Review of Various Metaheuristics Techniques for Tuning Parameters of PID/FOPID Controllers

Mohannad Nasir[1], Majd Saloumi[1], Ali Bou Nassif[2,*]

[1]*College of Engineering, University of Sharjah, Sharjah, UAE*
[2]*College of Computing and informatics, University of Sharjah, Sharjah, UAE*
[*]*Corresponding author. Email: anassif@sharjah.ac.ae*

ABSTRACT

Alongside the rapid advancement of technology, researchers are looking for accurate, flexible, and efficient ways to control systems. One big breakthrough in technology is the PID and its following advancement which is FOPID controller. The PID controller is becoming widely used due to its simplicity and cost-effectiveness, while the latter is more desirable because of its accuracy and flexibility. The parameters of the aforementioned controllers have an enormous effect on the transient responses. For instance, the settling time, rising time, Integral Absolute Error (IAE), and overshooting are greatly influenced by the controller parameters. However, the most difficult problem in delivering the active case of the transient response of any system is the tuning of system parameters. Ziegler-Nicolas (ZN), recursive least squares (RLS) for tuning PID controller, while Pole Placement, and Pole Distribution for tuning FOPID are some examples of classical algorithms that are utilized previously to tackle this problem. Recently, the optimization methods have been employed to tune these parameters in order to have a more stable controller system. This systematic literature review (SLR) will take into consideration various optimization methods that tackled this problem. Methods like PSO, GA and ACO are the most utilized in tackling this problem. This paper will be an introductory guide to other researchers which will immensely help in their metaheuristic method selection.

Keywords: *PID Controller, FOPID Controller, Transient response, Evolutionary algorithms.*

1. INTRODUCTION

The proportional-integral-derivative (PID) controllers have been used in numerous applications. The popular utilization of PID controllers in flight control, instrumentation, process control, engine drives, etc. The optimization of both steady-state response and transient is being enclosed by the three-term functionality of the PID controller. Unfortunately, it has been challenging to adjust PID controller gains in an accurate way; this is because numerous industrial plants are very complex comprising of issues, for instance, nonlinearities, time delays, and higher order [1]. Several techniques (such as Fuzzy logic control, adaptive control, and neural network control) are such examples of choices that are mainly illustrated by the science of automatic control. As no other controllers match the usefulness, applicability, and usability offered by the PID controllers, more than 90% of industrial controllers are still dependent on the PID control algorithms [2]. Nnumerous methods/techniques have been developed in the past for tuning the parameters of the PID controllers. Ziegler and Nichols [2] is introduced as the first method using the traditional tuning rules. In fact, the Z-N method cannot be applied on several industrial processes because it gives large settling time, rise time, and overshooting. Recently, the exponential progress and advancement in computer technology proposes the need of higher accuracy system. The fundamentals of fractional calculus were first introduced in 1695 by Leibniez and L'Hopital [3]. Fractional calculus is the mathematics of integral and derivatives of non-integer order. After years of progressive work and only in 1999, Podlubny offered the concept of fractional order PID (FOPID) which is considered as an enhancement of the classical PID controller, using the definition of Reimann-Liouville [4]. Ever since this benchmark, a huge attraction stated towards FOPID research, accomplishing a breakthrough in controller design. FOPID is a more general form of PID, if intended it can be operated as a PID as it proposes the same three parameters the PID does. In addition to these parameters, FOPID suggests the utilization of two new parameters which are μ (differentiator order) and λ (integrator order). These two parameters can take any positive real value, they also determine the order of the integral and derivative terms and setting them to $\mu = \lambda = 1$ sets the FOPID ($PI^{\lambda}D^{\mu}$) to act like the conventional PID, the above figure is a good demonstration of the functionality of the FOPID [5].

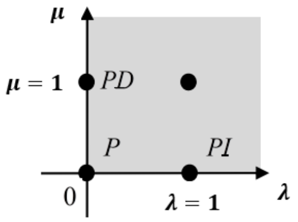

Figure 1 FOPID controller characteristic graph[5]

The complexity of tuning the FOPID gains comes from the number of parameters needed to be tuned which are five in total, and the fractional order of the integral and derivative parts. Different approaches have been implemented in the last few decades such as tuning in time domain and frequency domain approaches which is reliant on expected crossover with frequency and phase [6]. Moreover, approaches that are reliant on pole placement and pole distribution [7],[8]. In addition to some analytical approaches that suggest reducing the order of the system to three. Nevertheless, the implementation of the previous methods carries uncertainties and inaccuracies when it comes to tuning these parameters due to the high nonlinearity of the objective function caused by the fractional order terms.

Nowadays, tremendous evolutionary algorithms have been proposed to explore and find the optimal tuning of either PID or FOPID parameters. The first nature-inspired algorithm that has received great attention is the Genetic Algorithm (GA). This algorithm is motivated by populace hereditary genetics and advancement at the population level, just as the Mendelian comprehension of the structure [9]. Furthermore, Particle Swarm Optimization (PSO) has been effectively applied on several fields and applications [10]. In addition to the previously mentioned algorithms, (by pretending the behavior of ant colonies) , it can tackle a lot of optimization problems, and this method is known to be able to find the shortest track from their nest to a food source, which is Ant Colony Optimization (ACO) [11].

