades, metaheuristic algorithms have become increasingly prevalent due to their tremendous success in addressing a number real-world optimization challenges in various fields of human activities extending from economic, pharmaceutical and industrial applications to intellectual applications. This review, therefore, presents the optimization of the PID controller with metaheuristic algorithms for controlling the DC motor drives. A short description for each algorithm is presented along with papers published in various renowned journals. For a robust review, the application of various forms of PID controller, as well as different types of DC motors are examined. Finally, the paper presents some open issues and future directions for research.*

***Keywords**: PID Controller, Metaheuristic Algorithm, Computational Intelligence, Optimizing, Parameters, Classical Techniques*

Nomenclature

T_m	Motor torque
K_m	Constant of the motor
I_a	Armature current
L	Armature inductance
J_m	Inertia of the rotor
T_d	Disturbance torque
U_b	Back-emf
S	S-plane
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain
F	Fitness function
λ	Integral order
μ	Differentiator order
DC	Direct Current
AC	Alternating Current
PID	Proportional-Integral-Derivative
PI	Proportional-Integral
BLDCM	Brushless Direct Current Motor
FLC	Fuzzy Logic Controller
FOPID	Fractional-Order PID
EA	Evolutionary Algorithms
GA	Genetic Algorithm
DE	Differential Evolution
GP	Genetic Programming
ES	Evolutionary Strategy
BFA	Bacterial Foraging Algorithm
GWO	Grey Wolf Algorithm
AIS	Artificial Immune System
DCA	Dendritic Cell Algorithm
KHA	Krill Herd Algorithm
FA	Firefly Algorithm
FPA	Flower Pollinating Algorithm
BA	Bat Algorithm
IWO	Invasive Weed Optimization
CS	Cuckoo Search
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
ABC	Artificial Bee Colony
FSA	Fish Swarm Algorithm
MA	Memetic Algorithm
HS	Harmony Search
GS	Gravitational Search Algorithm
SA	Simulated Annealing
ITAE	Integral of Time multiplied by Absolute Error
ISE	Integral Square Error
ISTAE	Integral of the product between the Squared Time and Absolute Error
RMSE	Root Mean Square Error

 https://doi.org/10.15866/iree.v15i5.18688

ZN	Ziegler Nichols
CC	Cohen-Coon
MSE	Mean Square Error
PMDC	Permanent Magnet DC
SEDM	Separately excited DC motor
SBFA	Smart Bacterial Foraging Algorithm
DCSM	DC Servo Motor
SI	Swarm Intelligence
AI	Artificial Intelligence
SCA	Sine Cosine Algorithm
APSO	Accelerated Particle Swarm Optimization
RFG	Reference Current Generator
HCC	Hysteresis Current Controller
ANFIS	Adaptive Neuro-Fuzzy Inference System
WSDKT	Windows Servo Design Kit
PDPSO	Performance Dependant PSO
RB	Radial Basis Function
MF	Membership Function

I. Introduction

Motors are commonly categorized into two groups: AC motors and DC motors. The AC motors are operated by alternating current, while DC motors are powered by direct current [1]. Direct Current (DC) motors have received considerable interest in industrial applications due to their precision, convenience and continuous control features. Consequently, numerous industries have used DC motors extensively in a vast range of areas, such as electric vehicles, steel rolling mills, mechanical cranes, automated manipulators and home appliances [2]-[4]. As shown in Fig. 1, DC motors are of different types and are selected based on the field of operation. The brush DC motor is the first type where the stationary pole field coil system generates current flow. The second type is the brushless DC (BLDC) motor which has a permanent magnet that supplies air gap flow instead of a wire-wound field pole [5]. DC motors have many benefits over the AC motors, some of which include higher starting torque, quicker start and stop features, adjustable speed with input voltage levels, simplicity of operation and cost-effectiveness. In addition, DC motors are used as variable speed drives and have produced a range of options [6], [7].

In order to use the DC motor to accomplish a predetermined task, it becomes essential to control its torque, voltage and speed. To achieve this, the control process requires an appropriate controller with the intention of driving the motor at a target speed. The PID controller has for decades been used to control many operations in a variety of industrial applications [8]-[13].

For 83 years, control loop engineers have applied PID controllers extensively because of their exceptional capability to eradicate the system error by means of their integrator, their ability to improve the system output under control through their derivative mechanism and as well as many other advantages [14]. Therefore, the PID controller still stands out notwithstanding the advancement in new control theories.

This is as a result of its simple compositional structure [15], [16]. A basic PID configuration is made up of three terms: proportional gain (K_p), integration gain (K_i) and derivative gains (K_d) [17]. These three parameters can be adjusted to realize the desired objective of the control process [18]. Whereas the PID controller is an excellent option for regulating the speed of the DC motor, it becomes ineffective owing to load instability and adjustments in set speed [15], [19], [20]. To address this shortcoming, the controller needs an appropriate optimization technique to enhance its parameters [21].

A lot of controllers and tuning rules have been suggested in the last decades towards controlling the speed of the DC motor. Some of these controllers include Fuzzy Logic Controller (FLC), Neuro-Fuzzy Controller, H-infinity (H_∞) etc [4], [19], [22]-[27]. In the same way, several approaches extending from classical to metaheuristic techniques have over the years been used to improve the PID controller's parameters for different processes. However, there have been several disadvantages in designing the controller using classic methods such as the Huggland-Astrom, Zeigler-Nichols [28], [29], Lambda Tuning [30], Cohen-Coon [31], Chien-Hrones-Reswick [32], Tyreus Luyben [33], Internal Model Control method [34] etc. Typically these classical methods take a great deal of time to adjust their parameters, particularly for complex nonlinear systems.

This is because the optimization process needs to be done over and over until the optimum solution is reached [35]. The use of metaheuristic algorithms as a way of implementing Artificial Intelligence (AI) in this field has proven to be highly effective in overcoming these shortcomings. There are several reasons for choosing the metaheuristic algorithm to solve a given problem. One of them is their ability to find solutions in situations where the complexity or time of the problem does not allow effective optimization methods to be applied. Another advantage is the ability to avoid being stuck at the local optimal level during exploration while they strive to find a viable solution [36].

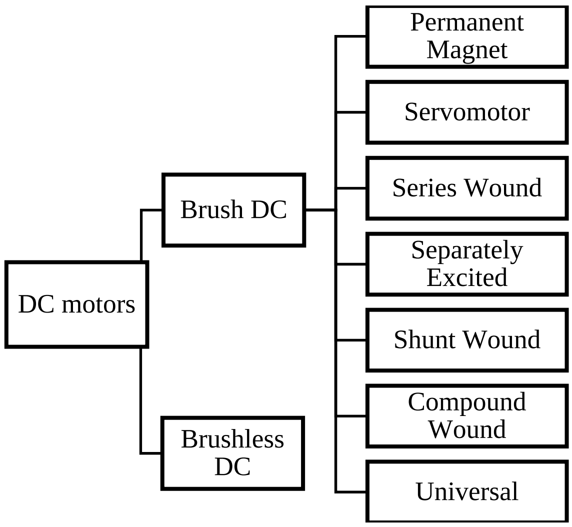


Fig. 1. Classification of DC motors

Review from works of the literature shows that metaheuristic algorithms can be classified into diverse groups depending on their characteristics and nature inspiration. Metaheuristic algorithms can be categorized as evolutionary algorithms, nature-inspired, bio-inspired, physics-inspired algorithms, population-based, single-solution based algorithms etc [37]-[39]. Other reviews and surveys have been conducted in the past on the optimization of the PID controller, however, this work focuses on the optimization of the PID controller in controlling the DC motor and also builds on other studies by considering several classes of metaheuristic algorithms. Ghosal et al. [40] conducted a review on the optimization of the PID parameters with different types of Swarm intelligence namely, Ant Colony Optimization (ACO), Bacteria Foraging Optimization (BFO) algorithm and Particle Swarm Optimization (PSO).

De Leon-Aldaco, Calleja, and Aguayo [41] conducted a comprehensive analysis of metaheuristic techniques used in the power converter domain and presented numerous advantages in resolving the difficulties faced by the design, operation and control of the power converters. The analysis consists of the description of the techniques and their key objective features. Singh and Garg [42] presented a review on the optimization of PID controller for regulating the speed of the DC motor.

However, within the scope of 2009-2014, only a few works of literature were considered in the paper for three techniques, namely GA, PSO and Fuzzy Logic Algorithm.

Nevertheless, the analysis of current literature will present some recent advances in the methodology of optimization, and thus provide a more robust review. Dineva et al. [43] carried out a review on the soft computing models in the design and control of rotating electrical machines. Several optimization techniques and their applications to rotating electrical machines were reviewed in the paper. Goswami and Joshi [44] focused on fuzzy logic based controllers for controlling the BLDC motor.

The authors only focused on the optimization of the classical PID with Fuzzy Logic Control Scheme between 2001-2017. This review, therefore, presents the optimization of the PID controller with metaheuristic algorithms for controlling the DC motor drives within the span of 2001-2019. For a robust review, the application of various forms of PID controller, as well as different types of DC motors are examined. Additionally, the paper also presents some open issues and future directions for research.

The remainder of this paper is organized as follows.

Section II comprises the mathematical model of a typical DC motor. Section III presents the structure of the PID controller. Section IV discusses the classification of metaheuristic algorithms. Section V reviews the optimization of PID controller with different classes of metaheuristic techniques, while their different challenges are presented in Section VI. Finally, the conclusion is given in Section VII.

II. Mathematical Model of a Typical DC Motor

The model of a system either in visual, pictorial, analytic or computational format reflects a specific property of the real system. Graphic representations are often in block diagrams and signal flow graphs. Mathematical models can be represented by transfer function or state-space equations. The speed of the DC motor is primarily controlled by the system of armature control and field control [45]. The block diagram of the model of the DC motor is shown in Fig. 2 while Eqs. (1)-(5) are the equations representing the dynamic characteristics of the DC motor [46]:

$$T_m(s) = K_m I_a(s) \tag{1}$$

$$U_a(s) = (r_a + Ls) I_a(s) + U_b(s) \tag{2}$$

$$U_b(s) = K_b \dot{\theta}(s) \tag{3}$$

where T_m is the motor torque, K_m is the constant of the motor, I_a is the armature current, U_a is the armature applied voltage, r_a is the resistance of the armature, L is the armature inductance, J_m is the inertia of the rotor, T_d is the disturbance torque, U_b is the back-emf, s is the s-plane. Armature current is expressed in Eq. (4), the torque delivered to load is presented in Eq. (6):

$$I_a(s) = \frac{U_a(s) - K_b \dot{\theta}(s)}{r_a + Ls} \tag{4}$$

$$T_l(s) = J_m s^2 \theta(s) + B_m s \theta(s) \tag{5}$$

$$T_l(s) = T_m(s) + T_d(s) \tag{6}$$

The transfer function of DC motor is as established in Eq. (7):

$$\frac{\dot{\theta}(s)}{U_a(s)} = \frac{K_m}{(r_a + Ls) + (J_m s + B_m s) + K_m K_b} \tag{7}$$

III. Proportional-Integral-Derivative Controller (PID)

The PID controller is among the most common types of feedback controllers used in control engineering [47].

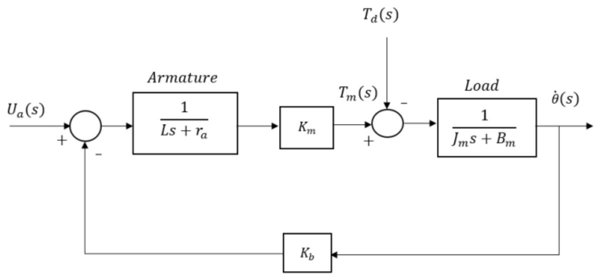


Fig. 2. Block diagram of DC motor [46]

This is attributable to its flexible feedback control loop architecture which makes it prominent in the industrial control system [48]. The conventional PID controller has three simple terms represented by letters 'P', 'I' and 'D'. PID is an acronym for proportion, integral and derivative. The proportional gain measures the contribution of the current error, the integral gain influences the reaction on the sum of the previous error, and the derivative gain determines the response based on the rate at which the error has changed. The weighted sum of these three events is used to adjust the control system through the final control element [49], [50]. The desired PID controller value is achieved through a systematic action that guarantees the equality of the measured value with the desired value, while the output of the controller is decreased by constant error. The structure of a conventional PID controller is shown in Fig. 3, while Eq. (8) and Eq. (9) illustrate the output of the controller [51]:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \tag{8}$$

$$G_c(s) \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \tag{9}$$

where $u(t)$ is the PID controller output, the proportional gain is represented by K_p, the integral gain is donated by K_i and K_d is the derivative gain. The error is represented as $e(t)$. On the other hand, the development of fractional calculus by Podlubny et al. [52] has lately paved way to migrate from classical models to those defined by non-integer-order differential equations [53]. The use of FOPID in industries is ascribed to some more significant benefits obtained from the two extra "tuning knobs" which can be used to improve control laws when implemented to the control loop. The output equation of the FOPID is given in Eq. (10):

$$G_c(s) = \frac{U(s)}{E(s)} = K_P + K_I s^{-\lambda} + K_D s^{\mu} \tag{10}$$

where K_P, K_I, K_D are proportional gain, integral gain and derivative gain respectively. The integral order is represented by λ while μ is the derivative order. As demonstrated in the works of [54], [55] and [56] the controller design has much more versatility in tuning and therefore, has a large area of parameters that govern the controlled system and increases the reliability of the control loop.

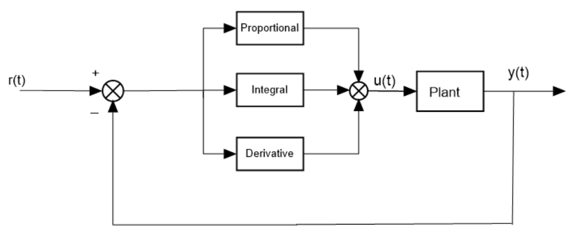


Fig. 3. Structure of the conventional PID controller [51]

The parameters of PID or FOPID can be optimized by different types of metaheuristic algorithms as shown in Fig. 4.

IV. Classification of Metaheuristic Algorithms

Metaheuristic algorithms in recent times are one of the very important research areas for scholars, academics and scientists [57]. This is because metaheuristic algorithms have important features and specific competences. Their capacities in addressing and providing near-optimal solutions to problems without providing extensive details of the problem concepts have given them an advantage over many traditional techniques. With reference to different publications on the web of science in the last decade, Fig. 5 shows that more studies and publications have been conducted on different applications of metaheuristic algorithms.

Metaheuristic algorithms are mostly motivated by some real-world phenomena. They are usually a natural technique of optimization. A handful of metaheuristic algorithms have been developed and implemented to tackle various problems over recent decades. It has also developed a tremendous interest in the field of engineering as shown in Fig. 6. Metaheuristic algorithms attempt to balance randomization with local search, so most of these algorithms are used to optimize globally [58]. The efficacy of a given metaheuristic algorithm is detected in a particular optimization problem if it is capable of achieving an ideal blend between the utilization of accumulated search information and the discovery of a search space in the selection of regions with high-quality solutions that are often considered to be the near-optimal solution. Predominantly, metaheuristic algorithms are influenced by the actions of animals/insects, humans, theories of evolution and different forms of natural phenomena [60]. As depicted in Fig. 7, they can be divided into five various classes dependent on the source of inspiration namely, Bio-inspired, Nature-inspired, Physics-based, Evolutionary and Swarm-based [59].

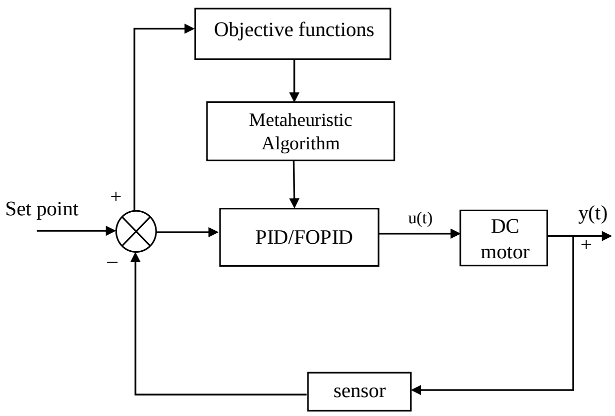


Fig. 4. PID/FOPID tuning techniques

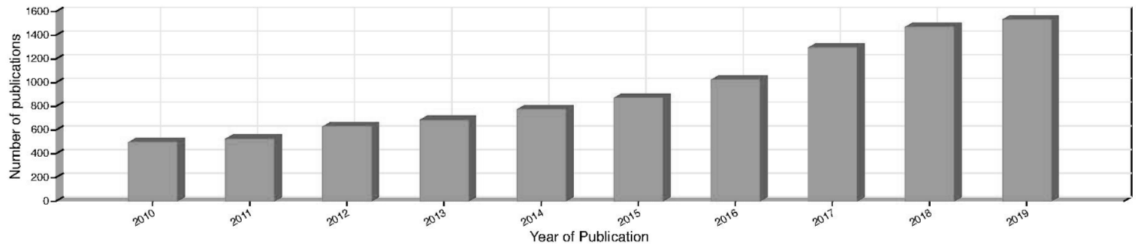


Fig. 5. Publications index on metaheuristic algorithms and their applications in the last decade (Source: Scopus & Web of Science).

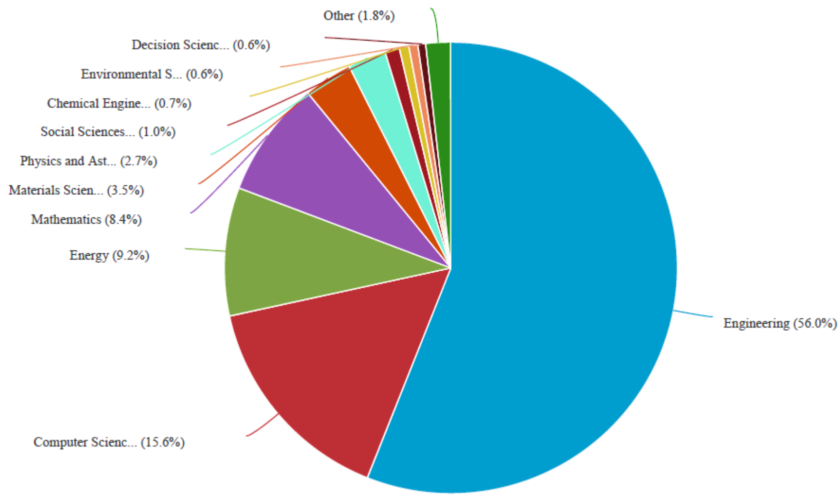


Fig. 6. Application of Metaheuristic Algorithm in different field of studies. (Source: Scopus & Web of Science)

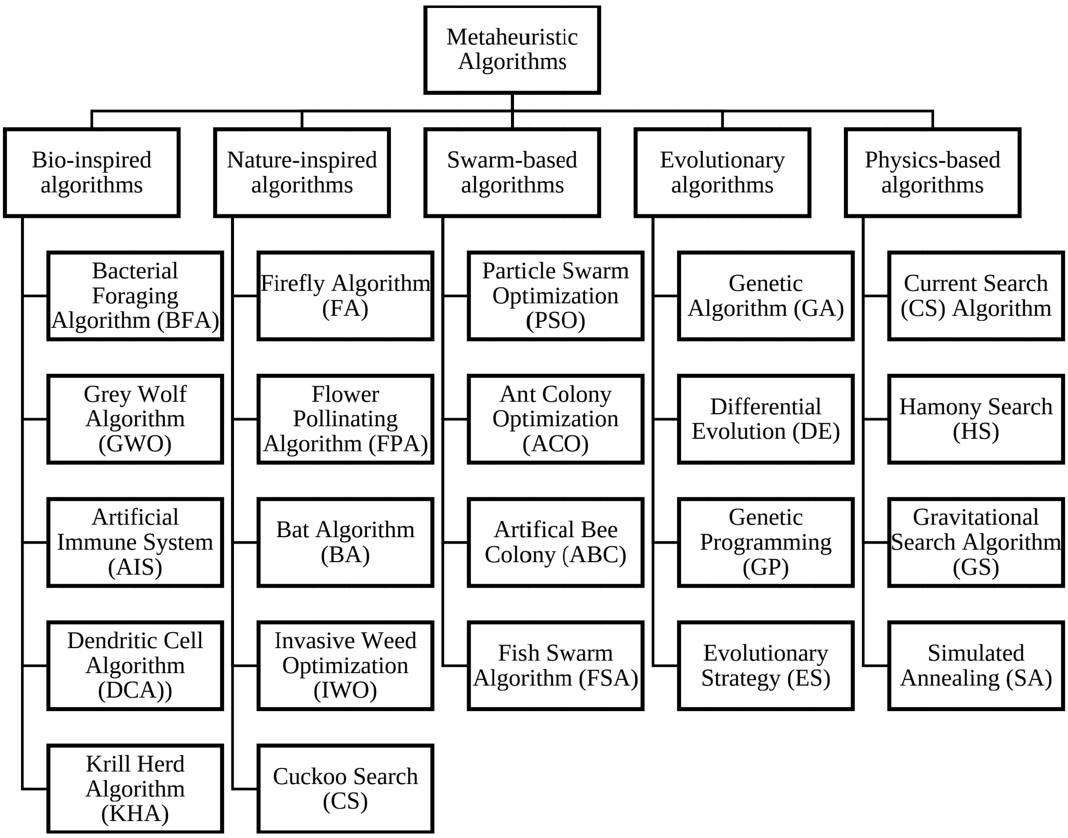


Fig. 7. Metaheuristic Algorithm Classification [59]

In recent years, numerous studies in computer science, mathematics and biology have been conducted under the theory of bio-inspired computation [61]. Bio-inspired computational optimization algorithms are innovative methods founded on the principles and motivation of the biological evolution of nature to create new and effective competitive techniques. Some of the Bio-inspired algorithms considered in this paper are Bacteria Foraging Algorithm (BFA), Grey Wolf Optimizer (GWO), Artificial Immune System (AIS), and Social Spider Optimization (SSO). The Nature-inspired algorithms are another category of metaheuristic algorithms which have become essential tools in addressing many computational problems. The algorithms are influenced by nature, human activities, animal social behaviour, and so on.

Firefly Algorithm (FA), Flower Pollinating Algorithm (FPA), Bat Algorithm (BA), Invasive Weed Optimization (IWO), Cuckoo Search (CS) are all examples of Nature-inspired algorithms [62]. The ability of these algorithms to address highly non-linear and complicated issues, particularly in science and technology, enable them to be very effective and reliable to solve problems of optimization in the real world [63]. Furthermore, Physics-based algorithms are another variety of metaheuristic algorithm enthused by the laws of physics [64]. Several Physics-based algorithms are motivated by quantum computing, Newton's gravitational laws and laws of motion, and have demonstrated to very successful in handling numerous problems of optimization. [65]. Some of the physics-based algorithms considered in this work are the Current Search (CS) algorithm, Harmony Search (HS) algorithm, Gravitational Search Algorithm (GSA) and Simulated Annealing (SA) algorithm. Evolutionary Algorithms (EAs) focus on the evolution of species. This suggests that EAs are based on Charles Darwin's evolutionary theory. The fundamental principle behind all EAs remains the same, even though the execution of their structure may change significantly. Evolutionary algorithms are typified by the existence of an individual population under environmental pressures, leading to the survival of the fittest and, besides, an improvement in the population average fitness [66]. Genetic Algorithm (GA), Differential Evolution (DE), Genetic Programming (GP) and Evolutionary Strategy (ES) are examples of EAs that have been used to tackle many optimization problems in recent times. Swarm Intelligence (SI) algorithms have drawn the attention of several researchers in different areas [67]. The flexibility, self-learning ability and the adaptability to external disruptions of the Swarm-based algorithms have been the key factors in captivating the minds of researchers across the globe [68]. Swarm intelligence is the study of collective intelligence-stimulated computational systems [69]. Collective intelligence arises via great numbers of homogeneous agents working together in the environment [70]. Sources of this include fish colleges, bird flocks, and ant colonies.

This intelligence is being dispersed, self-organized, and spread in an environment. Some of the prominent examples in recent times are Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC) and Fish Swarm Algorithm (FSA).

V. PID Parameters Optimization Using Metaheuristic Algorithms

V.1. Evolutionary Metaheuristic Techniques

An evolutionary-based technique is a common population-based type of metaheuristic algorithm which is motivated by biological evolution. Evolutionary Algorithms (EA) are motivated by processes of evolution such as reproduction mutation, recombination, and selection [71]. It involves a natural choice theory in which a group or set of solutions seek to thrive in an environment based on fitness evaluation. EA is able to solve a particular problem optimally because its approach requires no inference of human-environment or physical fitness ideally. Some examples of evolutionary algorithms are Genetic Algorithm (GA) [72], Differential Evolution (DE) [73] and Genetic Programming (GP) [74] many others. Genetic Algorithm was motivated by Darwin's theory of evolution and it is grounded on random classical EA. GA finds a solution to an optimization problem by applying random changes to current solutions so as to generate new ones. GA is a search method used in computation to look for exact and approximate solutions. GAs are known as global search heuristics and they are a special category of EAs that use evolutionary biology-inspired strategies such as mutation, cross over, selection and inheritance [75].

Kamal et al. [76] proposed the speed regulation of the brushless DC motor by optimizing the parameters of the PID controller with GA. The PID parameters namely, K_p, K_i and K_d were optimized using Integral Square Error (ISE)-based fitness function. Subsequently, the PID controller was also optimized with Fuzzy Logic Controller's (FLC) reasoning rules. A comparative study was conducted between the GA-based PID and the Fuzzy-based PID controller. Results obtained from simulation indicates that the proposed GA-PID controller reduces overshoot and demonstrates greater improvement with lesser rising time and settling time.

Therefore, it was concluded that GA-PID received a much better response for the speed regulation of the BLDC motor. Similarly, Tiwari et al. [77] suggested using a GA-based PID controller to control the DC motor. The response of the proposed controller was paralleled with the conventional Ziegler-Nichols (ZN) method under two different performance indexes namely, Mean Square Error (MSE) and Integral of Time multiplied by Absolute Error (ITAE). The proposed GA-based PID demonstrated a better performance by having the least overshoot, fastest-rising time and minimal settling time compared to ZN. Lin et al. [78] introduced a controlling technique involving an application of GA-based multi-objective PID control for a linear brushless

DC motor. Using rise time, peak overshoot and steady-state error, the performance of the proposed optimization technique was evaluated. With the application of the genetic exploration strategy, a comprehensive two-parameter PID control framework was created. The effectiveness of the proposed controlling structure was validated using experimental implementation. The proposed tuning approach was compared with other commonly used PID tuning techniques. Simulation and experimental results revealed an improved performance of the proposed GA-PID controller which has the shortest rise time, the least overshoot and the lowest steady-state error. Xiou [79] and Ming et al. [80] engaged GA to tune the gains of a PI controller. The intention of the research work was to improve the response of the control system over the traditional ZN technique. This is because of the difficulty in realizing the control plant exact mathematical model which places a design limitation on the determination of the PID parameters while utilizing the popular Z-N method. The cascade control of the PID controllers is an innovative technique to strengthen the control structures prone to significant lag. A Graphic User Interface (GUI) was used to model the cascade controllers. The purpose of the GA control technique is to determine the best collection of solutions for the controller that provides optimal adaptive and static output for the system. Simulation results indicate that the proposed cascade controller offered an improved dynamics in terms of the current and speed response with lower overshoots and rapid response for both the starting and loading stage of the drive. Sankardoss and Geethanjali [81] employed GA to determine the parameters and to adjust the speed of the permanent magnet DC (PMDC) motor. In addition, the researchers as well compared the speed control response of the PMDC engine between PI, PID and state feedback controllers. The electrical, mechanical and electromechanical parameters were calculated with the GA while modelling the PMDC motor in MATLAB/Simulink environment. Simulation results show that the state feedback controller presented the best result among others with the shortest settling time and least overshoot. Zahir et al. [82] conducted a comparative study to monitor the speed of the BLDC motor using the GA, ZN and Skogestad-IMC controllers. The three controllers were used to modify the parameters of the PID controller while ITAE was used as the analytical function. GA-based PID controller outperformed ZN and Skogestad-IMC controllers by providing the shortest rise time, settling time and least overshoot under the ITAE objective function. Differential Evolution algorithm was proposed in 1997 by Storn and Price [73]. It was inspired by biological evolution and belongs to the class of EA [60]. DE is a basic, efficient and robust optimization algorithm which is population-based. The DE algorithm operates on four major stages namely, initialization, mutation, recombination and population selection. DE is similar to GA as a contemporary evolutionary algorithm in that it uses the same evolutionary operators as mutation, crossover and selection to direct the population to an optimal solution [83]. To harness the features of the DE algorithm, Syed and Abido [84] worked on the regulation of the speed of the PMDC engine with the DE algorithm. The DE algorithm was used to select appropriate values for the gains of the controller. The success of the proposed DE-tuned PID controller was tested under different load disturbances. The algorithm showed good results because the optimum values produced by the proposed controller's parameters displayed excellent performance. Syafah et al. [85] suggested the design of the PID controller to enhance the dynamic steadiness of the speed of the DC motor by using DE to fine-tune the PID parameters. The proposed DE algorithm was compared with PSO-based PID during simulation and experimentation at various speed setpoint values. The results of the simulation and experimentation revealed that DE-PID provided better output under sudden speed change by reacting faster and being more stable than the PSO-PID and the conventional PID controllers. Additionally, DE-PID shows lesser overshoot than the PSO-PID and standard PID controllers. As a form of advancement in the work of Syafah et al. [85], Idir et al. [86] improved the conventional PID by using a newly developed fractional-order PID (FOPID) controller to regulate the DC motor speed. In their work, the DE algorithm was used to search for optimal gains of the FOPID controller. FOPID defers from the conventional PID in that it has two additional parameters apart from the proportional K_p, derivative (K_i) and integral (K_d) constants. The two additional parameters λ (integral order) and μ (derivative order) along with K_p, K_i and K_d were optimized with the DE and PSO algorithms respectively. The author reported a better time domain characteristics of the proposed DE-FOPID controller compared with the PSO-FOPID controller. Bosco et al. [87] explored the application of the DE algorithm in the estimation and optimization of the PI parameters for the permanent magnet DC motor. The first step was the utilization of the DE algorithm to estimate the moment inertia, constant torque, coefficient of friction, armature resistance and armature inductance. All these parameters were estimated for the PMDC motor. The velocity of the PMDC was then controlled by optimizing the PI controller under no-load and load variation situations. The proposed DE algorithm was analyzed using ITAE performance index. Comparison between the simulated and experimental analysis displayed the robustness of the proposed DE algorithm. A new adaptive control technique for the DC motor speed management function is introduced by Rodriguez-Molina [88]. The controlling scheme was designed to address the online dynamic optimization problem. To realize this, ten different variants of the proposed DE algorithm were used. A comparison was carried out to determine the most effective variant to be applied in the problem. In addition, two classic controllers namely, Model Reference Adaptive Controller (MRAC) and PI controller were compared with the new strategy to reveal its performance over them. The results of the computational analysis in the adaptive control of different DE variants illustrated the supremacy of the proposed speed control optimization technique compared with other variants. In addition, the proposed DE control technique outperformed MRAC and PI by having better regulation capability even at the occurrence of uncertainties. Further analysis could be done to handle the trade-off between the regulation errors and energy consumption by approaching the problem as a multi-objective optimization problem. Alternatively, it is recommended that the suggested technique be applied experimentally with a view to validating its true accuracy. While Syed [84], Bosco [87] and Syafaah [85] used the conventional DE algorithm in their works, Jigang, Hui and Jie [89] proposed a modified DE algorithm for regulating the speed of the BLDC motor by introducing a fitness-based adaptation scheme for mutation factor (F) as in Eq. (11). The crossover factor (CR) was designed as a constant value of 0.6:

$$F_j = F_{\max}\left(1 - e^{-f(X_j)}\right) \tag{11}$$

where $f(X_j)$ represents the fitness function of X_j, and $F_{\max}$=0.8. The adjusted DE algorithm was engaged to modify the gains of the PI controller focusing on the adaptive mutation factor, the multivariable fitness function and the starting rule. A comparison was conducted to display the performance of the improved DE-PI controller over the traditional DE and PI controllers. The results of simulation and experimentation conducted showed that the proposed controller provided a better-controlling capability with lower overshoot, reduced settling time and rise time opposed to other controllers under the same operating conditions. Biogeography Based Optimization (BBO) algorithm have a close relationship with other EAs like Genetic Algorithm and Differential Evolution [90]. However, BBO has some distinctive feature like inter-habitat distance on migration, nonlinear migration relationships, reproduction rates on migration, the effect of population sizes, and so on [91]. As a result of this, Mo and Xu [92] used the distinctive migrating model of BBO to fine-tune the PID parameters to regulate the DC motor. The authors compared the suggested BBO algorithm with other existing methods. Results of experiment and simulation show that the proposed BBO was competent to discover optimal solutions in a tiny local neighbourhood space. The BBO-PID gave zero overshoot, best steady-state error and least dynamic response time of the system. Similarly, Waley [93] optimized the PI controller with the BBO algorithm. The research was aimed at governing the speed response of the DC motor with the standard PI, GA-PI and proposed BBO-PI controllers. A comparison was made under Integral of Time-weighted Square of Error (ITSE) fitness function. The values obtained for the rise time, adjustment time, maximum overshoot and the power quality improvement, established the fact that the BBO-PI outperformed other controllers in the comparative study. Stochastic Fractal Search (SFS) algorithm has recently emerged as an effective metaheuristic algorithm that mimics the natural growth pattern and employs a fractal-based diffusion process [94]. Khanam and Parmar [95] examined the use of SFS algorithm in order to regulate the speed of the DC motor. The PID controller's gains were tuned with the proposed SFS algorithm while adopting the ITAE as the performance index. Results of the research work show that the suggested SFS-PID scheme with ITAE cost function gave a better performance with lesser rise time, adjustment time and overshoot compared to other existing techniques. The SFS-PID robustness was examined by subjecting the DC motor to different load variations. The authors reported that the proposed SFS-PID scheme outperformed Invasive Weed Optimization (IWO) and PSO algorithms by having the quickest rise time, shortest adjustment time and lesser overshoot. On the other hand, Çelik and Gör [96] introduced a reformed version of the conventional PID controller for speed relation of the DC servo system. In their work, a PI control's law was implemented with windup protection and is paired with a derivative path by applying a first-order low pass filter innovatively so as to come up with the reformed PID controller. This is recognized as a performant PI+DF controller. The SFS algorithm was utilized to adjust the parameters (proportional, integral, derivative and filter gains) of the developed controllers for performance enhancement. The choice of SFS algorithms was based on its outstanding performance in terms of convergence, precision and robustness. Subsequently, the same process was replicated with the PSO algorithm to estimate the reliability of the proposed SFS algorithm, resulting in a comparative study between the SFS-PI+DF and the PSO-PI+DF controllers. Results of simulation and experimentation indicate that the SFS-PI+DF delivered the best speed response result in terms of stability and accuracy compared to PSO-PI+DF. Jaya Optimization Algorithm (JOA) is a current metaheuristic algorithm that Rao proposed in 2016 to solve the constrained and unconstrained optimization problems [97]. JOA is predicated on the idea that the resolution to a problem should be moved to the best solution whereas eliminating the worst solution. The uniqueness of JOA is that it needs only a few control parameters such as the total number of generations and population size, and the number of layout variables typical to any algorithm most of the time [98]. Owing to this advantage, Achanta and Pamula [99] investigated the regulation of the DC motor by using JOA to enhance the parameters of the PID controller. In their work, the authors first accomplished a comparative examination between PSO, DE and Cuckoo Search (CS) algorithms in monitoring the velocity of the DC motor. Results presented show that PSO outperformed both DE and CS algorithms. Then an additional comparative analysis of the PSO with the proposed JOA was performed to further reveal the accuracy of the suggested algorithm in enhancing the PID gains while controlling the DC motor speed. Practical validation was carried out on QNET 2.0 DC motor using LabVIEW® software. The result obtained show that the JOA algorithm gave a better transient response compared to the PSO algorithm.

However, PSO algorithm outperformed JOA in terms of the steady-state response. Imperialist Competitive Algorithm (ICA) is an evolutionary algorithm (EA) developed by Atashpaz-Gargari and Lucas in 2007 [100]. ICA was motivated by imperialistic competition of the social-political process in the real world. Ghalehpardaz [101] regulated the speed of the DC motor by making use of the ICA and GA algorithms. In the work, ICA and GA were used to tune the PI-like FLC controller by optimizing the Membership Functions (MFs) and gain factors of the FLC controller. The ICA optimized PI-like FLC controller performed better than the GA optimized PI-like FLC considering the rise time, settling time and overshoot. This suggests that the ICA optimized PI-like FLC is recommendable for real-time applications. Afra, Aidin and Jafar [102] examined the position control of the DC motor by selecting appropriate PID parameters using ICA and ZN methods. The output of the simulation indicates that the ICA tuning technique is better than the classical ZN method. However, even though the algorithm has proven successful in finding solutions to some optimization problems, it gets stuck at local optimal if used to solve high-dimensional multi-model numerical optimization problems. Consequently, Sharifi and Mojallali [103] suggested a modified ICA for the BLDC motor optimization problem. The suggested algorithm focuses on shifting countries in the direction of the best imperialist and incorporates several methods to expand the single-objective algorithm to the multi-objective model. The algorithm was then utilized to increase the efficiency, mitigate the total weight and concurrently satisfy six inequality limitations in the design variables of the BLDC motor. Evolutionary Programming was proposed by Dr Lawrence J. Fogel [104]. It fits into the class of EA which is stimulated by the organic evolution. EP finds its application in solving different optimization problems. Its mode of operation is based on mutation, competition and evolution. There are three distinctive features of EP from other optimization techniques. EP implements searching through a population of points rather than from a single point in finding global optimal. Also, EP utilizes fitness or objective function information directly in the course of the search. When selecting generations, EP uses probabilistic transformation rules (not deterministic rules) so they can look for a complex and unpredictable area to find global optimum [105]. Therefore, the EP has proven efficient and reliable compared with conventional approaches. Chang, Li and Gang [106] worked on the optimal design of the PID controller for regulating the position of the permanent magnet DC motor with EP.

The concept is based on the opinion that EP is regarded as an effective approach of searching for a global optimization solution for a complex function. In the research work, the EP algorithm was incorporated into the PID controller to address the positioning control issue of the permanent magnet DC motor by minimizing the Integrated-Absolute Error (IAE) performance index. An observation was made to illustrate its performance under reference input taken as a unit step function to assert the viability of the proposed method. The study shows that the suggested controller can achieve an effective search for the parameters of the PID controller. Evaluating the proposed EP-based controller with the classical ZN-PID technique demonstrated a better dynamic system performance. Evolutionary Strategy was developed by Rechenberg and Schwefel in the 1960s. It has been used extensively by numerous researchers to find solutions to optimization problems [107]. ES generally uses a real-valued description (though binary and integer variants of ES exist) and depends predominantly on selection and mutation to propel the evolutionary process. Many ES systems incorporate self-adaptation as the algorithm adjusts its diversity-generation level during the optimization process in response to feedback. Given the common concept of adaptive EAs in recent years, ES was the first EAs family to integrate self-adaptation as an integral component of its algorithm [108]. Chun-Liang and Horn-Yong [109] introduced the application of the ES algorithm for adjusting the speed of a linear BLDC motor by optimizing the parameters of the multi-objective PID control. The evolution analysis methodology was used to build a two-parameter PID control structure that ensures that several requirements are met. The dynamic multi-objective model design problem was effectively undertaken using an Evolution Creation Algorithm (ECA) that presents a non-complicated and elegant way to bridge H_∞ control technique and pragmatic code models. The design approach was used to handle the efficient operation of a transport carriage by governing the speed of the linear DC brushless motor. Results of simulation and experimental analysis validated the superiority of the proposed controller over the standard ZN rules.

V.2. Bio-Inspired Metaheuristic Techniques

Bio-inspired computation has been the focus of various computer engineering, mathematics and biological researchers over the past few years [61]. Bio-inspired computational optimization techniques are innovative approaches that focus on the concepts of biological evolution in order to develop new and successful functional techniques. Bio-inspired optimization algorithms have been established in machine learning over the last few years to effectively address emerging science and engineering issues. This paper presents various Bio-inspired optimization techniques that have been used over time to address various control issues in different types of DC motor namely; Bacterial Foraging Algorithm (BFA) [118], Grey Wolf Algorithm (GWO) [119], Artificial Immune System (AIS) [120], Dendritic Cell Algorithm (DCA), Krill Herd Algorithm (KHA) [121].