To the best of our knowledge, this is the first paper that review the metaheuristic techniques and their application on tuning both PD and FOPID controllers' gains. The main motivation of this paper is that the related-work papers are lacked to make a comprehensive analysis into tackle the tuning of both PID and FOPID controllers' gains; where none of them stated what is the most evolutionary algorithm, what is the most domain that the PID controller tackled in, etc. This paper will provide such a systematic review of the papers published between 2010 and 2020, and it will take into consideration the issues that were existed in the previous surveys. Furthermore, the paper will focus on main optimization algorithms utilized in recent years and discusses the most efficient algorithm among them. The rest of the SLR will be organized as follow: Sec. II is the background, Sec. III is the related work, in Sec. IV recent metaheuristic algorithms will be discussed in brief, Sec. IV is the methodology, Sec. V is the results and discussion. Sec. VI is the limitations and review evaluation, and finally, Sec. VII is the conclusion and future work.

2. BACKGROUND

2.1. PID Controller

A typical structure of the PID controller is mainly known as the "three-term" controller, and its transfer function is written as,

$$u(t) = K_p e(t) + K_i \int e(k)dk + K_d \frac{de(\tau)}{d\tau} \quad (1)$$

where K_p , K_i , and K_d are the coefficients of the proportional, integral, and derivative terms of controller, respectively.

Figure 2 below illustrates the PID controller with that feedback loop, which is mainly broken into three terms proportional, integral, and derivative in order to control the process of the plant, where the real measured output is y(t) and the desired value is r(t) [12].

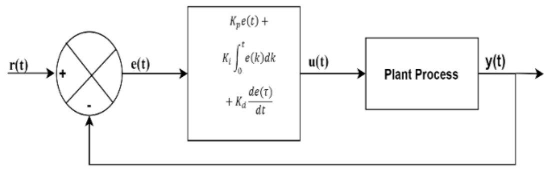

Figure 2 PID closed loop system

2.2. FOPID Controller

One of the better-known definitions for the fractional derivative is the Riemann-Liouville (RL), The RL equation is expressed as follows [13]:

$$aD_t^r f(t) = \frac{1}{\Gamma(n-r)} \frac{d^r}{dt^r} \int_a^t \frac{f(\tau)}{(t-\tau)^{r-n+1}} d\tau \quad (2)$$

Γ is the notation for gamma function. Therefore, using the definition above and by taking the Laplace transformation of both the fractional derivative and the fractional integral of f(t), the terms can be written as follows:

- Derivative term

$$L\{D^a f(t)\} = s^a F(s) - [D^{a-1} f(t)]_{t=0} \quad (3)$$

- Integral term

$$L\{D^a f(t)\} = s^{-a} F(s) \quad (4)$$

The terms above will help later with expressing the FOPID controller transfer function. The differential equation of Fractional Order PID controller can be written as [14]:

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t) \quad (5)$$

Table 1. Summary of the related work

Ref Number	Year	PID/FOPID	Algorithms used	Application
[15]	2010	FOPID	Improved Electromagnetism Like Algorithm, GA	Second Order System with Time Delay
[16]	2011	PID	RGA, SPSO, MPSO, NPSA	Higher order systems.
[17]	2012	PID	ACO, PSO, BFOA	Higher order systems.
[18]	2012	PID	DE, GA, BAT, PSO, CS	Higher order system, Time delay system
[19]	2012	PID	GA, SA, TS	Bioprocess control
[20]	2012	PID	DE, GA	Higher order system, Time delay system
[21]	2014	PID	GA, PSO, DE	IAE, ISE, MSMAE
[22]	2014	PID	MOEA	-
[23]	2016	PID	DE, GA, BAT, PSO, CS	Robot Arm mechanism
[24]	2016	FOPID	GA,PSO,CA, ABC	Tank Level Control System
[25]	2017	PID	MOEA	-
[26]	2018	FOPID	PSO,ABC	Unstable and Integrating Systems with Time Delay
[27]	2019	FOPID	PSO	Unmanned Aerial and Ground Vehicles
[28]	2020	FOPID	GA, PSO	Liquid Level Control
[29]	2020	FOPID	GWO,SCA,SSA	Automatic Voltage Regulator
[30]	2020	FOPID	GA,BA,MGA,ABC,PSO,GA-NM	Brushless DC Motor

and by taking the Laplace transformation of the above equation:

$$G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \quad (6)$$

From equation 6, the parameters in the controller's transfer function can be identified the following. s is the complex frequency $s = jw$. K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. μ and λ are the fractional order of the derivative and the integral terms and they can take the value of any positive real number. Figure 3 shows FOPID ($PI^{\lambda}D^{\mu}$) controller in a feedback system.