TABLE I
SUMMARY OF PID PARAMETERS OPTIMIZATION USING EVOLUTIONARY ALGORITHMS

Algorithm	Year	Brief description of the control scheme	Ref.
GA	2014	Speed regulation of a brushless DC motor by optimizing the parameters of the PID controller with GA.	[76]
	2019	GA-based PID Controller for DC Motor control	[77]
	2003	Application of GA-based multi-objective PID control linear BLDC motor	[78]
	2008	Regulating BLDC motor drive with GA-based PI controller	[79]
	2009	Position regulation of the DC motor with GA-PID controller	[110]
	2011	Modelling and control of three-phase BLDC motor using PID-based GA	[111]
	2012	Modelling and control of a BLDC motor using with GA-PID controller	[112]
	2013	Speed control of the DC motor using PID-based GA controller	[113]
	2018	Controlling the speed of the DC servo motor by optimizing the PID parameters with GA	[114]
	2017	Regulation of the rotor of the BLDC motor using a GA-based PID controller	[115]
	2016	Control of the speed of the DC motor by optimizing the PID controller with GA	[116]
	2014	Optimization of a cascade PID with GA for the speed control of the DC motor.	[117]
	2017	Estimation of the parameters and speed regulation of a wheelchair permanent magnet DC motor using a GA-based PID controller	[81]
	2018	PID optimization with GA for regulating a brushed DC motor	[82]
DE	2013	Optimization of the PID parameters using the DE algorithm for controlling the speed of the PMDC motor.	[84]
	2017	Reduction of damping oscillation for DC motor speed by optimizing the parameters of the PID controller using DE and PSO algorithms.	[85]
	2017	Application of DE in the estimation and optimization of PI controller parameters for a permanent magnet of DC motor.	[87]
	2018	Optimization of the FOPID parameters to regulate the DC motor speed.	[86]
	2018	Adaptive control technique for the DC motor speed using a DE-based PI control.	[88]
	2019	Optimization of the PI controller with a modified DE algorithm in controlling the frequency of the speed BLDC motor.	[89]
BBO	2015	Application of the distinctive migrating model of BBO in adjusting the PID parameters to control the speed of the DC motor.	[92]
	2019	Comparative study between the classical PI, BBO-PI and GA-PI controllers in controlling the speed of the DC motor.	[93]
SFS	2018	Regulation of the acceleration of the DC motor using a PID controller based on the SFS.	[95]
	2019	Speed control enhancement for DC servo system using an SFS-based PI + DF controller.	[96]
JOA	2018	Control of the DC motor using the JOA-based PID controller.	[99]
ICA	2011	Regulation of DC motor speed through a comparative study of ICA and GA optimization techniques by applying them to the developed PI-like FLC controller	[101]
	2013	Position control of the DC motor by selecting appropriate PID parameters using ICA and ZN methods.	[102]
	2019	Modified ICA for BLDC motor optimization problem.	[103]
EP	2011	Optimal design of a PID controller in controlling the position of the permanent magnet DC motor with EP	[106]
ES	2002	Evolutionary multi-objective PID control of a linear BLDC motor.	[109]

Bacteria Foraging Algorithm (BFA) is one of the categories of Bio-inspired metaheuristic algorithm which researchers have extensively used to address optimization problems in several fields. BFA was motivated by the social foraging characteristics of Escherichia coli [118]. Abed [122] developed a BFA- based PID (BFA-PID) controlling method for regulating the speed of a separately excited DC motor (SEDM). The PID parameter's optimization was handled by emulating the bacteria Escherichia's (E. Coli) social foraging behaviour. The mathematical model of the SEDM was formulated and simulated in the MATLAB software. The efficiency and performance of the suggested BFA-PID were examined by comparing it with the classical ZN tuning method. The authors reported that the BFA-PID surpassed the ZN method at no-load, light-load and half-full load scenarios by having lesser rise time, settling time and overshoot. Precup et al. [123] worked on the performance study of the optimal tuning of the PID controller with BFA algorithm for controlling the DC pancake driving motor system. The BFA model addresses an algorithm problem aiming at minimizing the optimal feature represented as the weighted amount of overshoot plus the integral of the measured error. Further study can be made to focus on expanding the model outcomes with experimental implementations by incorporating some comparative information with many other nature-inspired algorithms. Similarly, Oshaba and Ali [124] proposed the BFA for controlling the speed of the DC series motor. The speed of the DC motor was controlled by applying the proposed BFA to look for the optimal values of the PI controller's gains and in so doing reducing the time domain of the objective function. Evaluation of the proposed method was conducted while considering the load torque variation, radiation and ambient radiation. Alzuabi [125] suggested the regulation of the DC motor by adjusting the parameters of the PID controller with the BFA. The BFA optimization approach was utilized to search for the optimal gains of the PID controller so as to enhance the function and response of the DC motor system. The system was implemented and tested using MATLAB software. The controller's optimum gains were used to test the process. The effects are enhanced and more effective than the heuristic-adjusted PID controller. While the proposed technique has proved successful in the control system under consideration, standard BFA has a sluggish convergence rate downside. This is because a bacterium that is already close to the optimum location can be overtaken by another bacterium that is far away and therefore reduces the rate of convergence. To overcome this, Daryabeigi and Mirzeian [126] proposed an improved BFA. The new algorithm was enhanced by the introduction of adaptive social and individual foraging behaviours to the traditional BFA. In the work, Smart Bacterial Foraging Algorithm (SBFA) is provided with an advanced methodology for Switched Reluctance Motor (SRM).

The technique imitates the bacteria *E.Coli* chemotactic conduct for the optimization. The suggested algorithm utilizes personal emotional levels of intelligence so that the optimization problem can be adapted to hunt for solutions among local optimums. This method was explored to adjust the gains of the standard PI speed controller for the SRM, taking a decrease in torque ripples into account. The analysis of simulation and experimental results affirm improvement in the performance of the SRM making the proposed optimization technique to be adaptable to other applications. Likewise, Diao, Zhu and Zhang [127] also suggested an improved algorithm foraging bacteria algorithm (IBFA) to track the movement and acceleration of a brushless bearing-less DC motor. The key reason for improving the BFA is to resolve the lag problem in initialization duration and low accuracy that occurs within the standard BFA and also to augment the parameters of the PI controller during the control process. Results of simulation of the proposed IBFA presents a reduction in speed, peak overshoot, torque ripple and rotor position oscillation. The Artificial Immune System (AIS) copies the supreme features of the biological immune system and provides an effective approach of cognitive computation and system development [128]. The Artificial Immune System (AIS) has been thoroughly studied over the last few years and has been used in many fields including software security, anomalies identification, object segmentation, data mining and the likes [129].

Lifang and Shouda [130] have implemented an AIS-based PID controller to control the speed of a double closed-loop flywheel. Research shows that the proposed controller is efficient even under load changes over the regular PID controller. An immune PID regulation system based on AIS is introduced in [131] to boost the control performance of the in-wheel motor used in an electric car. The method takes the output index of the controller as the objective function, considering it as antigens, and takes the K_p, K_i and K_d of the PID as the solution and antibodies.

Result obtained indicates that the immune PID approach surpassed the standard PID in overshoot and time change process. Hadi and Zaidi [132] proposed the implementation of an AIS algorithm for addressing DC Servo Motor (DCSM) speed control problems. The proposed algorithm was applied to optimize the PID controller by minimizing the ITAE objective function.

The experiment was repeated using ZN tuning technique to evaluate the proposed controller's output over the conventional methods. Both tuning techniques were paralleled and analyzed in time domain. The result indicates that the AIS-based PID controller exceeded others in terms of rise time, settling time, overshoot and steady-state error relative to the ZN method

Mirjalili et al. proposed the Grey Wolf Optimizer (GWO) in 2014 [119]. GWO is an innovative meta-heuristic optimization technique which emulates the attribute of leadership and hunting behaviour of grey wolf species. It imitates the communal chain of command and hunting traits in the society of grey wolves [133]. Madadi and Motlagh [134] applied GWO and PSO to adjust the gains of PID to attain optimal control of the DC motor. The authors reported an improved response for proposed GWO-PID in terms of settling time and percentage overshoot. In the same way, Das [135] experimented with the application of GWO to configure the PID parameters for monitoring the speed of a second-order DC motor unit.

The proposed GWO has a better transient value compared to PSO, ABC and ZN methods. Bhatnagar and Potnuru [136], [137] proposed the use of the GWO algorithm to evaluate the PID controller's optimum gains for control the speed of the DC motor. The tuning process was conducted while adopting ITAE as the objective function.

The proposed GWO-PID controller was compared with the other controllers. Different time-domain operating points were examined to further verify the accuracy of the proposed GWO-PID controller.

Simulation results show that the GWO-PID scheme gave the least overshoot, shorter adjustment time and least rise time compared with the existing approaches.

Nevertheless, to obtain better performance of the controlled system, the exploitation ability of the GWO can be enhanced as proposed by Saremi [138]. Alternatively, the update of the three best positions of GWO can be improved as presented in [139]. Agarwal, Parmar and Gupta [140] carried out a comparative study between GWO and Sine Cosine Algorithm (SCA). The PID controller’s parameters were optimized using the two algorithms.

Performance metrics used are rise time, settling time and overshoot. The GWO-PID surpassed the SCA-PID controller for all the three performance metrics. Another comparative study was conducted by Ahmed [141]; however, in this case, Fractional Order-PID controller (FOPID) was used instead of the conventional PID controller.

The GWO-FOPID delivered a superior response compared to the generic PID controller. In both cases, more objective functions can be explored to further reveal the performance of the algorithms rather than simply applying the ITAE objective function. Social Spider Optimization (SSO) was introduced by Erik Cuevas et al. in 2013 [142]. SSO is a population-based algorithm that imitates the social spider's cooperative characteristics.

Othman [143] examined and analyzed the cost value and step response of the PID controller for the DC motor control using Spider Based controller. In the work, the step response was described in terms of the rise time, settling time, peak overshoot and steady-state error. Results obtained and compared with the Firefly Algorithm show that the proposed algorithm provided a precise solution to complex mathematical problems, especially optimization problems. This is due to its fast convergence rate and the prospect of providing structured solutions to problems in the real world.

TABLE II
SUMMARY OF PID PARAMETERS OPTIMIZATION FOR BIO-INSPIRED ALGORITHMS

Algorithm	Year	Brief description of the control scheme	Ref.
BFA	2014	BFA-based PID controlling technique for regulating separately excited DC motor speed.	[122]
	2014	Performance analysis of BFA-based PID controller for a DC pancake driving motor system.	[123]
	2014	BFA-based PI controller for DC series speed motor control.	[124]
	2018	Optimization of the PI controller using an improved BFA in regulating the speed of a switch reluctance motor.	[126]
	2016	Improved bacteria foraging algorithm (IBFA) to track the movement and acceleration of a brushless bearing-less DC motor.	[127]
	2018	Speed control of a BFA-based PI controller for DC motor.	[125]
AIS	2011	AIS-based PID controller for double closed-loop flywheel speed control.	[130]
	2017	Performance control of an in-wheel motor used in electric car using AIS-based PID	[131]
	2016	Application of AIS algorithm in controlling the DC servo motor system.	[132]
GWO	2014	Comparative study between GWO and PSO in optimizing the PID parameters for controlling the speed of the DC motor.	[134]
	2018	DC motor speed control via optimized GWO-based PID	[136]
	2016	Regulation of the speed of the DC motor with GWO-PID controller	[144]
	2016	Optimization of the FOPID parameters with GWO algorithm for controlling the speed of the BLDC motor.	[145]
	2019	GWO-based speed regulation for the BLDC motor drive.	[137]
	2019	DC motor control using GWO-PID controller.	[140]
	2019	Comparative study between GWO and SCA in optimizing the FOPID parameters for the DC motor speed regulation.	[141]
SSO	2018	PID based Social Spider Optimization (SSO) for DC motors control	[143]

V.3. Nature-Inspired Metaheuristic Techniques

Researches have shown in recent decades that nature is a tremendous resource for developing intelligent systems and for offering solutions to complex problems [146]. Nature has influenced numerous scientists in several ways and is thus a significant source of inspiration. Currently, much of the new algorithms are inspired by nature [147]. When reflecting on the source of inspiration, we could still have a distinct classification, depending on how detailed and how many sub-sources we choose to use. Among some of the recent nature-inspired algorithm that have proven quite successful in solving engineering problems are Firefly Algorithm (FA) [148], Flower Pollinating Algorithm (FPA) [149], Bat Algorithm (BA) [150], Invasive Weed Optimization (IWO) [151], Cuckoo Search (CS) [152]. Invasive weed optimization (IWO) is an agricultural-based metaheuristic algorithm which was proposed in 2006 by Mehrabian and Lucas [153]. IWO algorithm was enthused by the colonization of invasive weeds. Khalilpour, Razmjooy and Moallem [154] suggested a soft computing control strategy to set the parameters of the PID using the IWO algorithm to regulate the speed of the DC motor. The proposed approached was paralleled with other algorithms namely, PSO, GA and Memetic Algorithms (MAs). IWO-PID was found to have a distinctive property in spatial dispersal, reproduction and competitive exclusion compared with other methods. Further investigation via experimental studies shows that IWO is as good and in some cases surpassed other methods. Simulation of the proposed involved the following steps: Initializing a population, Reproduction, spatial dispersal and Competitive exclusion. Fig. 9 displays the flowchart of the IWO algorithm. Results obtained show that the proposed controller performed efficiently in searching for optimal values for the PID gains and also improved the dynamic response of the system in an improved manner. Nevertheless, the modification of the IWO algorithm, especially in overcoming the drawback of improper selection of standard deviation parameters as reported in [155] will guarantee better controlling mechanism. Mishaghi and Yagboobi [155] addressed this drawback by suggesting an improved IWO algorithm premised on chaos theory for the optimal design of the PID controller for the DC motor. The proposed improved IWO applied chaotic mappings first to the preliminary population and from there to the standard deviation algorithm (sigma). It was then evaluated under five common benchmark functions to assess its performance and then employed to set the correct parameters for the PID controller in order to drive the DC motor. The simulation result shows an enhanced chaotic IWO with quick converging speed, good precision and optimum setting of the PID controller parameters.

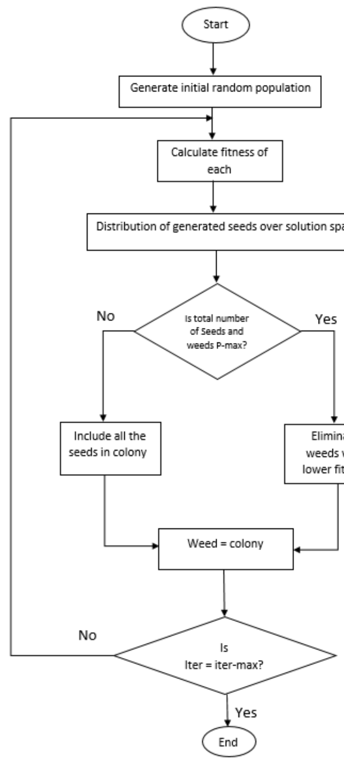


Fig. 9. IWO Algorithm flowchart [154]

Yand and Deb in 2009 developed Cuckoo Search (CS) optimization algorithm [156]. The CS algorithm is premised on the obligatory brood parasite activity of cuckoo groups in conjunction with the Levy flight traits of some birds and fruit flies [157]. Vishal et al. [158] studied the performance of the nature-inspired Cuckoo Search (CS) algorithm among other four different optimization techniques in selecting suitable optimal gains for the PI controller to regulate the speed of the DC motor. The performance of the suggested CS algorithm was tested along with other algorithms namely DE, GA and Accelerated PSO (APSO) under the ITAE objective function. With the shortest rise time, settling time, least overshoot and disturbance rejection, the proposed CS algorithm surpassed other algorithms in the comparative study. Sing et al [159] examined the performance of the CS algorithm and ZN tuning rules in setting the parameters of the PID controller for the DC servo motor speed regulation. The simulation and real-time implementation of CS-PID and ZN-PID were successfully performed. The overall response of the CS-PID was higher than that of the ZN-PID. That being said, this algorithm has difficulty in adjusting and achieving optimal search results with a slow rate of convergence, and incapable of addressing complex issues. Consequently, Jagindar et al. [160] presented a further work on [159] by offering an improved CS (ICS) algorithm to supervise the speed of the DC servo motor.

The suggested ICS was contrasted with the standard CS algorithm by analyzing their competence as to how precisely appropriate parameters for the PID controller can be selected while regulating the speed of the DC servo motor, whereas four fitness functions were considered. The ICS optimized PID scheme provided better results compared to the generic CS for the four fitness functions. It can be established from their work that improving the CS algorithm would lead to a better optimization strategy. Optimum design of the BLDC engine was proposed by Niaz Azari [161] using the CS algorithm. The mathematical parameters of the BLDC motor are known to be the control variables. The target functions are the expenses, construction costs and the volume of the motor. A comparative analysis was carried out in order to optimize the design of the BLDC motor using three different optimization methods, namely GA, PSO and COA. Results of simulation show that CS congregated to an optimum response in less than 250 iterations while PSO and GA had 400 and 450 iterations respectively. Additionally, the fitness value of CS was more applicable compared to GA and PSO. Whereas Vishal et al. [158] applied CS to the conventional PID algorithm, Puangdownreong [162] implemented the algorithm on a modified version of the PID controller while Cvetkovski [163] used a single-phase permanent magnet brushless DC motor (SPBLDCM). Ardiansyah [164] controlled the angular position of the BLDC motor using CS algorithm. In their works, CS performed outstandingly with the smallest overshoot, fast rising time and quick settling time. Different from [158], [163], [165]. The modified PID controller version known as the I-PD controller was developed by Puangdownreong [162]. The intention is to jettison the set-point kick that is triggered by the proportional and derivative terms during set-point change. In the work, I-PD controller parameters were optimized by CS Algorithm. Results of simulation show that the CS-based I-PD controller provided a better response with little overshoot and quicker response time compared to the conventional PID controller. The Firefly Algorithm (FFA) was presented by Yang in 2008 [166]. It is a nature-inspired algorithm that mimics the social behaviour of fireflies founded on flashing and fireflies' attracting attributes. Vashistha and Ganguli [167] proposed the application of Firefly Algorithm (FFA) to control a developed model of the DC motor using the PI controller.

To determine the competence of the proposed algorithm in addressing optimization problems while achieving optimum value or close optimum value at minimum time, it was first evaluated under some common linear benchmarking functions, such as Greiwank, Hyper-Ellipsoid, Ackley and Sphere. Results indicate that the suggested FFA algorithm performed well under the benchmark functions. It was able to regulate the speed of the DC motor at a faster rising time, shorter settling time and with lesser overshoot. In a similar work, the optimal parameters of the PI controller were also configured with the FFA for speed regulation and duty cycle of DC/DC converter of DC series motor [168], [169]. The suggested problem was presented as a problem of optimization and FFA was used to look for optimum PID parameters.

This was achieved by the minimization of the time domain objective function. The proposed FA-based speed controlling design was compared with GA-based PI (GA-PI) and ZN-based PI (ZN-PI) controllers under different conditions of operation and disturbances.

Under time-domain analysis and different performance indices, results of simulation show the superiority of FFA-PI over GA-PI and ZN-PI controllers. Nevertheless, the improvement of the proposed algorithm by boosting the balance between exploitation and exploration as suggested by Yelghi [170] will lead to a better controlling method. Jaber [171] introduced a novel modification of the FFA algorithm to optimize the PID parameters and present a better-regulated speed response of the DC motor. The new algorithm is referred to as Firefly-Segmentation (FS) method. It comprises of a blend of the FFA and division of the search operation, segment-by-segment.

Four segments were selected for K_p and two for K_i as the initial values of the PID parameters. A further modification was introduced by Klempka [172] which involves the adjustment of the Firefly's equations with regards to how each firefly in subsequent iterations shifts its location. The modification improved the characteristics of FFA for controlling the DC motor.

However, Kommula [173] utilized a direct instantaneous scheme where the reference torques were compared with the estimated torques and the FFA-based FOPID error was presented. The FOPID parameters were regulated with the Firefly algorithms while the simulation was conducted in MATLAB/Simulink environment. The performance of the FFA-FOPID surpassed other techniques.

The Flower Pollination Algorithm (FPA) was introduced by Yang in 2012 [174] for solving optimization problems. FPA was stimulated by the pollination attributes of plants. FPA has demonstrated to be successful in addressing many optimization problems. Dwi [175] presented an optimum design of the PID controller for monitoring the speed of the DC motor using Flower Pollination Algorithm (FPA). To evaluate the performance of the proposed algorithm, two other metaheuristic algorithms namely CS and ABC algorithms were used to augment the PID controller. Performance features of the system step response such as settling time, overshoot, rise time were compared.

The simulation result showed that FPA performed better by having lesser overshoot, faster rise and settling time compared to CSA and ABC algorithms. Potnuru et al. [176] proposed the development and deployment of a nature-inspired FPA to control the speed control of the BLDC motor. By implementing it on hardware with a laboratory setup, the reliability of the suggested algorithm was examined. The closed-loop performance of the speed control was experimented under different circumstances such as sinusoidal, stepped, ramp and step speed commands. The response of the proposed algorithm was compared with some other tuning techniques such as ZN, FA and

PSO algorithms in terms of absolute mean error. The mathematical expression for calculating the absolute mean error is given in equation (12):

$$\text{Absolute mean error} = \frac{1}{N_k}\sum_{k=1}^{N_k}\left|[\omega_m^*(k) - \omega_k(k)]\right| \quad (12)$$

Observation from the results of simulation shows that the absolute mean speed error in the closed-loop DC motor speed control for the FPA is negligibly small relative to PSO, FFA and ZN methods.

V.4. Swarm-Based Metaheuristic Techniques

Swarm-based algorithms are influenced by social creatures' collective behaviour. Mutual awareness is influenced by the interaction of swarms with one another and their environment [71]. Particle Swarm Optimization (PSO) algorithm is prominent in this group and has been explored in many problems of optimization. Other examples are the Firefly Algorithm [177], Artificial Bee Colony Optimization (ABC) [178] and Ant Colony Optimization, (ACO) [179]. Artificial Bee Colony Optimization (ABC) was introduced in late 2005 [180]. It fits in the class of swarm-based metaheuristic algorithm and mimics the intelligent foraging features of the honeybee swarm in finding an optimal solution [181].

ABC has found its usefulness in addressing different multi-objective optimization problems due to its capacity to combine the exploitative neighbourhood search with random explorative search [180]. ABC was initially designed to address unconstrained benchmark optimization functions but then the improved version was later introduced to tackle constrained optimization problems [182]. To explore the latter algorithm in the control system, Mishra [183] and Liao [184] suggested ABC optimization method for modifying the PID controller to monitor the speed of the DC motor. The proposed ABC-PID was designed to obtain a better dynamic and static output with minimum errors. The parameters K_P, K_i and K_d of the PID controller were optimized with the proposed ABC algorithm along with other conventional approaches such as Cohen-Coon and Ziegler Nichols tuning rules. With the shortest rising time, settling time and peak overshoot, the proposed ABC-PID controller performed better than other tuning techniques. The findings of their research indicates that the suggested algorithm could be effective in controlling errors in higher-order system. Whereas Mishra and Liao [183], [184] used the generic PID controller, in a different work, Rajasekhar and Abraham [185] utilized the FOPID controller.

TABLE III
SUMMARY OF PID PARAMETERS OPTIMIZATION FOR NATURE-SPIRED ALGORITHMS

Algorithm	Year	Brief Description of the control scheme	Ref.
IWO	2011	Optimal DC motor control using an IWO-based PID controller.	[154]
	2019	Operation of the DC motor using IWO-based chaos theory for the optimal design of the PID controller.	[155]
CS	2014	Optimization of the PID controller using the CS algorithm for regulating the DC motor.	[158]
	2015	Application of the CS-PID for controlling the DC servo motor	[159]
	2017	Regulation of the DC servo motor with CS-PID controller	[160]
	2017	Optimal design of the BLDC motor by using a PID-based CS algorithm	[161]
	2016	Speed control of the DC motor using a CS-based I-PD controller.	[162]
	2019	Brushless DC motor angular position control using CS-PD Controller	[164]
FFA	2013	Application of Firefly Algorithm (FFA) to control a developed model of the DC motor using the PI controller.	[167]
	2015	PID-based FFA speed control of the DC series motor	[168]
	2015	PID-based FFA speed and duty cycle control of the DC/DC converter of the DC series motor	[169]
	2017	Optimization of the PID controller's parameters by means of a modified FFA algorithm to obtain better controllability of the DC motor.	[171]
	2018	Application of Firefly Algorithm (FFA) to control a developed model of DC motor using a FOPID controller.	[172]
FPA	2016	Regulation of the speed of the DC motor using FPA-based PID	[175]
	2019	Development and application of FPA for regulating the speed of the BLDC motor	[176]

This is rooted in the fact that the FOPID controller developed by Podlubny [52], [186], offers an improved control functionality than the classical PID. The additional parameters integral order (λ) and differentiator order (μ) are responsible for the higher performance. A comparative study was also performed to show the strength of the FOPID controller over the typical PID controller for the DC variable speed system. To validate the achievability of the suggested strategy, detailed simulation results were presented. Results of simulations established the superiority of FOPID-ABC over the standard PID with the least rise time, minimum overshoot and settling time. Huang [187] in an effort to improve the exploitation competence of the standard ABC algorithm, proposed an improved version by introducing powder place elimination mechanism in the search scheme. This reduces the inferior choice solutions randomly selected by colony bees to search for new solutions and slowly decreases the range of search in order to increase the capacity for local exploitation and rate of convergence. A comparison was made between the optimization of FOPID with the ordinary ABC and improved ABC algorithms. Outcomes indicated that the improved ABC displayed superior performance with lesser rise time, minimum overshoot and shorter settling time. However, further investigation is necessary to advance the accuracy of the optimization and also boost the rate of convergence of the ABC algorithm. This will prevent the output of the FOPID controller from being influenced by the optimization error. Moreover, Geng et al. [188] offered a controlling technique for governing the speed of the DC motor by utilizing a dual closed-loop PID speed-tuning system established on the ABC algorithm. The intention of the work is to overcome the tuning challenges that occur during the tuning cycle and also optimize the DC Double closed-loop PID controller using the Nectar Collecting characteristics of the ABC algorithm. The step response correlation and evaluation carried out between ABC and other methods revealed that the proposed ABC algorithm can contribute a superior control behaviour, performance index and stability to the DC motor. Notwithstanding the success of the proposed ABC algorithm, there are two drawbacks; the first is its tendency to escape from the local optima and the second is its propensity to accelerate the convergence rate prematurely so that a satisfactory solution can be reached prematurely. The combination of another algorithm with the ABC algorithm will be able to provide a solution to these drawbacks [189]-[191] The Bat Algorithm was designed by Xin-She Yangin 2010. It was motivated by the echolocation behaviour of micro-bats with varying emission and loudness levels of pulses [192], [193]. Singh [194] used BA to optimize PID controller’s gains to control the DC servo engine speed. Comparing the response of BA and PSO algorithms, the proposed BA demonstrated a better performance than PSO algorithm by having the quickest rising time, shortest settling time and least overshoot. Additional work on [194] is suggested by considering load and speed variation for a more robust analysis. Furthermore, the hybridization of the two algorithms will also present a better controlling scheme rather than using them individually. Premkumar and Manikandan [195] proposed the application of BA to optimize an online ANFIS and PID controller so as to regulate the speed of the BLDC motor. GA, PSO and BA were applied to optimize the online ANFIS controllers learning parameters under various conditions. Subsequently, the algorithms were also harnessed to configure the PID controller. The performance comparison of the evolved algorithm was implemented using time-domain parameters such as time changes, settling time, maximum overshoot, undershoot, recovery time and steady-state error. The standard performance indices for PID controllers such as IAE, ITAE, RMSE and ISE were evaluated and related. The simulation was conducted under changing load conditions, static load situation and variation to substantiate the reliability of the proposed scheme. The simulation results showed that the proposed BA-based controller surpassed other controllers in all operating conditions, with a lower average computational time, minimum fitness value and better time-domain parameters for all output indexes. Similarly, the proposed controller’s real-time implementation revealed that the controller was able to mitigate the problem of uncertainty owing to variations in load and speed. Merugumalla [196] examined the effectiveness of the PSO and BA algorithms over classical techniques specifically Ziegler-Nichols and Tyreus-Luyben techniques. The author stated that the results show that the BA and PSO algorithms perform better than conventional methods. Premkumar [197] optimized the Fuzzy-PD and Fuzzy-PID controllers with Bat Algorithm in order to regulate the speed of the BLDC motor. A comprehensive comparative study was conducted between PSO, Cuckoo Search Algorithm (CSA) and the proposed algorithm under RMSE, IAE, ITAE and ISE objective functions.

The performance of the controlling approach was analyzed under diverse operating conditions while considering undershoot, overshoot, settling time, steady-state error as the performance metrics. Simulation and experimental results show that the proposed BA-optimized Fuzzy PD-based speed controller is in the best position to eradicate the uncertainty hitches occurring because of load disparities and set speed variations compared to other algorithms. Anshory [198] automated the regulation of various BLDC parameters such as speed, position and acceleration with the BA-optimized PID controller. The performance analysis of the BLDC motor speed control stability was evaluated under open-loop and closed-loop systems with the traditional PID controller. Subsequently, the closed-loop system was also controlled with the BA-based PID controller. The proposed controller was superior to other techniques with the lowest rise in time, settling time and lowest overshoot in all cases.The PSO algorithm is a swarm-based metaheuristic algorithm commonly used to address the problems of optimization. It was first introduced in 2005 by Eberhart and Kennedy [199]. The concept of the PSO algorithm is grounded on the movement of many animals like fish schools and bird flocks [200], [201]. The PSO algorithm has been lately reported to be very successful in many recent works involving different optimization problems [202]. Owing to this fact, Bayoumi and Soliman [203] suggested a PSO-based PI/PID controller to control the current and speed of the permanent magnet BLDC motor by optimizing the parameters of the PI and PID controllers. The PI controller tracked the current while the PID controller regulated the engine's speed. The peak overshoot performance index was mitigated in the tuning process to determine the validity of the dynamic response of the system. Comparative investigation between the suggested PSO-based PI/PID and ZN-based PI/PID showed that the suggested technique demonstrated a more controlling competence than the ZN-based PI/PID. Portillo, Frye and Qian [204] carried out a comparative study between PSO and the Windows Servo Design Kit (WSDKT) in finding the optimal gains of the PID controller for controlling the BLDC motor. WSDKT has an adaptive tuning feature for Auto Crossover Frequency (ACF) that allows the user to automatically check for optimum PID gains. The output obtained after implementation shows that the PSO-PID converges towards stability in lesser time better than the WSDKT-PID. Similarly, PSO-PID has a shorter settling time and lesser overshoot than with WSDKT-PID. On the other hand, Payakkawan, Klomkarn, and Sooraksa [205] suggested a dual-line PID controller based on PSO algorithm for controlling the speed of the DC motors. The PSO algorithm was used twice in their work. The first was to select the parameters of the DC motor using the algorithm, while the second was to adjust PID controller gains. To determine the strength of the proposed PSO-PID controller, three performance indexes, namely peak overshoot, rise time and settling time were adopted under the ITAE objective function.

For automatic gain scheduling, an on-line variable with fast-acting, adaptive PSO-PID gain scheduling was introduced. The proposed controlling techniques were compared with the standard ZN tuning method. Results of simulation and experimentation indicate that the proposed PSO-PID surpassed the classical ZN for the three performance indices. Sharaf and El-Gammal [206] described the implementation of PSO algorithm for adjusting an error-driven multi-loop PID velocity regulator for big manufacturing PMDC motor. The aim of their work was to smoothening the starting torque, improve the acceleration and dynamic tracking with reference to the desired speed. The controlling scheme uses speed, current and current dynamic ripple errors as inputs with a view to changing the firing delay angle of the six-pulse thyristor rectifiers. The AC supply through the six pulse thyristor was used to enhance the permanent magnet DC motor to provide adequate control of the speed, armature current and rectification. The controller was driven by a three-loop dynamic controller with speed error (e_w), deviance from maximum armature current (e_i) and dynamic current ripple error (e_r). The results verified that the proposed PSO-PID controller has an enhanced performance in drastically reducing the absolute error. Sharaf [207] improved the performance of the proposed controller through the modification of the gains of the PID controller with Integral Squared Error (ISE). In reducing the total system error, the modified controller has a better performance. Different from the approach used in [204], [205], Verma and Jain [208] employed Performance Dependant PSO (PDPSO) to monitor the speed of a linear BLDC motor. The purpose of the work was to resolve the vulnerability of the conventional PSO of falling and getting stuck into local optima and also address premature convergence. The work gave an overview of the alternative PDPSO-driven evolutionary performance algorithm. The suggested PDPSO showed a connection between the selection of particle and the performance of the device so as to obtain maximal solutions and proved its robustness under critical circumstances where conventional optimization approaches have been unsuccessful. In another work, El-Gammal 2009 [209] used multi-objective PSO (MPSO) to select optimum gains for the PID controller's parameters to control a separately excited DC motor drive. The work was aimed at reducing the peak overshoot, rise time, speed tracking error and steady-state error. The results of the optimization solution are described by the near-optimal trade-off values known as the Pareto front or optimal surfaces. Pareto front helps the user to choose the optimum or near-optimal solution that represents a trade-off between the key objectives. Results obtained shows the efficiency of the proposed PID based MOPSO techniques for the control application of the DC motor. Ibrahim, Hassan and Shomer [201] compared the performance of PSO and BF algorithms for the speed control of the BLDC motor. PSO and BFA optimization techniques were used in their work to control the BLDC engine speed. The motor was modelled in MATLAB/Simulink environment. Related to [95], [99], both optimization techniques were employed to adjust the parameters of the PID controller. Observation from the simulation results indicates that the suggested PID-based PSO was more potent in enhancing step response features, steady-state error, rise time, settling time and peak overshoot compared with the BFA method. As opposed to [183], [201], [210] Patel [211] and Kanojiya [212] applied PSO algorithm to augment the gains of the PI controller. The characteristics of the proposed PSO algorithm were observed under the process of simulation. PSO algorithm has a reduced state error and an improved rise time with low disturbances compared to the traditional tuning techniques. Kamal [213] applied PSO and GA to obtain an optimal solution for the BLDC motor in order to reduce the cogging torque. The results obtained show a decrease in the cogging torque with the PSO algorithm displaying a rapid convergence pace, requiring a few seconds to reach the optimum level than the GA. The method uses three variables of design; the opening of the slot, the length of the air gap and the magnetic length. In a different work, Roy and Srivastava [214] offered a novel control approach for monitoring the speed of the PMDC motor by optimizing the FOPID controller with Constrained PSO (CPSO) and ZN tuning rules. The original PSO was improved to solve the constraints problem of non-linear optimization. In CPSO, initialization of the particles are executed in a repetitive pattern and only the particles that fulfil the requirement of the constraints are included in the estimation of the best fitness function of the particle and the best global fitness value [215]. With these modifications, the PSO algorithm was able to explore the global best position which satisfies all the constraints. The comparison between the CPSO-FOPID and ZN-FOPID show that the proposed controller presented a better controlling accuracy with lesser rise time, minimum overshoot, shortest settling and quick convergence than the ZN-FOPID controller. Ruchi et al. [216] developed a PSO-based FOPID controller for the speed control of the DC motor. The PSO algorithm was implemented to refine the FOPID controller's parameters. PSO-based FOPID demonstrated better ISO-damping properties under different load variations than the conventional PID with minimum peak overshoot, faster rise time and the shortest settling time. This indicates a more robust system performance. Ant Colony Optimization (ACO) is among the prominent category of metaheuristic algorithms driven by the ant ability to discern the smallest route from the nest to a source of food [217], [218]. ACO algorithm was motivated through a careful study of ants' colonies. Ants belong to a group of social insects in colonies that focus on the survival of the entire colony rather than the survival of a single colony component [219]. One of the main reasons why ants as social insects have drawn the curiosity of many researchers is their high level of organization that the ant colonies could attain as a whole. Consequently, Wang [220] applied the ACO algorithm to optimize the gains of a nonlinear PI controller to regulate the speed of the BLDC motor.

The aim of the work was to lessen the peak overshoot, settling time and increase the step function of the BLDC engine. The speed of the BLDC motor was observed under the optimized PI controller using the ACO algorithm and the original PI controller.

The proposed ACO-PI offered superior performance to the PI controller with quick rise time, short set time and less overshoot. In a similar work, Ibrahim, Hakim and Mahmood [221] examined the alteration of the global rules to avert trapping at the local minimum and hasten the convergence rate. The reliability of the optimal solution was therefore boosted and the overall system performance was improved. The algorithm was expended to find the appropriate parameters for the PID controller. To analyze the response of the proposed ACO-PID, the DC motor served as the evaluation benchmark. To this end, the DC mathematical model was developed and simulated in MATLAB/Simulink environment. The proposed ACO-PID was compared with the ZN tuning rules. The results of the simulation indicated that ACO provides self-adaptation and positive feedback mechanisms to effectively avoid local constraint and deliver the best solutions. The proposed ACO-PID surpassed the ZN-PID in terms of the rising time, settling time and peak overshoot. Sandoval, Soto and Adasme [222] investigated the application of ACO algorithm to control the DC motor of a robotic arm by Visible Light Communication (VLC) with 6 degrees of freedom (DOF). The DC motor handles the motion of each DOF, which is continuously regulated by an automated ACO-PID controller. The DOFs were uniquely calibrated to the appropriate movement of each axis. The PID structure was optimized by the ACO algorithm to allow the guided movement of the robotic arm. To verify the efficacy of the proposed ACO-PID controller, other tuning techniques such as ZN and manual tuning were also implemented with the DC motor. Results of simulation revealed that the proposed ACO-PID performed better than ZN and manual tuning rules.

Further analysis was performed to test the control system effect on the number of iterations. Results showed that the output of the ACO algorithm obtained with a higher number of iterations (500 iterations) was better than those with a lower number of iterations (100 iterations). Oshaba, Ali, and Abd Elazim [223] proposed the speed regulation of a Switched Reluctance Motor (SRM) powered by Photo Voltaic (PV) system utilizing the PI-based ACO algorithm. The suggested controller model was developed as an optimization problem using the ACO algorithm to adjust the PI controller's parameters and also to minimize the time domain objective function.

A comparative examination between the proposed ACO algorithm and GA was conducted to check the reliability of the proposed algorithm. The outcome of simulation has shown that the proposed ACO-based PI controller is reliable and delivers excellent output over the GA-based PI controller for load change, reference speed, radiation and temperature. In addition to the flexibility of the proposed system architecture, the results also show that it can be applied in real-time as well. In a closely related work, Ebrahim [224] worked on speed and current control of the BLDC motor for driving a hybrid electric bike.

The suggested controller model was designed as an optimization problem to address the dynamic process variations in the hybrid electric bike system. The ACO algorithm was adopted to explore for the best PID gains while decreasing the time domain of the objective function. Detailed simulation results were presented to substantiate the feasibility and durability of the offered method alongside process dynamics and PV variations.

The proposed ACO-PID gave a better performance at different trajectories speed compared to the ZN-PID controller. Artificial Fish Swarm Algorithm (AFSA) belongs to the set of Swarm Intelligence (SI) and operate on the bedrock of population and stochastic search.

TABLE IV
SUMMARY OF PID PARAMETERS OPTIMIZATION USING SWARM BASED ALGORITHMS

Algorithm	Year	Brief Description of the control scheme	Ref.
ABC	2014	ABC optimization technique for modifying the PID controller to track the speed of the DC motor.	[184]
	2013	FOPID controller design for the speed control of ABC algorithm-driven DC motor.	[185]
	2016	Design of the FOPID-ABC DC motor speed controller	[187]
	2014	Speed control of the DC motor using a dual closed-loop PID speed tuning system based on ABC algorithm.	[188]
BA	2015	BA-based PID controller for regulating the speed of the DC servo motor.	[194]
	2015	Implementing the BA to configure the BLDC motor's PID controller for speed control.	[195]
	2016	Speed control of the Brushless DC motor using BA algorithm	[197]
	2017	Regulation of the various BLDC parameters with BA-PID controller.	[198]
	2018	BA-based speed control of the DC motor.	[196]
PSO	2007	Control of the speed and current of the DC motor using a PSO-based PI/PID controller.	[203]
	2009	Comparative study between PSO and WSDK on the best PID control gains to regulate the speed of the BLDC motor	[204]
	2009	Speed regulation of the DC motor using a PSO-based Dual-line PID controller.	[205]
	2009	Implementation of the PSO algorithm for adjusting the error-driven multi-loop PID velocity regulator for big manufacturing PMDC engines.	[206]
	2009	Enhancing the gains of the PID controller with PSO by using Integral Squared Error (ISE) error criterion.	[207]
	2014	Performance comparison of PSO and BF algorithms in regulating the speed of the BLDC motor	[201]
	2011	Speed regulation of the linear BLDC motor with the PDPSO scheme	[208]
	2009	Application of a multi-objective PSO (MPSO) algorithm to select optimal values of the PID controller in order to control a Separately Excited DC motor drive.	[209]
	2014	PSO-based PI controller for reducing steady-state error and improving rise time with low disturbances.	[211]
	2016	Speed regulation of the PMDC motor using FOPID controller with Constrained PSO (CPSO) and ZN.	[214]
	2016	Speed control of the DC motor using PSO-based FOPID	[216]
	2017	Optimizing the PI controller with PSO algorithm for diminishing the cogging torque of the BLDC motor	[213]
ACO	2008	PI-based ACO algorithm for parameter selection of a nonlinear PI controller while regulating the speed of the BLDC motor.	[220]
	2014	Control of the DC motor using ACO-PID controller.	[221]
	2016	Application of ACO to monitor the DC engine of a robotic arm by visible light communication (VLC) with 6 degrees of freedom (DOF).	[222]
	2015	Control of the speed of the Switched Reluctance Motor (SRM) supplied by Photo Voltaic (PV) system.	[223]
	2016	Speed and current monitoring of a BLDC motor in driving a hybrid electric bike.	[224]
AFSA	2012	Model optimization of PMDC motor control system based on AFSA.	[226]

AFSA is one of the very effective metaheuristic algorithms that is stimulated by the social behaviour of fishes and is known for its strength in having quick convergence rate, error tolerance, flexibility and great accuracy [225]. Zhu, Liu and Ren [226] utilized AFSA to find optimum gains for the PID controller while controlling the speed of the BLDC motor. During the experiment, an adequate fitness index was chosen as the objective function and evaluation of the fundamental principle of the AFSA was explored to optimize the PID parameters. Experimental outcomes revealed that the PID optimized AFSA allows satisfactory control of BLDC motor control system response. The experimental results clearly illustrated that the AFSA-PID controller helps the BLDC speed control system to react quickly, with a slight overshoot and successfully enhance the dynamic output of the BLDC motor control system.

V.5. Physics-Based Metaheuristic Techniques

Physics-based algorithms make use of search agents to communicate and move all the way through the search space. The communication and movement depend on physics rules such as inertia force, gravitational force and the electromagnetic force. Several Physics-based algorithms are motivated by quantum computing, Newton's gravitational laws and laws of motion. Some of the algorithms that are in this kind are Simulated Annealing (SA) [227], Gravitational Search Algorithm (GSA) [228], Charged System Search (CSS) [228], Current Search Algorithms (CS) [229], Harmony Search Algorithm [230]. The Current Search (CS) algorithms is an example of a physics-based metaheuristic algorithm which mimics the flow of electrical networks; it was introduced in 2012 to address optimization problems [229]. The algorithm was implemented by Deacha [231] to monitor the speed of the DC motor. The dual distinct characteristics, namely the exploration and exploitation of the CS algorithm were explored to discover a global optimum in the process of tuning the parameters of the PID controller. A comparative examination was conducted between the proposed CS-PID technique and some other common search optimization methods such as GA, PSO and Adaptive Tabu Search (ATU) while regulating the speed of the DC motor. The proposed CS-PID demonstrated better control characteristics compared with other techniques. Harmony Search (HS) algorithm was introduced in 2001 by Zong Woo Geem et al. [232]. HS has turned out to be very effective in many recent optimization problems and in other various applications.

Harmony Search is a music-based metaheuristic optimization algorithm. It emulates the music ability to seek a state of perfect harmony [233]. This music harmony is comparable to seeking an optimum solution in the optimization procedure. While HS has succeeded to be very successful, especially in recognizing the optimal output regions of the solution space within a short timeframe, it has become feeble in handling local search for numerical applications. To alleviate this deficiency, Yadav et al. [234] offered a modified HS algorithm which was proposed by Mahdavi [235] for designing the BLDC wheel motor. The aim of the modification was to enhance the tuning characteristics and heighten the convergence pace of the HS algorithm. Parallel with other standard algorithms such as PSO, GA, ACO and normal HS algorithms, the proposed improved HS (IHS) was designed to determine its strength in locating the lowest possible objective function values and improving the efficiency of the BLDC motor. IHS exceeds other methods with greater implementation simplicity, a better solution, fewer configuration parameters and quicker convergence. Mahendra, Kumar and Chauriya [236] solved the position control problem of the BLDC motor by applying the HS and PSO to adjust the K_p, K_i and K_d gains of the PID. The proposed HS algorithm was able to regulate the position of the BLDC motor better than the PSO algorithm in terms of the rise time, settling time, peak overshoot and steady-state error. The Gravitational Search Algorithm (GSA) is another the type of the physics-based algorithms introduced by Rashedi et. al. [237]. It focuses on Newton's principle of gravitational force and mass interaction. The proposed algorithm theory is based on the principle that the gravitational forces between the two particles are proportional to the magnitude of their mass but inversely proportional to the square of the distance between them [238]. Through the gravitational attraction effect, all agents attract each other, and this force prompts the drive of all agents globally in the direction of heavyweight agents. Duman, Maden and Guvenc [239] studied the speed control position of the DC motor using the GSA. In the study, the DC motor was regarded as a second and third-order system. GSA was utilized to optimize the three gains of the PID controller. A test of efficiency was carried out by comparing the suggested GSA-PID with ZN tuning technique while using the Means Squared Error (MSE) as the objective function. The authors reported that the GSA-PID outperformed the classical ZN tuning method by having a better rising time, settling time and peak overshoot.

SA (Simulated Annealing) algorithm is a metaheuristic technique motivated by the process of metallurgy annealing whereby deformation of metal is easy at high temperature and becomes challenging as the temperature decreases [240]. The SA method is a global optimization technique which was founded on the physical procedure of annealing of metals. The origin of SA algorithm is in statistical mechanics and it was first presented for combinatorial optimization problems [241]. In [242], [243], the SA algorithm was used to enhance the conventional technique by finding the optimum parameters of the PID controller to regulate the speed of the DC motor. In the work, a robust linear time-invariant system for the DC motor was investigated with four error criteria, namely IAE, ISE, ITAE, ITSE and MSE. Paralleled with the classical ZN-PID controller, the authors studied the response of the proposed SA-PID controller with the four error criteria. The outcome of the simulation presented show that for all the error criteria, SA-based. PID gave a better performance than the classical ZN-PID controller. Kok, Elamvazuthi and Ramani [244] provided a comparative analysis between SA, DE and ZN algorithms. Their research was aimed at developing a control scheme for augmenting the gains the PID controller with the aforementioned algorithms.

The outcomes of the simulation indicate that both the SA-PID and DE-PID algorithms produced a better response compared to the ZN-PID controller. Further work on [243], [245] was carried out by Kumar [246] using FOPID instead of the conventional PID controller.

The objective of the research work was to harness the extra parameters present in FOPID controller. The FOPID controller provides a better response, good tracking capacity and is less susceptible to external disturbances. In their work GA and SA were used to optimize the five parameters of the FOPID namely, proportional gain (K_p), the integral gain (K_i), the derivative gain (K_d), the integral order (λ) and the derivative order (μ) which are represented by Eq. (13):

$$G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \tag{13}$$

The authors stated that the output of SA-FOPID is substandard to the GA-FOPID and frequency domain design approach. It was also reported that SA required a lot of iteration and more time to converge compared to the GA approach during the optimization process. In a related work to [242], [243], Shatnawi and Bayoumi [247] investigated the performance of the BLDC motor by applying the PI controller to regulate the current of the motor while using the PID to monitor its speed. In order to reveal the adequate optimization strategy in the control system, the PI/PID parameters were optimized with SA, PSO and classical ZN tuning methods. The proposed SA-based PI/PID controller outperformed other optimization techniques by having the least overshoot, rise time, and settling time. The authors proposed that by analyzing their output under various loading situations, the proposed control scheme could be generalized.

TABLE V
SUMMARY OF PID PARAMETERS FOR PHYSICS-BASED METAHEURISTIC ALGORITHMS

Algorithm	Year	Brief description of the control scheme	Ref.
CS	2013	Performance evaluation and application of CS algorithm to control system in designing the speed of the DC	[231]
HS	2010	Design of the DC motor using an improved harmony search algorithm.	[234]
	2017	Position control of a BLDC motor using PID-based HS algorithm.	[236]
GSA	2011	Regulation of the speed and position the DC motor with GSA	[239]
SA	2014	Optimal tuning of DC motor via SA-based PID controller	[242]
	2014	Optimization of PID controller for BLDC motor using SA algorithms	[243]
	2017	Development of a SA-based PID controller for the DC servo motor	[244]
	2017	Comparison of the FOPID tuning process for a field operated DC servo motor	[246]
	2019	Performance of the BLDC motor by applying a PI controller to regulate the current of the motor while using the PID monitor the speed of the motor.	[247]

VI. Hybridization Study

In recent times, several hybrid metaheuristic approaches have been developed by researchers in order to advance the balance between the exploration and exploitation of the existing algorithms. Based on [248] and according to [249] when two algorithms are hybridized at either high level or low level, this is referred to as co-evolutionary techniques of hybridization. As per 'no-free-lunch' theorem, no metaheuristic method is well suited for all problems and there is scope for improvement [250], [251]. The ability to overcome the limitations of individual algorithms without compromising their strength helps hybrid strategies to be better than stand-alone approaches. Wang et al. [252] presented an adaptive speed control of the BLDC motor which is based on the combination of Radial Basis Function (RBF) neural network controlling scheme and the GA. In the study, the configuration and parameters of the RBF neural network, being a hidden-unit were trained by GA. Comparison with the conventional PID established the robustness and improvement in the dynamic response of the proposed controller. One major advantage is that while the off-line modification optimizes the neural RBF network, the on-line configuration of the neural network interface parameters guarantee that the system has a reasonable adaptive and reliable performance. Elsrogy, Fkirin and Hassan [253] designed a speed controlling technique for the DC motor by using the hybridization of GA and Adaptive Neuro-Fuzzy Inference System (ANFIS) to select optimal values for the PID controller. In their work, the non-linearity and inconsistencies of the system model were put into consideration for effective control of the speed of the DC motor. The model was regarded as a third-order system. The proposed PID-based GA-ANFIS gave the faster response, shortest settling time and least error compared to conventional methods. Like [253], Dasari, Reddy and Kumar [254] also worked on the optimization of the PID controller using ANFIS trained GA. In this case, however, the recommended hybrid algorithm was utilized to control the developed mathematical model representing a commercial BLDC engine. To investigate stability and efficiency, the mathematical model was subjected to open-loop and closed-loop analysis. A Simulink prototype with a PID controller was devised to control the BLDC model and also applied to authenticate the proposed hybrid algorithm. From the results, it can be established that GA-ANFIS offered an increased in performance compared with conventional ANFIS when applied to enhance the parameters of the PID controller. Obaid Ali et al. [255] offered a hybridization of GA and AIS for tuning the gains of the PID controller for the speed control of a linear BLDC motor. In order to test the efficacy of the proposed algorithm, the authors subjected the proposed algorithm to eight common benchmark functions while comparing the results with the standard GA and AIS algorithm. Finally, the proposed algorithm was utilized to modify the gains of the PID controller for controlling the speed of the DC motor. Results of simulation showed that the proposed hybrid GA-AIS provided a better response compared with individual GA and AIS algorithm. Ozturk and Celik [256] used GA to tune the FLC rules in order to regulate the speed of the permanent magnet synchronous motor (PMSM). An assessment was carried out between the Genetic-Fuzzy controller and the conventional Fuzzy Logic Controller (FLC) through computer simulations. The findings displayed an improved performance of the proposed GA-FLC even under different working conditions, with better transient and steady responses than the traditional FLCs. Pongai and Assawinchaichote [257] introduced a new controlling technique by blending the Neural Network (NN) and GA for optimizing the PID parameters to control the speed of the BLDC motor. The aim of their study was to enhance the weight of the NN with the GA algorithm. The authors reported that the suggested NN-GA showed superior performance with lesser overshoot, steady-state error, rise time and settling time in optimizing the PID controller than the stand-alone GA and NN. Valdez [258] worked on the regulation of the speed of the DC motor by hybridizing the PSO with FLC. In the work, the controlling technique involved the application of the PSO algorithm to tune the MFs of the FLC in order to find optimum values for K_p, K_i and K_d. The authors reported that the proposed model displayed a better performance than the traditional FLC method and also indicated that other metaheuristic algorithms could be adapted for the same approach. Milani [259] utilized the PSO algorithm to select the parameters of ZN to regulate the PID controller while regulating the speed of the BLDC motor. PSO and ZN were hybridized to determine optimal values of K_p, K_i and K_d. The work involves an innovative technique of searching a twin-dimensional space instead of a tri-dimensional space since smaller search space presents a more accurate calculation of K_p, K_i and K_d. Performance of the proposed PSO-ZN was tested along with GA, conventional PSO and Modified PSO algorithms. The proposed PSO-ZN performed better than other algorithms with the quickest rise time, least settling time and minimum overshoot. In closely related study, El-Wakeel, Ellisy and Abdel-Hamed [260] suggested a hybridization of BFA and PSO algorithms for finding optimum parameters of the PID controller in the process of controlling the speed of BLDC motor. The BFA was utilized to boost the performance of the PSO algorithm, especially to prevent the PSO from falling prematurely into local optima and also to increase the convergence rate. A comparative analysis between the suggested PID optimized by hybrid BFA-PSO and separate BFA and PSO was performed. The hybrid BFA-PSO delivered a better result than the separate BFA and PSO algorithms.

Furthermore, a hybrid of PSO and DE was developed by Mahendrin and Thanushkodi [261] for monitoring the speed of the BLDC motor. The proposed PSO-DE algorithm was used to optimize the parameters of the PI controller and the fuzzy logic controller. The controllers were subjected to different situations such as a change in speed with no load, change in speed at a constant load, change in load at a constant speed and simultaneous change in speed and load. The controllers were implemented in MATLAB/Simulink environment. The proposed hybrid PSODE-Fuzzy PI delivered the best performance under different conditions. Tyagi [262] controlled the speed of the DC motor by tuning the gains of the PID controller with the combination of an Artificial Immune System (AIS) and Biological Evolutionary System (BES) algorithm. The idea of mixing AIS and BES pair is to emulate an evolutionary biological protection system. The control algorithm falls within the group bio-inspired category. The proposed hybridized AIS-BES and separate AIS and BES were used to tune the PID parameters. The PID-based AIS-BES outperformed separate AIS and BES techniques under the performance study. Rahmani [263] examined the optimization of Takagi-Sugeno (T-S) fuzzy logic controller with PSO algorithm for DC motor speed regulation. The proposed PSO algorithm was used to tune the FLC rules and MFs instead of using the conventional trial-and-error method. The developed model of the controller was simulated in MATLAB software while the experimental test was conducted in the DC motor laboratory. The proposed PSO-FLC was compared with the standard PID and FLC. Simulation and experimental results show that the optimization of MFs with PSO demonstrated a robust and higher performance compared with the regular fuzzy model and standard PID controller. For simulation and experimentation, the PSO-FLC offers improved speed control despite sudden load torque changes without overshooting. Related to [260], Bhatia et al. [264] offered a blend of BFA and PSO algorithms in searching for the optimal parameters of the PID controller with a view to regulating the speed of the DC motor. The main goal of hybridization was to use the exploration of the PSO algorithm to communicate social information and the exploitation of the BFA to find new solutions through elimination and dispersal. The combined BFA-PSO tuned PID has a superior performance compared to individual BFA and PSO algorithm. ANFIS was merged with the Firefly Algorithm in [265], with the intention of mitigating the BLDC motor torque ripple effect and also to regulate its speed. The proposed algorithm was utilized to tune the parameters of the FOPID controller.

A relative analysis between the PSO, BAT, Ant-Lion (ALO) and the proposed Firefly-ANFIS algorithm was conducted under IAE, ISE and ISTE error criteria. The efficacy of the proposed controller was evaluated using rise time, settling time and overshoot time. The simulation result indicates an improved performance of the Firefly-ANFIS compared to standard PSO, BAT and ALO algorithms. Mustafa et al. [266] merged the PSO and GSA algorithms to automate the parameters of the PID controller to regulate the speed of the BLDC motor by compelling the rotor to follow a required speed. The intent of the work is to mitigate the weakness of GSA's poor local search and slow convergence rate by integrating it with the PSO algorithm. The author stated that the proposed PSO-GSA showed a better control dynamics compared to separate PSO and GSA algorithms by having slight overshoot, less steady-state error, and small torque ripples.

VII. Open Issues

It is no understatement to say that metaheuristic algorithms are indeed a great success in addressing numerous difficult optimization issues. However, despite this huge success, there are many important questions which remain unanswered [267]. Whereas we know how metaheuristic algorithms work and partially comprehend why these algorithms operate, it is nevertheless, difficult to explain mathematically how all these algorithms perform so effectively, although significant improvements have been made in recent years [268], [269]. However, several issues still remain to be tackled in this direction. Evolutionary algorithms (EAs) belong to the category of population-based metaheuristics algorithm which remains computationally efficient in finding solutions to real and complicated problems including multimodal, epistatic, highly constrained and differentiate multi-objective issues. EA has achieved the greatest reputation within the population-based algorithms community. Evolutionary algorithms are grounded on the concept of competitiveness and focus on the evolution of individuals population. In EA, the genotype represents the encoding phase while the phenotype signifies the solution. The variance operators function on the basis of the genotype whereas the fitness feature uses the individual's phenotype to determines its ability to thrive in their environment. However, the complexity of setting their parameters is one of the main challenges of EAs. Attempting to find successful alternatives for this is itself a difficult problem with little or no speculative guidance. In reality, researchers must focus on any existing studies done about related issues, as well as dozens of trials and errors. While using EA to solve problems, a more realistic approach generally encouraged is not to use them in isolation but to merge them with several known heuristics such as hill-climbing, simulated annealing etc. The concept of bio-inspired optimization is a field of research that encompasses all sub-fields associated with connectionism, engineering, social behaviour and emergence [270]. Biologically inspired computation is a significant branch of natural computing, which has proved to be a proficient optimization algorithm. The most critical and extensively deliberated theoretical problems are the problem of convergence and the standard problem of evaluation [271]. Since most Bio-inspired algorithms are premised on searching probability, convergence and effectiveness, these algorithms in mathematics are difficult to stringently prove. As suggested by Jianjun et al [271], the incorporation of some similar algorithms into the bio-inspired algorithms will help to alleviate the issue of premature convergence and present a more effective algorithm. An improved or a modified bio-inspired algorithm will be more reliable in optimizing the PID controller when applied to the DC motor than conventional bio-inspired algorithms. As discussed earlier, Physics-based algorithms are inspired by different phenomenon and laws in physics. The key aspects explored by these algorithms include quantum theory, electrostatics, electromagnetism, Newton gravitational theory, and theory of motion. The hybridization between quantum computing and biological process is actually gaining more attention by researchers [65]. The development of different methods of improvement such as binary, multi-modal, single-objective and multi-objective optimization will also provide a more reliable optimization technique [272].

These modifications are intended to tackle problems of optimization with different kinds of objective functions. Swarm intelligence is an evolving computational research area centred on the behavioural models of social insects such as flies, bees, wasps, termites, etc. A good balance between exploration and exploitation is required to adequately use them to solve optimization problems. Exploration is meant to ensure that every section of the space is surveyed extensively to provide an accurate estimate of the global optimum.

Exploitation is essential because the improvement of the current solution will often lead to a better solution [248]. However, one of the major weaknesses of the Swarm-based metaheuristic algorithm is its tendency to get stocked at local optima and premature convergence [273]. To overcome these weaknesses, a population-based metaheuristic algorithm like Tabu Search algorithm, Simulated annealing algorithm, Grey wolf optimizer which are known for their robust exploitability is suggested to be coupled with the swarm-based algorithms. These two categories of algorithms have complementary strengths and weaknesses. While the population-based algorithms are capable of optimizing globally, the swarm-based algorithms will optimize locally. The complementary optimization of the algorithms is suggested to present a better optimization method for selecting the parameters of the PID/FOPID in controlling the DC motor.

VIII. Conclusion

This paper reviews the optimum tuning of PI, PD, PID and FOPID controllers with metaheuristic algorithms for the design and control of DC motors. A short explanation of the method used was preceded by the discussion of the work done in optimizing the controllers. When some comparative analysis was conducted, it was stated and the results of the comparative analysis were also presented. This review has indicated that metaheuristic algorithms have demonstrated a robust and efficient controlling capability in the selection of optimum gains for PI, PD, PID and FOPID controllers compared to many other conventional strategies. However, in terms of the frequency of use, the application of GA and PSO algorithm in optimizing the PID controller for the control of DC motor are more prevalent compared to other algorithms. This is due to their rapid search capabilities, flexibility and robustness. Furthermore, this review shows that researchers need to concentrate better on optimizing the FOPID controller and its variations with different types of metaheuristic algorithms than the classical PID controller. This is because the FOPID controller has some more significant advantages from the two extra tuning parameters which can be used when applied to control loops to boost the performance of the control system. This will lead to a cutting-edge research area as the continuous development of optimization algorithms and control theories emerge. In addition, the application of multi-objective optimization framework to optimize the FOPID controller will also provide a more effective, next-generation, auto-regulation and profound self-evolving intelligent algorithms. It is further suggested that researchers need to explore the hybridization of different metaheuristic algorithms to optimize the FOPID controller for DC motor control.

Studies from past works have shown that the use of hybridized methods offers superior performance compared to stand-alone algorithms. The mixed algorithm performs better because it chooses the right algorithm attributes to improve on the vulnerabilities that exist in individual algorithms. Another advantage of the hybrid technique is its ability to achieve a good balance between exploration and exploitation. Exploration ensures that the algorithm reaches the various favourable regions of the search space, while the exploitation guarantees the search for optimal solutions within the region. The fine-tuning of these components is necessary to find an optimal solution for a given problem. This is particularly important when the algorithm is aimed at optimizing the parameters of the FOPID controllers in controlling the speed of the DC motor. Finally, many of the works carried out on the optimization of the PID controller engrossed solely on simulation and comparison with conventional techniques. It is therefore suggested that future research studies should also concentrate on experimenting with real-life situations to demonstrate the robustness of the mathematical and theoretical convergence evaluation of the proposed algorithms. This review will help to act as a quick reference for researchers working on computational intelligence as well as understanding the current status in this area.

Acknowledgements

This research is supported partially by South African National Research Foundation Grants (No. 112108 and 112142), and South African National Research Foundation Incentive Grant (No. 95687), Eskom Tertiary Education Support Programme (Y. Sun, Z. Wang), Research grant from URC of University of Johannesburg.

References

[1] K. Shrivastava, A Review on Types of DC Motors and the Necessity of Starter for Its Speed Regulation, *Int. J. Adv. Res. Comput. Commun. Eng.*, vol. 5, no. 4, pp. 61–63, 2016.

[2] T. R. DilKumar and S. J. Mija, Design and performance evaluation of robust SMC schemes for speed control of DC motor, in *Proceedings of 2014 IEEE International Conference on Advanced Communication, Control and Computing Technologies, ICACCCT 2014*, Ramanathapuram, 2015, pp. 88–92.

[3] A. A. A. Emhemed and R. Bin Mamat, Modelling and simulation for Industrial DC Motor using Intelligent control, in *Procedia Engineering*, 2012, vol. 41, pp. 420–425.

[4] W. Lan and Q. Zhou, Speed control of DC motor using composite nonlinear feedback control, in *2009 IEEE International Conference on Control and Automation, ICCA 2009*, Christchurch, 2009, pp. 2160–2164.

[5] M. M. Mehdi Nasri, Hossein Nezamabadi-pour, “A PSO-Based Optimum Design of PID Controller for a Linear Brushless DC Motor,” *Int. J. Electr. Inf. Eng.*, vol. 1, pp. 179–183, 2007.

[6] N. Tripathi, R. Singh, and R. Yadav, Analysis of Speed Control of DC Motor-A review study, *Int. Res. J. Eng. Technol.*, vol. 2, no. 8, pp. 1616–1621, 2015.

[7] M. A. H. Azman, J. M. Aris, Z. Hussain, A. A. A. Samat, and A. M. Nazelan, A comparative study of fuzzy logic controller and artificial neural network in speed control of separately excited DC motor, in *Proceedings - 7th IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2017*, Penang, 2017, pp. 336–341.

[8] R. Namba, T. Yamamoto, and M. Kaneda, Robust PID controller and its application, in *1997 IEEE International Conference on Systems, Man, and Cybernetics. Computational Cybernetics and Simulation*, Orleans, LA, USA, 1997, vol. 4, pp. 3636–3641.

[9] J. Chacón, H. Vargas, S. Dormido, and J. Sánchez, Experimental Study of Nonlinear PID Controllers in an Air Levitation System, *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 304–309, Jan. 2018.

[10] M. J. Mahmoodabadi, R. Abedzadeh Maafi, and M. Taherkhorsandi, An optimal adaptive robust PID controller subject to fuzzy rules and sliding modes for MIMO uncertain chaotic systems, *Appl. Soft Comput. J.*, vol. 52, pp. 1191–1199, Mar. 2017.

[11] X. Zhou, C. Yang, and W. Gui, Nonlinear system identification and control using state transition algorithm, *Appl. Math. Comput.*, vol. 226, pp. 169–179, 2014.

[12] Manuaba, I., Priyadi, A., Hery P., M., Coordination Tuning PID-PSS and TCSC Based Model of Single Machine Infinite-Bus Using Combination Bacteria Foraging-Particle Swam Optimization Method, (2015) *International Review of Electrical Engineering (IREE)*, 10 (6), pp. 787-794.
doi: https://doi.org/10.15866/iree.v10i6.7330

[13] Khodja, M., Larbes, C., Ramzan, N., Ibrahim, A., Implementation of Heuristical PID Tuning for Nonlinear System Control, (2019) *International Review of Automatic Control (IREACO)*, 12 (2), pp. 108-114.
doi: https://doi.org/10.15866/ireaco.v12i2.16791

[14] Š. Bucz and A. Kozáková, Advanced Methods of PID Controller Tuning for Specified Performance, in *PID Control for Industrial Processes*, InTech, 2018, pp. 73–119.

[15] A. Sungthong and W. Assawinchaichote, Particle Swam Optimization Based Optimal PID Parameters for Air Heater Temperature Control System, in *Procedia Computer Science*, 2016, vol. 86, pp. 108–111.

[16] C. T. Chao, N. Sutarna, J. S. Chiou, and C. J. Wang, An optimal fuzzy PID controller design based on conventional PID control and nonlinear factors, *Appl. Sci.*, vol. 9, no. 6, 2019.

[17] C. Sánchez-López, V. H. Carbajal-Gómez, M. A. Carrasco-Aguilar, and F. E. Morales-López, PID controller design based on memductor, *AEU - Int. J. Electron. Commun.*, vol. 101, pp. 9–14, Mar. 2019.

[18] L. Chaib, A. Choucha, and S. Arif, Optimal design and tuning of novel fractional order PID power system stabilizer using a new metaheuristic Bat algorithm, *Ain Shams Eng. J.*, vol. 8, pp. 113–125, 2017.

[19] R. A. Krohling, J. P. Rey, R. A. Krohling, and J. P. Rey, Design of optimal disturbance rejection PID controllers using genetic algorithms, *IEEE Transactions on Evolutionary Computation*, vol. 5, no. 1. pp. 78–82, Feb-2001.

[20] R. Babu and R. Swarnalath, Comparison of Different Tuning Methods for pH Neutralization in Textile Industry, *J. Appl. Sci.*, vol. 17, no. 3, pp. 142–147, Feb. 2017.

[21] S. M. H. Mousakazemi and N. Ayoobian, Robust tuned PID controller with PSO based on two-point kinetic model and adaptive disturbance rejection for a PWR-type reactor, *Prog. Nucl. Energy*, vol. 111, pp. 183–194, Mar. 2019.

[22] B. Singh and S. Singh, Single-phase power factor controller topologies for permanent magnet brushless DC motor drives, *IET Power Electron.*, vol. 3, no. 2, pp. 147–175, Mar. 2010.

[23] J. Gao and Y. Hu, Direct self-control for BLDC motor drives based on three-dimensional coordinate system, *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2836–2844, Aug. 2010.

[24] C. S. Joice, S. R. Paranjothi, and V. J. S. Kumar, Digital control strategy for four quadrant operation of three phase BLDC motor with load variations, *IEEE Trans. Ind. Informatics*, vol. 9, no. 2, pp. 974–982, May 2013.

[25] K. Premkumar and B. V. Manikandan, Adaptive fuzzy logic speed controller for brushless DC motor, in *Proceedings of 2013 International Conference on Power, Energy and Control, ICPEC 2013*, Sri Rangalatchum Dindigul, 2013, pp. 290–295.

[26] G. G. Rigatos, Adaptive fuzzy control of DC motors using state and output feedback, *Electr. Power Syst. Res.*, vol. 79, no. 11, pp. 1579–1592, Nov. 2009.

[27] J. Jing, Y. Wang, and Y. Huang, The fuzzy-PID control of brushless DC motor, in *2016 IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2016*, Harbin, 2016, pp. 1440–1444.

[28] J. J. Gude and E. Kahoraho, Modified Ziegler-Nichols method for fractional PI controllers, in *Proceedings of the 15th IEEE International Conference on Emerging Technologies and Factory Automation, ETFA 2010*, Bilbao, 2010, pp. 1–5.

[29] N. Yadaiah and S. Malladi, An optimized relation between Ti and Td in Modified Ziegler Nichols PID controller tuning, in *Proceedings of the IEEE International Conference on Control Applications*, Hyderabad, 2013, pp. 1275–1280.

[30] E. Pruna, E. R. Sasig, and S. Mullo, PI and PID controller tuning tool based on the lambda method, in *2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies, (CHILECON) - Proceedings*, Pucon, 2017, pp. 1–6.

[31] M. Z. F. B. M. Zawawi, I. Elamvazuthi, A. B. A. Aziz, and S. A. Daud, Comparison of PID and fuzzy logic controller for DC servo motor in the development of lower extremity exoskeleton for rehabilitation, in *2017 IEEE 3rd International Symposium in Robotics and Manufacturing Automation, (ROMA)*, Kuala Lumpur, 2017, pp. 1–6.

[32] A. A. Hassan, N. K. Al-Shamaa, and K. K. Abdalla, Comparative Study for DC Motor Speed Control Using PID Controller, *Int. J. Eng. Technol.*, vol. 9, no. 6, pp. 4181–4192, Dec. 2017.

[33] A. Giwa and S. O. Giwa, Dynamics and Tyreus-Luyben Tuned Control of a Fatty Acid Methyl Ester Reactive Distillation Process, *Int. J. Eng. Res. Gen. Sci.*, vol. 3, no. 5.

[34] M. Shamsuzzoha, IMC based robust PID controller tuning for disturbance rejection, *J. Cent. South Univ.*, vol. 23, no. 3, pp. 581–597, Mar. 2016.

[35] M. N. Ab Malek and M. S. Mohamed Ali, Evolutionary tuning method for PID controller parameters of a cruise control system using metamodeling, *Modelling and Simulation in Engineering*, vol. 2009. pp. 1–8, 2010.

[36] A. R. A. Rahman, A. R. A. Rahim, and A. Memari, Metaheuristic Algorithms: Guidelines for Implementation, *J. Soft Comput. Decis. Support Syst.*, vol. 4, no. 6, pp. 1–6, 2017.

[37] C. Blum and A. Roli, Metaheuristics in Combinatorial Optimization: Overview and Conceptual Comparison, *ACM Computing Surveys*, vol. 35, no. 3. pp. 268–308, Sep-2003.

[38] E. G. Talbi, A taxonomy of hybrid metaheuristics, *J. Heuristics*, vol. 8, no. 5, pp. 541–564, Sep. 2002.

[39] Z. Wu, D. Li, Y. Xue, T. He, and S. Zheng, Tuning for Fractional Order PID Controller based on Probabilistic Robustness, *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 675–680, Jan. 2018.

[40] S. Ghosal, R. Darbar, B. Neogi, A. Das, and D. N. Tibarewala, Application of Swarm Intelligence Computation Techniques in PID Controller Tuning: A Review, in *International Conference on Information Systems Design and Intelligent Applications 2012 (INDIA 2012)*, Visakhapatnam, India, 2012, pp. 195–208.

[41] S. E. De Leon-Aldaco, H. Calleja, and J. Aguayo Alquicira, Metaheuristic Optimization Methods Applied to Power Converters: A Review, *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 6791–6803, Dec. 2015.

[42] V. Singh and V. K. Garg, Tuning of PID Controller for Speed Control of DC Motor Using Soft Computing Techniques-A Review, *Int. J. Appl. Eng. Res.*, vol. 9, no. 9, pp. 1141–1148, 2014.

[43] A. Dineva, A. Mosavi, S. F. Ardabili, I. Vajda, S. Shamshirband, T. Rabczuk, and K.-W. Chau, Review of Soft Computing Models in Design and Control of Rotating Electrical Machines, *Energies*, vol. 12, no. 6, pp. 1–29, 2019.

[44] R. Goswami and D. Joshi, Performance Review of Fuzzy Logic Based Controllers Employed in Brushless DC Motor, in *Procedia Computer Science*, 2018, vol. 132, pp. 623–631.

[45] H. Yazgan, F. Yener, S. Soysal, and A. Gür, Comparison Performances of PSO and GA to Tuning PID Controller for the DC Motor, *Sak. Univ. J. Sci.*, vol. 23, no. 2, pp. 162–174, Apr. 2019.

[46] M. M. Sabir and J. A. Khan, Optimal Design of PID Controller for the Speed Control of DC Motor by Using Metaheuristic Techniques, *Adv. Artif. Neural Syst.*, vol. 2014, pp. 1–8, 2014.

[47] A. Kharola, P. Patil, S. Raiwani, and D. Rajput, A comparison study for control and stabilisation of inverted pendulum on inclined surface (IPIS) using PID and fuzzy controllers, *Perspect. Sci.*, vol. 8, pp. 187–190, Sep. 2016.

[48] E. Gowthaman, V. Vinodhini, M. Y. Hussain, S. K. Dhinakaran, and T. Sabarinathan, Speed Control of Permanent Magnet Brushless DC Motor Using Hybrid Fuzzy Proportional plus Integral plus Derivative Controller, *Energy Procedia*, vol. 117, pp. 1101–1108, Jun. 2017.

[49] B. Nagaraj and N. Murugananth, A comparative study of PID controller thning using GA, EP, PSO and ACO, in *2010 IEEE International Conference on Communication Control and Computing Technologies, ICCCCT 2010*, Ramanathapuram, 2010, pp. 305–313.

[50] A. David O and O. Stephen, Poultry House Temperature Control Using Fuzzy-PID Controller, *Int. J. Eng. Trends Technol.*, vol. 11, no. 6, pp. 310–314, May 2014.

[51] H. Huang, H. Qin, Z. Hao, and A. Lim, Example-based learning particle swarm optimization for continuous optimization, *Inf. Sci. (Ny).*, vol. 182, no. 1, pp. 125–138, Jan. 2012.

[52] I. Podlubny, Fractional-order systems and PIλDμ-controllers, *IEEE Trans. Automat. Contr.*, vol. 44, no. 1, pp. 208–214, 1999.

[53] A. Tepljakov, B. B. Alagoz, C. Yeroglu, E. Gonzalez, S. H. HosseinNia, and E. Petlenkov, FOPID Controllers and Their Industrial Applications: A Survey of Recent Results 1, *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 25–30, Jan. 2018.

[54] D. Xue, C. Zhao, and Y. Q. Chen, Fractional order PID control of A DC-motor with elastic shaft: A case study, in *Proceedings of the American Control Conference*, 2006, vol. 2006, pp. 3182–3187.

[55] Y. Luo and Y. Chen, Stabilizing and robust fractional order PI controller synthesis for first order plus time delay systems, in *Automatica*, 2012, vol. 48, no. 9, pp. 2159–2167.

[56] M. Cech and M. Schlegel, Computing PID tuning regions based on fractional-order model set, in *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 2012, vol. 2, no. PART 1, pp. 661–666.

[57] J. Rajpurohit, T. Kumar Sharma, and A. Abraham, Glossary of Metaheuristic Algorithms, *Int. J. Comput. Inf. Syst. Ind. Manag. Appl.*, vol. 9, pp. 181–205, 2017.

[58] V. Ho-Huu, T. Nguyen-Thoi, M. H. Nguyen-Thoi, and L. Le-Anh, An improved constrained differential evolution using discrete variables (D-ICDE) for layout optimization of truss structures, *Expert Syst. Appl.*, vol. 42, no. 20, pp. 7057–7069, Jun. 2015.

[59] A. Kumar and S. Bawa, A comparative review of meta-heuristic approaches to optimize the SLA violation costs for dynamic execution of cloud services, *Soft Comput.*, vol. 24, pp. 3909–3922, 2019.

[60] G. Dhiman and V. Kumar, Spotted hyena optimizer: A novel bio-inspired based metaheuristic technique for engineering applications, *Adv. Eng. Softw.*, vol. 114, pp. 48–70, Dec. 2017.

[61] A. Darwish, Bio-inspired computing: Algorithms review, deep analysis, and the scope of applications, *Futur. Comput. Informatics J.*, vol. 3, no. 2, pp. 231–246, Dec. 2018.

[62] H. Chiroma, A. Y. Gital, N. Rana, S. M. Abdulhamid, A. N. Muhammad, A. Y. Umar, and A. I. Abubakar, Nature Inspired Meta-heuristic Algorithms for Deep Learning: Recent Progress and Novel Perspective, in *Advances in Intelligent Systems and Computing*, 2020, vol. 943, pp. 59–70.

[63] X. S. Yang, S. Fong, X. He, S. Deb, and Y. Zhao, Swarm Intelligence: Today and Tomorrow, in *Proceedings - 2016 3rd International Conference on Soft Computing and Machine Intelligence, ISCMI 2016*, Dubai, 2017, pp. 219–223.

[64] H. Abedinpourshotorban, S. Mariyam Shamsuddin, Z. Beheshti, and D. N. A. Jawawi, Electromagnetic field optimization: A physics-inspired metaheuristic optimization algorithm, *Swarm Evol. Comput.*, vol. 26, pp. 8–22, Feb. 2016.

[65] A. Biswas, K. K. Mishra, S. Tiwari, and A. K. Misra, Physics-Inspired Optimization Algorithms: A Survey, *J. Optim.*, vol. 2013, pp. 1–16, 2013.

[66] C. K. Chow and S. Y. Yuen, An evolutionary algorithm that makes decision based on the entire previous search history, *IEEE Trans. Evol. Comput.*, vol. 15, no. 6, pp. 741–769, Dec. 2011.

[67] M. N. Ab Wahab, S. Nefti-Meziani, and A. Atyabi, A comprehensive review of swarm optimization algorithms, *PLoS One*, vol. 10, no. 5, pp. 1–36, May 2015.

[68] A. Chakraborty and A. K. Kar, Swarm intelligence: A review of algorithms, in *Modeling and Optimization in Science and Technologies*, vol. 10, Springer Verlag, 2017, pp. 475–494.

[69] S. Das, A. Abraham, and A. Konar, Swarm intelligence algorithms in bioinformatics, *Stud. Comput. Intell.*, vol. 94, pp. 113–147, 2008.

[70] X. S. Yang, Z. Cui, R. Xiao, A. H. Gandomi, and M. Karamanoglu, *Swarm Intelligence and Bio-Inspired Computation*. Hendon: Elsevier Inc., 2013.

[71] G. Dhiman and A. Kaur, Optimizing the Design of Airfoil and Optical Buffer Problems Using Spotted Hyena Optimizer, *Designs*, vol. 2, no. 3, p. 28, Aug. 2018.

[72] E. Bonabeau, M. Dorigo, and G. Theraulaz, *From Natural to Artificial Swarm Intelligence*. New York: Oxford University Press, Inc., 1999.

[73] R. Storn and K. Price, Differential Evolution - A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces, *J. Glob. Optim.*, vol. 11, no. 4, pp. 341–359, 1997.

[74] J. H. Holland, C. Langton, S. W. Wilson, F. J. Varela, P. Bourgine, J. R. Koza, and A. B. Book, *Genetic Programming Complex Adaptive Systems Genetic Programming On the Programming of Computers by Means of Natural Selection*, MIT Press edition, London, 1992.

[75] M. Kumar, M. Husian, N. Upreti, and D. Gupta, Genetic Algorithm: Review and Application, *Int. J. Inf. Technol. Knowl. Manag.*, vol. 2, pp. 451–454, 2010.

[76] M. M. Kamal, L. Mathew, and S. Chatterji, Speed control of brushless DC motor using intelligent controllers, in *SCES 2014: Inspiring Engineering and Systems for Global Sustainability*, 2014, pp. 1–5.

[77] S. Tiwari, A. Bhatt, A. C. Unni, J. G. Singh, and W. Ongsakul, Control of DC Motor Using Genetic Algorithm Based PID Controller, in *2018 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE)*, 2019, pp. 1–6.

[78] C. L. Lin, H. Y. Jan, and N. C. Shieh, GA-based multiobjective PID control for a linear brushless DC motor, *IEEE/ASME Trans. Mechatronics*, vol. 8, no. 1, pp. 56–65, 2003.

[79] J. Xiu, L. Liu, Y. Che, and S. Wang, GA based PI control of BLDCM drive, in *Proceedings of the 27th Chinese Control Conference, CCC*, 2008, pp. 189–193.

[80] Z. H. Ming Yang, Lei Zhang, Weiping Zhao, Optimization of dc motor rotary speed controller based on the genetic algorithm - IEEE Conference Publication, *World Autom. Congr. 2012, Puerto Vallarta, Mex.*, pp. 1–4, 2012.

[81] V. Sankardoss and P. Geethanjali, Parameter estimation and speed control of a PMDC motor used in wheelchair, in *Energy Procedia*, 2017, vol. 117, pp. 345–352.

[82] A. A. M. Zahir, S. S. N. Alhady, W. A. F. W. Othman, and M. F. Ahmad, Genetic algorithm optimization of pid controller for brushed DC motor, in *Lecture Notes in Mechanical Engineering*, Pleiades Publishing, 2018, pp. 427–437.

[83] L. Zhang, X. Xu, C. Zhou, M. Ma, and Z. Yu, An Improved Differential Evolution Algorithm for Optimization Problems, *Adv. Comput. Sci. Intell. Syst. Environ.*, vol. 104, pp. 233–238, 2011.

[84] A. H. Syed and M. A. Abido, Differential evolution based intelligent control for speed regulation of a PMDC motor, in *2013 21st Mediterranean Conference on Control and Automation, MED 2013 - Conference Proceedings*, 2013, pp. 1451–1456.

[85] L. Syafaah, Widianto, I. Pakaya, D. Suhardi, and M. Irfan, PID designs using DE and PSO algorithms for damping oscillations in a DC motor speed, in *2017 4th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, Yogyakarta, 2017, pp. 1–5.

[86] A. Idir, M. Kidouche, Y. Bensafia, K. Khettab, and S. A. Tadjer, Speed control of DC motor using PID and FOPID controllers based on differential evolution and PSO, *Int. J. Intell. Eng. Syst.*, vol. 11, no. 4, pp. 241–249, Aug. 2018.

[87] M. C. Bosco, J. J. Guedes, M. F. Castoldi, A. Goedtel, E. R. Pires Da Silva, and L. F. S. Buzachero, Estimation of parameters and tuning of a speed PI of permanent magnet DC motor using differential evolution, in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, Miami, FL, 2017, pp. 1–6.

[88] A. Rodriguez-Molina, M. G. Villarreal-Cervantes, and M. Aldape-Perez, Optimal Adaptive Control of a DC Motor Using Differential Evolution Variants, in *2017 IEEE 7th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems, CYBER 2017*, Honolulu, HI, 2017, pp. 283–288.

[89] H. Jigang, F. Hui, and W. Jie, A PI controller optimized with modified differential evolution algorithm for speed control of BLDC motor, *Automatika*, vol. 60, no. 2, pp. 135–148, Apr. 2019.

[90] S. Das, S. S. Mullick, and P. N. Suganthan, Recent advances in differential evolution-An updated survey, *Swarm Evol. Comput.*, vol. 27, pp. 1–30, Apr. 2016.

[91] H. Ma, D. Simon, P. Siarry, Z. Yang, and M. Fei, Biogeography-Based Optimization: A 10-Year Review, *IEEE Trans. Emerg. Top. Comput. Intell.*, vol. 1, no. 5, pp. 391–407, Sep. 2017.

[92] H. Mo and L. Xu, Biogeography optimization algorithm for DC motor PID control, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2015, vol. 9140, pp. 385–394.

[93] S. Waley Shneen, BBO_PI Controller for DC Motor, *Int. Res. J. Adv. Eng. Sci.*, vol. 4, no. 1, pp. 271–274, 2019.

[94] N. H. Awad, M. Z. Ali, P. N. Suganthan, and E. Jaser, Differential evolution with stochastic fractal search algorithm for global numerical optimization, in *2016 IEEE Congress on Evolutionary Computation, CEC 2016*, Vancouver, BC, 2016, pp. 3154–3161.

[95] I. Khanam and G. Parmar, Application of SFS algorithm in control of DC motor and comparative analysis, in *2017 4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics (UPCON)*, Mathura, 2018, pp. 256–261.

[96] E. Çelik and H. Gör, Enhanced speed control of a DC servo system using PI + DF controller tuned by stochastic fractal search technique, *J. Franklin Inst.*, vol. 356, no. 3, pp. 1333–1359, Feb. 2019.

[97] R. Rao, Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems, *Int. J. Ind. Eng. Comput.*, vol. 7, no. 1, pp. 19–34, 2016.

[98] H. M. Pandey, Jaya a novel optimization algorithm: What, how and why?, in *2016 6th International Conference - Cloud System and Big Data Engineering (Confluence)*, Noida, 2016, pp. 728–730.

[99] R. K. Achanta and V. K. Pamula, DC motor speed control using PID controller tuned by jaya optimization algorithm, in *IEEE International Conference on Power, Control, Signals and Instrumentation Engineering, ICPCSI 2017*, Chennai, 2018, pp. 983-987.

[100] E. Atashpaz-Gargari and C. Lucas, Imperialist competitive algorithm: An algorithm for optimization inspired by imperialistic competition, in *2007 IEEE Congress on Evolutionary Computation, CEC 2007*, Singapore, 2007, pp. 4661–4667.

[101] S. L. Ghalehpardaz and M. Shafiee, Speed control of DC motor using imperialist competitive algorithm based on PI-like FLC, in *Proceedings - CIMSim 2011: 3rd International Conference on Computational Intelligence, Modelling and Simulation*, Langkawi, 2011, pp. 28–33.

[102] A. Afra, S. Aidin, and G. Jafar, Position Control of DC Motor Using Imperialist Competitive Algorithm Based PID Controller, in *First National Conference on Advances in Computer Science and Information Retrieval Approaches*, Iran, 2013, pp. 1–5.

[103] M. A. Sharifi and H. Mojallali, Multi-Objective Modified Imperialist Competitive Algorithm for Brushless DC Motor Optimization, *IETE J. Res.*, vol. 65, no. 1, pp. 96–103, Jan. 2019.

[104] D. B. Fogel, An Overview of Evolutionary Programming, in *Evolutionary Algorithms. The IMA Volumes in Mathematics and its Applications*, New York, NY: Springer, 1999, pp. 89–109.

[105] L. L. Lai and J. T. Ma, Application of evolutionary programming to reactive power planning-comparison with nonlinear programming approach, *IEEE Power Eng. Rev.*, vol. 17, no. 2, p. 56, 1997.

[106] G. H. Chang, Y. F. Li, and Q. Gang, Intelligent controller design for PM DC motor position control using evolutionary programming, in *2011 IEEE 2nd International Conference on Computing, Control and Industrial Engineering*, Wuhan, 2011, pp. 37–40.

[107] T. Bäck, *Evolutionary algorithms in theory and practice : evolution strategies, evolutionary programming, genetic algorithms*. Oxford University Press, 1996.

[108] S. M. Anthony Brabazon, Michael O'Neill, Evolution strategies and evolutionary programming, in *Natural Computing Series*, vol. 28, Springer Verlag, 2015, pp. 73–82.

[109] Chun-Liang Lin and Horn-Yong Jan, Evolutionarily multiobjective PID control for linear brushless DC motors, in *IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02*, Sevilla, 2002, vol. 3, pp. 2033–2038.

[110] N. Thomas and P. Poongodi, Position Control of DC Motor Using Genetic Algorithm Based PID Controller, *Proc. World Congr. Eng.*, vol. 2, pp. 1–5, 2009.

[111] U. Ansari, S. Alam, and S. M. U. N. Jafri, Modeling and control of three phase BLDC motor using PID with genetic algorithm, in *2011 UkSim 13th International Conference on Computer Modelling and Simulation*, Cambridge, 2011, pp. 189–194.

[112] S. Srikanth and G. Chandra, Modeling and PID control of the brushless DC motor with the help of Genetic Algorithm, in *IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM -2012)*, Nagapattinam, Tamil Nadu, 2012, pp. 639–644.

[113] M. Jaiswal, M. Phadnis, and H. O. D. Ex, Speed Control of DC Motor Using Genetic Algorithm Based PID Controller, *Int. J. Adv. Res. Comput. Sci. Softw. Eng.*, vol. 3, no. 7, p. 2277, 2013.

[114] D. K. Meena and S. Chahar, "Speed control of DC servo motor using genetic algorithm," in *IEEE International Conference on Information, Communication, Instrumentation and Control, ICICIC 2017*, Indore, 2018, pp. 1–7.

[115] M. J. Prabu, P. Poongodi, and K. Premkumar, Genetic Algorithm Tuned PID Controller for Rotor Position Control of BLDC Motor, *World Appl. Sci. J.*, vol. 35, no. 2, pp. 199–207, 2017.

[116] S. Kumar Suman and V. Kumar Giri, Genetic Algorithms Techniques Based Optimal PID Tuning For Speed Control of DC Motor, *Am. J. Eng. Technol. Manag.*, vol. 1, no. 4, pp. 59–64, 2016.

[117] G. A. M. Ismeal, K. Kyslan, and V. Fedák, CAD of cascade controllers for DC drives using genetic algorithm methods, in *Procedia Engineering*, 2014, vol. 96, pp. 182–189.

[118] S. Das, A. Biswas, S. Dasgupta, and A. Abraham, Bacterial foraging optimization algorithm: Theoretical foundations, analysis, and applications, *Stud. Comput. Intell.*, vol. 203, pp. 23–55, 2009.

[119] S. Mirjalili, S. M. Mirjalili, and A. Lewis, Grey Wolf Optimizer, *Adv. Eng. Softw.*, vol. 69, pp. 46–61, Mar. 2014.

[120] J. Timmis, A. Hone, T. Stibor, and E. Clark, Theoretical advances in artificial immune systems, *Theor. Comput. Sci.*, vol. 403, pp. 11–32, 2008.

[121] A. H. Gandomi and A. H. Alavi, Krill herd: A new bio-inspired optimization algorithm, *Commun. Nonlinear Sci. Numer. Simul.*, vol. 17, no. 12, pp. 4831–4845, Dec. 2012.

[122] W. N. A. Abed, Speed control of DC motors using PID-controller tuned by bacterial foraging optimization technique, *J. Sci. Eng. Res.*, vol. 1, no. 2, pp. 55–63, 2014.

[123] R. E. Precup, A. L. Borza, M. B. Radac, and E. M. Petriu, Performance analysis of torque motor systems with PID controllers tuned by Bacterial Foraging Optimization algorithms, in *2014 IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA)*, Ottawa, ON, 2014, pp. 141–146.

[124] A. S. Oshaba and E. S. Ali, Bacteria Foraging: A New Technique for Speed Control of DC Series Motor Supplied by Photovoltaic System, *WSEAS Trans. Power Syst.*, vol. 9, pp. 185–195, 2014.

[125] R. Alzuabi, International Journal of Current Engineering and Technology Optimally Tuned PID Controller of A DC Motor System using Bacterial Foraging Algorithm, *294| Int. J. Curr. Eng. Technol.*, vol. 8, no. 2, 2018.

[126] E. Daryabeigi and B. Mirzaeian Dehkordi, Smart bacterial foraging algorithm based controller for speed control of switched reluctance motor drives, *Int. J. Electr. Power Energy Syst.*, vol. 62, pp. 364–373, 2014.

[127] X. Diao, H. Zhu, and D. Zhang, Speed and Displacement Control System of Bearingless Brushless DC Motor Based on Improved Bacterial Foraging Algorithm, in *MATEC Web of Conferences*, 2016, vol. 75, pp. 1–5.

[128] X. Zhou, Research on immune pathology in artificial immune system, in *2009 Chinese Control and Decision Conference*, Guilin, 2009, pp. 1366–1370.

[129] M. Gong, L. Zhang, L. Jiao, and S. Gou, Solving multiobjective clustering using an immune-inspired algorithm, in *2007 IEEE Congress on Evolutionary Computation*, Singapore, 2007, pp. 15–22.

[130] L. Xu and S. Jiang, Research of dynamics of DC speed regulator of flywheel double closed loop based on immune principle, in *IEEE International Conference on Computer Science and Automation Engineering*, Shanghai, 2011, vol. 2, pp. 259–263.

[131] Q. Meng and T. Liu, Study on Immune PID control method of an in-wheel motor used in an electric car, in *2017 36th Chinese Control Conference (CCC)*, Dalian, 2017, pp. 9554–9559.

[132] M. Hadi and S. Zaid, Artificial Immune System based PID Tuning for DC Servo Speed Control, *Int. J. Comput. Appl.*, vol. 155, no. 2, pp. 23–26, Dec. 2016.

[133] M. A. Şen and M. Kalyoncu, Optimal Tuning of PID Controller Using Grey Wolf Optimizer Algorithm for Quadruped Robot, *Balk. J. Electr. Comput. Eng.*, vol. 6, no. 1, pp. 29–35, Feb. 2018.

[134] A. Madadi and M. M. Motlagh, Optimal Control of DC motor using Grey Wolf Optimizer Algorithm, *Tech. J. Eng. Appl. Sci.*, vol. 4, no. 4, pp. 373–379, 2014.

[135] K. R. Das, D. Das, and J. Das, Optimal tuning of PID controller using GWO algorithm for speed control in DC motor, in *International Conference on Soft Computing Techniques and Implementations, ICSCTI 2015*, Faridabad, 2016, pp. 108–112.

[136] U. Bhatnagar and A. Gupta, Application of Grey Wolf Optimization in Optimal Control of DC Motor and Robustness Analysis, *Ski. Res. J.*, vol. 8, no. 1, pp. 19–25, 2018.

[137] D. Potnuru and A. S. L. V. Tummala, Grey wolf optimization-based improved closed-loop speed control for a BLDC motor drive, in *Smart Innovation, Systems and Technologies*, 2019, vol. 104, pp. 145–152.

[138] S. Saremi, S. Z. Mirjalili, and S. M. Mirjalili, Evolutionary population dynamics and grey wolf optimizer, *Neural Comput. Appl.*, vol. 26, no. 5, pp. 1257–1263, Jul. 2015.

[139] A. Zhu, C. Xu, Z. Li, J. Wu, and Z. Liu, Hybridizing grey Wolf optimization with differential evolution for global optimization and test scheduling for 3D stacked SoC, *J. Syst. Eng. Electron.*, vol. 26, no. 2, pp. 317–328, Apr. 2015.

[140] J. Agarwal, G. Parmar, and R. Gupta, Comparative Analysis of PID Controller for Speed Control of DC motor with Intelligent Optimization Algorithms, in *2018 International Conference on Advances in Computing, Communication Control and Networking (ICACCCN)*, Greater Noida (UP), India, 2019, pp. 273–277.

[141] A. Ahmed, G. Parmar, and R. Gupta, Application of GWO in Design of Fractional Order PID Controller for Control of DC Motor and Robustness Analysis, in *International Conference on Advances in Computing, Communication Control and Networking (ICACCCN)*, Greater Noida (UP), 2019, pp. 646–651.

[142] E. Cuevas, M. Cienfuegos, D. Zaldívar, and M. Pérez-Cisneros, A swarm optimization algorithm inspired in the behavior of the social-spider, *Expert Syst. Appl.*, vol. 40, no. 16, pp. 6374–6384, 2013.

[143] Wan Amir Fuad Wajdi Othman, Social Spider Optimization (SSO) for Tuning PID Controller on DC Motors, *Int. J. Res.*, vol. 5, no. 21, pp. 495–501, 2018.

[144] K. R. Das, D. Das, and J. Das, Optimal tuning of PID controller using GWO algorithm for speed control in DC motor, in *International Conference on Soft Computing Techniques and Implementations, ICSCTI 2015*, 2016, pp. 108–112.

[145] W. I. Hameed, A. S. Kadhim, and A. A. K. Al-Thuwaynee, Field Weakening Control of a Separately Excited DC Motor Using Neural Network Optemized by Social Spider Algorithm, *Engineering*, vol. 08, no. 01, pp. 1–10, 2016.

[146] H. Zang, S. Zhang, and K. Hapeshi, A review of nature-inspired algorithms, *J. Bionic Eng.*, vol. 7, no. SUPPL., Sep. 2010.

[147] I. Fister, X.-S. Yang, I. Fister, J. Brest, and D. Fister, A Brief Review of Nature-Inspired Algorithms for Optimization, *Elektroteh. Vestnik/Electrotechnical Rev.*, vol. 80, no. 3, pp. 116–122, Jul. 2013.

[148] K. C. Udaiyakumar and M. Chandrasekaran, Application of firefly algorithm in job shop scheduling problem for minimization of Makespan, in *Procedia Engineering*, 2014, vol. 97, pp. 1798–1807.

[149] R. Salgotra and U. Singh, Application of mutation operators to flower pollination algorithm, *Expert Syst. Appl.*, vol. 79, pp. 112–129, Aug. 2017.

[150] P. W. Tsai, J. S. Pan, B. Y. Liao, M. J. Tsai, and V. Istanda, Bat algorithm inspired algorithm for solving numerical optimization problems, in *Applied Mechanics and Materials*, 2012, vol. 148–149, pp. 134–137.

[151] T. Jayabarathi, A. Yazdani, and V. Ramesh, Application of the invasive weed optimization algorithm to economic dispatch problems, *Front. Energy*, vol. 6, no. 3, pp. 255–259, Sep. 2012.

[152] M. Sopa and N. Angkawisittpan, An Application of Cuckoo Search Algorithm for Series System with Cost and Multiple Choices Constraints, in *Procedia Computer Science*, 2016, vol. 86, pp. 453–456.

[153] A. R. Mehrabian and C. Lucas, A novel numerical optimization algorithm inspired from weed colonization, *Ecol. Inform.*, vol. 1, no. 4, pp. 355–366, Dec. 2006.

[154] M. Khalilpour, H. H. Razmjooy, N., and P. Moallem, Optimal Control of DC motor using Invasive Weed Optimization (IWO) Algorithm, in *Majlesi Conference on Electrical Engineering*, Isfahan, Iran, 2011, pp. 1–7.

[155] M. Misaghi and M. Yaghoobi, Improved invasive weed optimization algorithm (IWO) based on chaos theory for optimal design of PID controller, *J. Comput. Des. Eng.*, vol. 6, no. 3, pp. 284–295, Jul. 2019.

[156] X. S. Yang and S. Deb, Cuckoo search via Lévy flights, in *2009 World Congress on Nature and Biologically Inspired Computing, NABIC 2009 - Proceedings*, Coimbatore, 2009, pp. 210–214.

[157] A. S. Joshi, O. Kulkarni, G. M. Kakandikar, and V. M. Nandedkar, Cuckoo Search Optimization- A Review, in *Materials Today: Proceedings*, 2017, vol. 4, no. 8, pp. 7262–7269.

[158] V. Vishal, V. Kumar, K. P. S. Rana, and P. Mishra, Comparative study of some optimization techniques applied to DC motor control, in *Souvenir of the 2014 IEEE International Advance Computing Conference, IACC 2014*, Gurgaon, 2014, pp. 1342–1347.

[159] K. S. M. J. Singh, I. Elamvazuthi, K. Z. K. Shaari, and F. V. Lima, PID tuning control strategy using Cuckoo Search algorithm, in *2015 IEEE Student Conference on Research and Development, SCOReD 2015*, Lumpur, 2015, pp. 129–133.

[160] K. S. M. Jagindar Singh, I. Elamvazuthi, K. Z. K. Shaari, and S. Pranavanand, Tuning of PID controller for DC servo motor using

improved Cuckoo search algorithm, *Int. J. Simul. Syst. Sci. Technol.*, vol. 18, no. 2, pp. 6.1-6.9, Jun. 2017.

[161] M. Niaz Azari, M. Samami, and S. M. Abedi Pahnehkolaei, Optimal design of a brushless DC motor, by using the cuckoo optimization algorithm, *Int. J. Eng. Trans. B Appl.*, vol. 30, no. 5, pp. 668–677, May 2017.

[162] D. Puangdownreong, A. Nawikavatan, and C. Thammarat, Optimal Design of I-PD Controller for DC Motor Speed Control System by Cuckoo Search, in *Procedia Computer Science*, 2016, vol. 86, pp. 83–86.

[163] G. V. Cvetkovski, L. Petkovska, and P. Lefley, Cuckoo search as a tool for optimal design of PM brushless DC motor, *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 37, no. 5, pp. 1732–1743, Sep. 2018.

[164] R. A. Ardiansyah and E. Yazid, Angular Position Control of Brushless DC Motor Using Cuckoo Search algorithm Optimized PD Controller, in *2018 International Conference on Computer, Control, Informatics and its Applications (IC3INA)*, Tangeran, Indonesia, 2019, pp. 152–157.

[165] B. Yang, J. Miao, Z. Fan, J. Long, and X. Liu, Modified cuckoo search algorithm for the optimal placement of actuators problem, *Appl. Soft Comput. J.*, vol. 67, pp. 48–60, Jun. 2018.

[166] X.-S. Yang, P. San, D. San, F. Singapore, and S. Tokyo, *Nature-Inspired Optimization Algorithms*. Elsevier: London, 2014.

[167] A. Vashistha and S. (Guide) *Ganguli, Parameter Identification and Control of DC Motor using Firefly Algorithm*, Electrical and Instr. Engr., M.S. thesis, Thapar Unvi., Patiala, 2013.

[168] E. S. Ali, Speed control of DC series motor supplied by photovoltaic system via firefly algorithm, *Neural Comput. Appl.*, vol. 26, no. 6, pp. 1321–1332, Aug. 2015.

[169] P. Pal and R. Dey, Optimal PID Controller Design for Speed Control of a Separately Excited DC Motor: A Firefly Based Optimization Approach, *Int. J. Soft Comput. Math. Control,* vol. 4, no. 4, pp. 39–48, Nov. 2015.

[170] A. Yelghi and C. Köse, A modified firefly algorithm for global minimum optimization, *Appl. Soft Comput.*, vol. 62, pp. 29–44, Jan. 2018.

[171] A. S. Jaber, A Novel Tuning Method of PID Controller for a BLDC Motor based on Segmentation of Firefly Algorithm, *Indian J. Sci. Technol.*, vol. 10, no. 6, pp. 1–5, Feb. 2017.

[172] R. Klempka and B. Filipowicz, Optimization of a DC motor drive using a firefly algorithm, in *2018 International Symposium on Electrical Machines, SME 2018*, Andrychów, 2018, pp. 1–6.

[173] B. N. Kommula and V. R. Kota, Direct instantaneous torque control of Brushless DC motor using firefly Algorithm based fractional order PID controller, *J. King Saud Univ. - Eng. Sci.*, vol. 32, pp. 133–140, 2018.

[174] X. S. Yang, Flower pollination algorithm for global optimization, in *Unconventional Computation and Natural Computation. UCNC 2012*, 2012, vol. 7445, pp. 240–249.

[175] L. Dwi, R. D. Muhammad, W. Widodo, and R. Imam, Optimization of PID Controller Design for DC Motor Based on Flower Pollination Algorithm, in *The 2015 International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM 2015)*, Medan, 2016, pp. 1–5.

[176] D. Potnuru, K. Alice Mary, and C. Sai Babu, Experimental implementation of Flower Pollination Algorithm for speed controller of a BLDC motor, *Ain Shams Engineering Journal*, vol. 10, no. 2. pp. 287–295, 01-Jun-2019.

[177] X.-S. Yang, Firefly Algorithm, Stochastic Test Functions and Design Optimisation, *Int. J. Bio-inspired Comput.*, vol. 2, pp. 78–84, Mar. 2010.

[178] D. T. Pham, M. Castellani, M. Sholedolu, and A. Ghanbarzadeh, The Bees Algorithm and Mechanical Design Optimisation, in *ICINCO 2008 - Proceedings of the 5th International Conference on Informatics in Control, Automation and Robotics*, Madeira, Portugal, 2008, pp. 250–255.

[179] M. Dorigo and L. M. Gambardella, Ant colony system: A cooperative learning approach to the traveling salesman problem, *IEEE Trans. Evol. Comput.*, vol. 1, no. 1, pp. 53–66, 1997.

[180] D. T. Pham and M. Castellani, The bees algorithm: Modelling foraging behaviour to solve continuous optimization problems, *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 223, no. 12, pp. 2919–2938, Dec. 2009.

[181] D. Karaboga and B. Basturk, A powerful and efficient algorithm for numerical function optimization: Artificial bee colony (ABC) algorithm, *J. Glob. Optim.*, vol. 39, no. 3, pp. 459–471, Nov. 2007.

[182] F. S. Abu-Mouti and M. E. El-Hawary, Overview of Artificial Bee Colony (ABC) algorithm and its applications, in *2012 IEEE International Systems Conference SysCon 2012*, Vancouver, BC, 2012, pp. 1–6.

[183] A. K. Mishra, V. K. Tiwari, R. Kumar, and T. Verma, Speed control of dc motor using artificial bee colony optimization technique, in *2013 International Conference on Control, Automation, Robotics and Embedded Systems (CARE)*, Jabalpur, 2013, pp. 1–6.

[184] W. Liao, Y. Hu, and H. Wang, Optimization of PID control for DC motor based on artificial bee colony algorithm, in *International Conference on Advanced Mechatronic Systems, ICAMechS*, Kumamoto, 2014, pp. 23–27.

[185] A. Rajasekhar, S. Das, and A. Abraham, Fractional order PID controller design for speed control of chopper fed DC motor drive using artificial bee colony algorithm, in *2013 World Congress on Nature and Biologically Inspired Computing, NaBIC 2013*, 2013, pp. 259–266.

[186] R. El-Khazali, Fractional-order PI λdμ controller design, *Comput. Math. with Appl.*, vol. 66, no. 5, pp. 639–646, Sep. 2013.

[187] L. Huang and Y. Wang, Design for motor speed fractional order controller based on improved artificial bee colony algorithm, in *2016 Chinese Control and Decision Conference (CCDC)*, Yinchuan, 2016, pp. 3244–3249.

[188] D. Geng, K. Chen, Y. Yang, S. Li, and Q. Ai, A research of DC motor dual close-loop PID speed-tuning system on the basis of ABC Algorithm, in *26th Chinese Control and Decision Conference, CCDC 2014*, Changsha, 2014, pp. 3450–3454.

[189] Q. Jia and Y. Guo, Hybridization of ABC and PSO algorithms for improved solutions of RCPSP, *J. Chinese Inst. Eng. Trans. Chinese Inst. Eng. A/Chung-kuo K. Ch'eng Hsuch K'an*, vol. 39, no. 6, pp. 727–734, Aug. 2016.

[190] M. El-Abd, A hybrid ABC-SPSO algorithm for continuous function optimization, in *IEEE SSCI 2011 - Symposium Series on Computational Intelligence - SIS 2011: 2011 IEEE Symposium on Swarm Intelligence*, Paris, 2011, pp. 1–6.

[191] S.-M. Chen, A. Sarosh, and Y.-F. Dong, Simulated annealing based artificial bee colony algorithm for global numerical optimization, *Appl. Math. Comput.*, vol. 219, no. 8, pp. 3575–3589, Dec. 2012.

[192] X. S. Yang, A new metaheuristic Bat-inspired Algorithm, in *Studies in Computational Intelligence*, 2010, vol. 284, pp. 65–74.

[193] X. S. Yang and A. H. Gandomi, Bat algorithm: A novel approach for global engineering optimization, *Eng. Comput. (Swansea, Wales)*, vol. 29, no. 5, pp. 464–483, 2012.

[194] K. Singh, P. Vasant, I. Elamvazuthi, and R. Kannan, PID tuning of servo motor using bat algorithm, in *Procedia Computer Science*, 2015, vol. 60, no. 1, pp. 1798–1808.

[195] K. Premkumar and B. V. Manikandan, Speed control of Brushless DC motor using bat algorithm optimized Adaptive Neuro-Fuzzy Inference System, *Appl. Soft Comput. J.*, vol. 32, pp. 403–419, 2015.

[196] M. K. Merugumalla and P. K. Navuri, PSO and firefly algorithms based control of BLDC motor drive, in *Proceedings of the 2nd International Conference on Inventive Systems and Control, ICISC 2018*, Coimbatore, 2018, pp. 994–999.

[197] K. Premkumar and B. V. Manikandan, Bat algorithm optimized fuzzy PD based speed controller for brushless direct current motor, *Eng. Sci. Technol. an Int. J.*, vol. 19, no. 2, pp. 818–840, Jun. 2016.

[198] M. I. Anshory, Performance Analysis Stability Of Speed Control Of BLDC Motor Using PID-BAT Algorithm In Electric Vehicle, *J. Electr. Electron. Eng.*, vol. 1, no. 1, p. 22, May 2017.

[199] R. Eberhart and J. Kennedy, New optimizer using particle swarm theory, in *Proceedings of the International Symposium on Micro Machine and Human Science*, Nagoya, Japan, 1995, pp. 39–43.

[200] Y. Y. Nazaruddin, A. D. Andrini, and B. Anditio, PSO Based PID Controller for Quadrotor with Virtual Sensor, *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 358–363, Jan. 2018.

[201] H. E. A. Ibrahim, F. N. Hassan, and A. O. Shomer, Optimal PID

control of a brushless DC motor using PSO and BF techniques, *Ain Shams Eng. J.*, vol. 5, no. 2, pp. 391–398, Jun. 2014.

[202] M. Kohler, M. M. B. R. Vellasco, and R. Tanscheit, PSO+: A new particle swarm optimization algorithm for constrained problems, *Appl. Soft Comput.*, p. 105865, Oct. 2019.

[203] E. H. E. Bayoumi and H. M. Soliman, PID/PI tuning for minimal overshoot of permanent-magnet brushless DC motor drive using particle swarm optimization, *Electromotion*, vol. 14, pp. 198–208, 2007.

[204] A. A. Portillo, M. Frye, and C. Qian, Particle swarm optimization for PID tuning of a BLDC motor, in *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, San Antonio, TX, 2009, pp. 3917–3922.

[205] P. Payakkawan, K. Klomkarn, and P. Sooraksa, Dual-line PID controller based on PSO for speed control of DC motors, in *2009 9th International Symposium on Communications and Information Technology, ISCIT 2009*, Icheon, 2009, pp. 134–139.

[206] A. M. Sharaf and A. A. A. El-Gammal, A novel particle swarm optimization pso tuning scheme for pmdc motor drives controllers, in *2009 International Conference on Power Engineering, Energy and Electrical Drives*, Lisbon, 2009, pp. 134–139.

[207] A. M. Sharaf and A. A. A. El-Gammal, An Integral Squared Error -ISE optimal parameters tuning of modified PID controller for industrial PMDC motor based on Particle Swarm Optimization-PSO, *2009 IEEE 6th Int. Power Electron. Motion Control Conf. IPEMC '09*, vol. 3, pp. 1953–1959, 2009.

[208] H. K. Verma and M. C. Jain, A performance-dependent PSO based optimization of PID controller for DC motor, in *2011 1st International Conference on Electrical Energy Systems, ICEES 2011*, Newport Beach, CA, 2011, pp. 198–202.

[209] A. A. A. El-Gammal and A. A. El-Samahy, Adaptive tuning of a PID speed controller for DC motor drives using multi-objective particle swarm optimization, in *11th International Conference on Computer Modelling and Simulation, UKSim 2009*, Cambridge, 2009, pp. 398–404.

[210] R. Çoban and Ö. Erçđn, Multi-objective Bees Algorithm to Optimal Tuning of PID Controller, *Çukurova Univ. J. Fac. Eng. Archit.*, vol. 27, no. 2, pp. 13–26, 2012.

[211] A. Patel and K. Parikh, Speed Control of DC Motor Using PSO Tuned PI Controller, *IOSR J. Electr. Electron. Eng.*, vol. 9, no. 2, pp. 04–08, 2014.

[212] R. G. Kanojiya and P. M. Meshram, Optimal tuning of PI controller for speed control of DC motor drive using particle swarm optimization, in *2012 International Conference on Advances in Power Conversion and Energy Technologies, APCET 2012*, Mylavaram, Andhra Pradesh, 2012, pp. 1–6.

[213] C. Kamal, T. Thyagarajan, M. Selvakumari, and D. Kalpana, Cogging torque minimization in brushless DC motor using PSO and GA based optimization, in *Proceedings - TIMA 2017: 9th International Conference on Trends in Industrial Measurement and Automation*, Chennai, 2017, no. 4, pp. 1–5.

[214] A. Roy and S. Srivastava, Design of optimal PIλDδ controller for speed control of DC motor using constrained particle swarm optimization, in *Proceedings of IEEE International Conference on Circuit, Power and Computing Technologies, ICCPCT 2016*, Nagercoil, 2016, pp. 1–6.

[215] X. Hu, X. Hu, and R. Eberhart, Solving Constrained Nonlinear Optimization Problems with Particle Swarm Optimization, *6th World Multiconference Syst. Cybern. Informatics*, vol. 5, pp. 203--206, 2002.

[216] R. V. Jain, M. V. Aware, and A. S. Junghare, Tuning of Fractional Order PID controller using particle swarm optimization technique for DC motor speed control, in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, 2017, pp. 1–4.

[217] A. K. Deb, Introduction to soft computing techniques: Artificial neural networks, fuzzy logic and genetic algorithms, in *Soft Computing in Textile Engineering*, Elsevier Inc., 2011, pp. 3–24.

[218] M. Dorigo, G. Di Caro, and L. M. Gambardella, Ant algorithms for discrete optimization, *Artif. Life*, vol. 5, no. 2, pp. 137–172, 1999.

[219] S. Haldenbilen, O. Baskan, and C. Oz, An Ant Colony Optimization Algorithm for Area Traffic Control, in *Ant Colony Optimization - Techniques and Applications*, InTech, 2013, pp. 87–104.

[220] C. Wang, W. Cao, B. Li, Z. Shi, and A. Geng, A fuzzy mathematical method to evaluate the suitability of an evaporative pad cooling system for poultry houses in China, *Biosyst. Eng.*, vol. 101, no. 3, pp. 370–375, 2008.

[221] Ibrahim, H., Mahmoud, A., DC Motor Control Using PID Controller Based on Improved Ant Colony Algorithm, (2014) *International Review of Automatic Control (IREACO)*, 7 (1), pp. 1-6.
doi: https://doi.org/10.15866/ireaco.v7i1.1283

[222] D. Sandoval, I. Soto, and P. Adasme, Control of direct current motor using Ant Colony optimization, in *CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)*, Santiago, 2016, pp. 79–82.

[223] A. S. Oshaba, E. S. Ali, and S. M. Abd Elazim, ACO based speed control of SRM fed by photovoltaic system, *Int. J. Electr. Power Energy Syst.*, vol. 67, pp. 529–536, 2015.

[224] E. A. Ebrahim, Ant-colony optimization control of brushless-DC motor driving a hybrid electric-bike and fed from photovoltaic generator, in *2016 IEEE Congress on Evolutionary Computation (CEC)*, Vancouver, BC, 2016, pp. 4221–4228.

[225] M. Neshat, A. Adeli, G. Sepidnam, M. Sargolzaei, and A. N. Toosi, A review of Artificial Fish Swarm Optimization methods and applications, *International Journal on Smart Sensing and Intelligent Systems*, vol. 5, no. 1. Exeley Inc, pp. 107–148, 2012.

[226] J. Zhu, H. Liu, and Z. Ren, Optimization design of permanent-magnetism brushless DC motor governing system based on artificial fish swarm algorithm, in *Advanced Materials Research*, 2012, vol. 546–547, pp. 278–283.

[227] A. H. Gandomi and X. S. Yang, Benchmark problems in structural optimization, *Stud. Comput. Intell.*, vol. 356, pp. 259–281, 2011.

[228] Kaveh and S. Talatahari, A novel heuristic optimization method: Charged system search, *Acta Mech.*, vol. 213, no. 3–4, pp. 267–289, 2010.

[229] A. Sakulin and D. Puangdownreong, A Novel Meta-Heuristic Optimization Algorithm: Current Search, in *Proceedings of the 11th WSEAS international conference on Artificial Intelligence, Knowledge Engineering and Data Bases*, Wisconsin, USA, 2012, pp. 125–130.

[230] H. Kim, Harmony Search Algorithm: A Unique Music-inspired Algorithm, in *Procedia Engineering*, 2016, vol. 154, pp. 1401–1405.

[231] D. Puangdownreong, Current Search: Performance Evaluation and Application to DC Motor Speed Control System Design *Intell. Control Autom.*, vol. 04, no. 01, pp. 42–54, 2013.

[232] Z. W. Geem, J. H. Kim, and G. V. Loganathan, A New Heuristic Optimization Algorithm: Harmony Search, *Simulation*, vol. 76, no. 2, pp. 60–68, 2001.

[233] X. S. Yang and S. Deb, Cuckoo search via Lévy flights, in *2009 World Congress on Nature and Biologically Inspired Computing, NABIC 2009 - Proceedings*, Coimbatore, 2009, pp. 210–214.

[234] P. Yadav, R. Kumar, S. K. Panda, and C. S. Chang, Improved harmony search algorithm based optimal design of the brushless DC wheel motor, in *2010 IEEE International Conference on Sustainable Energy Technologies (ICSET)*, Kandy, 2010, pp. 1–6.

[235] M. Mahdavi, M. Fesanghary, and E. Damangir, An improved harmony search algorithm for solving optimization problems, *Appl. Math. Comput.*, vol. 188, no. 2, pp. 1567–1579, May 2007.

[236] M. Kumar and K. Chaursiya, Position control of brushless DC motor using harmony search algorithm optimization technique, in *2017 International conference of Electronics, Communication and Aerospace Technology (ICECA)*, Coimbatore, 2017, pp. 754–757.

[237] E. Rashedi, H. Nezamabadi-pour, and S. Saryazdi, GSA: A Gravitational Search Algorithm, *Inf. Sci. (Ny).*, vol. 179, no. 13, pp. 2232–2248, Jun. 2009.

[238] T. Nacer and S. D. Eddine, Newton's law of universal gravitation based genetic algorithm for graph distribution, *Int. J. Comput. Intell. Appl.*, vol. 15, no. 4, Dec. 2016.

[239] S. Duman, D. Maden, and U. Guvenc, Determination of the PID controller parameters for speed and position control of DC motor using Gravitational Search Algorithm, in *2011 7th International*

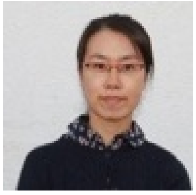
Conference on Electrical and Electronics Engineering (ELECO), Bursa, 2011, pp. 225–229.
[240] V. Andrean and K. L. Lian, A new MPPT method for partially shaded PV system by combining modified INC and simulated annealing algorithm, in *2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Sanur, 2017, pp. 388–393.
[241] A. Gupta, S. Goindi, G. Singh, H. Saini, and R. Kumar, Optimal design of PID controllers for time delay systems using genetic algorithm and simulated annealing, in *IEEE International Conference on Innovative Mechanisms for Industry Applications, ICIMIA 2017 - Proceedings*, Bangalore, 2017, pp. 66–69.
[242] M. Kishnani, S. Pareek, and R. Gupta, Optimal tuning of DC motor via simulated annealing, in *2014 International Conference on Advances in Engineering and Technology Research, ICAETR 2014*, Faridabad, 2014, pp. 1–5.
[243] S. K. Singh, N. Katal, and S. G. Modani, Optimization of PID controller for brushless DC motor by using bio-inspired algorithms, *Res. J. Appl. Sci. Eng. Technol.*, vol. 7, no. 7, pp. 1116–1122, 2014.
[244] L. Y. Kok, I. Elamvazuthi, and K. Ramani, Development of a nature inspired algorithm based controller for DC servo motor, in *2017 IEEE 3rd International Symposium in Robotics and Manufacturing Automation, ROMA 2017*, Kuala Lumpur, 2017, pp. 1–5.
[245] M. Kishnani, S. Pareek, and R. Gupta, Optimal tuning of DC motor via simulated annealing, in *2014 International Conference on Advances in Engineering and Technology Research, ICAETR 2014*, Unnao, Faridabad, 2014, pp. 1–5.
[246] P. Kumar, S. Chatterjee, D. Shah, U. K. Saha, and S. Chatterjee, On comparison of tuning method of FOPID controller for controlling field controlled DC servo motor, *Cogent Eng.*, vol. 4, p. 1357875, 2017.
[247] M. Shatnawi and E. Bayoumi, Brushless DC Motor Controller Optimization Using Simulated Annealing, in *2019 International Conference on Electrical Drives & Power Electronics (EDPE)*, Slovakia, 2019, pp. 292–297.
[248] E. G. Talbi, Metaheuristics, in *From Design to Implementation*, Hoboken, NJ, USA: Wiley, 2009.
[249] N. Singh and S. B. Singh, Hybrid Algorithm of Particle Swarm Optimization and Grey Wolf Optimizer for Improving Convergence Performance, *J. Appl. Math.*, vol. 2017, 2017.
[250] T. Joyce and J. M. Herrmann, A review of no free lunch theorems, and their implications for metaheuristic optimisation, in *Studies in Computational Intelligence*, vol. 744, Springer Verlag, 2018, pp. 27–51.
[251] D. H. Wolpert and W. G. Macready, No free lunch theorems for optimization, *IEEE Trans. Evol. Comput.*, vol. 1, no. 1, pp. 67–82, 1997.
[252] Y. Wang, C. Xia, M. Zhang, and D. Liu, Adaptive speed control for brushless DC motors based on genetic algorithm and RBF neural network, in *2007 IEEE International Conference on Control and Automation, ICCA*, 2008, pp. 1219–1222.
[253] W. M. Elsrogy, M. A. Fkirin, and M. A. M. Hassan, Speed control of DC motor using PID controller based on artificial intelligence techniques, in *2013 International Conference on Control, Decision and Information Technologies, CoDIT 2013*, 2013, pp. 196–201.
[254] M. Dasari, A. S. Reddy, and M. V. Kumar, Modeling of a commercial BLDC motor and control using GA-ANFIS tuned PID controller, in *2017 International Conference on Innovative Research in Electrical Sciences, IICIRES 2017*, Nagapattinam, 2017, pp. 1–6.
[255] M. Obaid Ali, S. P. Koh, K. H. Chong, and A. S. Hamoodi, Design a PID Controller of BLDC Motor by Using Hybrid Genetic-Immune, *Mod. Appl. Sci.*, vol. 5, no. 1, Jan. 2011.
[256] N. Öztürk and E. Çelik, Speed control of permanent magnet synchronous motors using fuzzy controller based on genetic algorithms, *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 889–898, Dec. 2012.
[257] J. Pongfai and W. Assawinchaichote, Self-tuning PID parameters using NN-GA for brush DC motor control system, in *2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Phuket, 2017, pp. 111–114.
[258] F. Valdez, P. Melin, and O. Castillo, Particle swarm optimization for designing an optimal fuzzy logic controller of a DC motor, in *2012 Annual Meeting of the North American Fuzzy Information Processing Society, NAFIPS 2012*, Berkeley, CA, 2012, pp. 1–6.
[259] M. M. R. A. Milani, T. Çavdar, and V. F. Aghjehkand, Particle swarm optimization - Based determination of Ziegler-Nichols parameters for PID controller of brushless DC motors, in *INISTA 2012 - International Symposium on INnovations in Intelligent SysTems and Applications*, Trabzon, 2012, pp. 1–5.
[260] A. S. El-Wakeel, A. E. E. K. M. Ellissy, and A. M. Abdel-Hamed, A hybrid bacterial foraging-particle swarm optimization technique for optimal tuning of proportional-integral-derivative controller of a permanent magnet brushless DC motor, *Electr. Power Components Syst.*, vol. 43, no. 3, pp. 309–319, Feb. 2015.
[261] T. V. Mahendiran and K. Thanushkodi, A new improved algorithm for speed control of brushless DC motor, in *2013 International Conference on Current Trends in Engineering and Technology, ICCTET 2013*, 2013, pp. 46–51.
[262] M. Tyagi, *Biological Algorithm based PID Tuning for Speed Control of DC Motor Evolutionary & Immune algorithms come under the category of bio-inspired optimization techniques*. Lap Lambert Academic Publishing, 2012.
[263] R. Rahmani, M. S. Mahmodian, S. Mekhilef, and A. A. Shojaei, Fuzzy logic controller optimized by particle swarm optimization for DC motor speed control, in *2012 IEEE Student Conference on Research and Development (SCOReD)*, Pulau Pinang, 2012, pp. 109–113.
[264] B. Bhatia, F. Khanam, R. Gahlot, and S. Shrivastava, PID Controller Tuning Using Bacteria Foraging based Particle Swarm Optimization (BF-PSO) Technique for DC Motor System, *Int. J. Electron. Electr. Comput. Syst.*, vol. 6, no. 3, pp. 105–109, 2017.
[265] K. Prathibanandhi and R. Ramesh, Hybrid control technique for minimizing the torque ripple of brushless direct current motor, *Meas. Control (United Kingdom)*, vol. 51, no. 7–8, pp. 321–335, Sep. 2018.
[266] D. M. Mustafa, K. H. Youssef, I. F. Elarabawy, and T. H. Abdelhamid, Hybrid Particle Swarm Optimization and Gravitational Search Algorithm for BLDC Motor Speed Control, in *2018 Twentieth International Middle East Power Systems Conference (MEPCON)*, Cairo, Egypt, 2019, pp. 1140–1147.
[267] X. S. Yang, Metaheuristic optimization: Algorithm analysis and open problems, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2011, vol. 6630, pp. 21–32.
[268] F. Neumann and C. Witt, Bioinspired computation in combinatorial optimization - Algorithms and their computational complexity, in *GECCO'12 - Proceedings of the 14th International Conference on Genetic and Evolutionary Computation Companion*, New York, NY, USA, 2012, pp. 1035–1058.
[269] A. Auger and O. Teytaud, Continuous lunches are free plus the design of optimal optimization algorithms, in *Algorithmica (New York)*, 2010, vol. 57, no. 1, pp. 121–146.
[270] N. Pazhaniraja, P. V. Paul, G. Roja, K. Shanmugapriya, and B. Sonali, A study on recent bio-inspired optimization algorithms, in *2017 Fourth International Conference on Signal Processing, Communication and Networking (ICSCN)*, Chennai, 2017, pp. 1–6.
[271] J. Ni, L. Wu, X. Fan, and S. X. Yang, Bioinspired intelligent algorithm and its applications for mobile robot control: A survey, *Computational Intelligence and Neuroscience*, vol. 2016. Hindawi Publishing Corporation, 2016.
[272] E. Rashedi, E. Rashedi, and H. Nezamabadi-Pour, A comprehensive survey on gravitational search algorithm, *Swarm Evol. Comput.*, vol. 41, pp. 141–158, 2018.
[273] C. Fuchs, S. Spolaor, M. S. Nobile, and U. Kaymak, A Swarm Intelligence Approach to Avoid Local Optima in Fuzzy C-Means Clustering, in *IEEE International Conference on Fuzzy Systems*, Orleans, LA, USA, 2019, pp. 1–6.

Authors' information

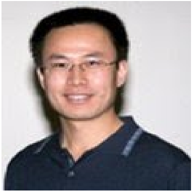
[1]Department of Electrical and Engineering Science, University of Johannesburg, South Africa.

[2]Department of Electrical and Mining Engineering, University of South Africa, Florida 1710, South Africa.

Stephen Oladipo was born in Nigeria in 1987. He obtained his engineering degree in Electronic & Electrical Engineering in 2010 from Ladoke Akintola University of Technology, Oyo State, Nigeria. He also obtained his M.Tech in the same university. Currently, he is a PhD student in the Department of Electrical and Electronic Engineering Science, University of Johannesburg, South Africa. His research interests are in Control Systems, Artificial Intelligent and Process Control.
E-mail: oladipostephen@gmail.com



Prof. **Yanxia Sun** is currently serving as an Associate Professor and the vice dean of the Faculty of Engineering and Built Science, University of Johannesburg, South Africa. She received her DTech in Electrical Engineering, Tshwane University of Technology, South Africa and PhD in Computer Science, University Paris-EST, France in 2012. She is doing research in Particle Swarm Optimization, Neural Network, Nonlinear Dynamics, Control Systems, and Renewable Energy. Prof Yanxia Sun has published 90 papers including 30 ISI master indexed journal papers. She was awarded NRF rating Y2 (2015-2020) and obtained the NRF incentive grant. She is an IEEE member and reviewer for several international journals and conferences.
E-mail: ysun@uj.ac.za



Prof. **Zenghui Wang** is a National Research Foundation (NRF) C2-rated researcher in Electrical Engineering. He is currently a Professor at the University of South Africa. After he graduated with a Doctoral degree in 2007, he worked as an Associate Professor in the Department of Automation at Shandong University of Science and Technology and a post-Doctoral Fellow at the French South African Technical Institute in Electronics at the Tshwane University of Technology (TUT). He joined Unisa in 2010 as an Associate Professor in the Department of Electrical and Mining Engineering and soon thereafter (July 2012) became a Professor in the same Department. Prof Wang specializes in Electrical Engineering and Computer Science. He is the leader of Intelligent System research group/laboratory. He has been involved in ten major research projects in South Africa and China. To August 2018, he has more than 100 papers published or accepted, including more than 50 ISI master indexed journal papers.
E-mail: wangz@unisa.ac.za