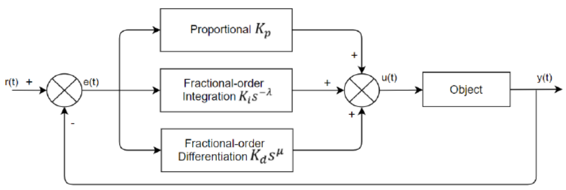

Figure 3 FOPID closed loop system

It is obvious from equation 6 that tuning the Fractional order PID does not depend only on tuning the three gains K_p, K_i, and K_d. μ and λ also, must be tuned.

The tuning of the PID controller gains can be considered as an optimization objective function as,

$$Min\,\vec{f}\,(\vec{k}) = [f_1(\vec{k}), f_2(\vec{k}) \ldots . f_j(\vec{k})] \quad (7)$$

$$S.t\; g_i(\vec{k}) \leq 0 \; i = 1,2, .. m \quad (8)$$

where $\vec{k} = [K_p, K_i, K_d]$ is the vector of PID gain parameters, while $\vec{k} = [K_p, K_i, \lambda, K_d, \mu]$ is the vector in case of FOPID, $\vec{f}$ is the objective function, $f_j(\vec{k})\colon R_3 \rightarrow R, i = 1,2, \ldots j$ are the objective functions, and $g_i(\vec{k})$: $h_i(\vec{k})$: $R_3 \rightarrow R, i = 1,2 \ldots m, i = 1,2..p$ are the constraints function.

3. RELATED WORK

The analysis of the associated survey articles is conducted in this section. In addition, these articles tackled the tuning gains of both PID and FOPID controllers with various optimization techniques in different domains and for different applications. Table.1 represents a comparison among these papers [15-30].

4. METAHEURISTICS ALGORITHMS

This section will mainly focus and discuss four main optimization techniques that being widely used for almost all complex and nonlinear systems.

4.1. Genetic Algorithm (GA)

The genetic algorithm is a random search algorithm that utilizes the Darwinian Hypothesis of evolution [9], in addition, it can be utilized to optimize and solve nonlinear systems and complex problems. Rather than utilizing a deterministic rule, the Genetic algorithm utilizes probabilistic transition rules, in addition to dealing with a population of potential solutions noted as individuals or chromosomes that evolve iteratively. Generation is known as each iteration of the GA algorithm. The genetic algorithm is usually initialized with a random population, and this population is always denoted by a real-valued number, or a binary string named as a chromosome. By utilizing the objective function, the performance of the is measured and evaluated, which mainly assigns each individual an analogous number called its fitness. As in this work, the execution of the tuning method through genetic algorithms begins with the meaning of the chromosome representation. To accomplish a suitable behavior, the chromosome should consist of either three values that correspond to the three gains to be tuned or five values in case of FOPID. Where these values can be K_p, K_i, K_d or $K_p, K_i, \lambda, K_d, \mu$ depending on the utilized controller.

4.2. Particle Swarm Optimization (PSO)

In view of the evolutionary computation technique, particle swarm optimization (PSO) is produced [10]. From research on swarms such as bird flocking and fish schooling, the PSO algorithm is developed. The PSO was firstly presented in 1995 [10], later, an improved PSO was then presented in 1998 to enhance the performance of the original PSO algorithm. In the PSO algorithm, mutation and crossover are replaced to control algorithms, for d-variable optimization problem, a flock of particles are put into the d-dimensional search space with randomly chosen positions and velocities getting their optimum value. Yet (pbest) and the position in the d-dimensional space. However, the velocity of every particle changed accordingly to its the particle experience and the others experience. For instance, the ith particle is characterized, as

$$x_i = (x_{i,1}, x_{i,2}, \dots, x_{i,d}) \tag{9}$$

In the d-dimensional space. The best previous position of the ith is recorded as,

$$Pbest_i = (Pbest_{i,1}, Pbest_{i,2}, \dots, Pbest_{i,d}) \tag{10}$$

The velocity for particle i is represented as

$$V_i = \left(V_{i,1}, V_{i,2}, \dots, V_{i,d}\right) \tag{11}$$

The adjusted position and velocity of every particle can be computed by applying the current velocity and distance from $Pbest_d$ to $gbest_d$ as illustrated in the following formulas,

$$V_{i,m}(t+1) = W.V_{i,m}(t) + c_1 * rand() * (Pbest_{i,m}x_{i,m}(t)) + \quad c_2 * rand() * gbest_m - x_{i,m}(t)) \tag{12}$$

$$x_{i,m}(t+1) = x_{i,m} + V_{i,m}(t+1), i = 1,2, \dots, n. m\ 1,2, \dots, d. \tag{13}$$

where n=number of particles in each group, d=dimension, t=pointer of iterations, $V_{i,m}^{(1)}$=Velocity of particle i at iteration t , W=Inertial weight factor, c_1 and c_2= Acceleration constants, rand()=Random number between 0 and 1, $x_{i,m}^{(t)}$= Current position of particle i at t iteration, $Pbest_i$ is the best previous position of the ith ,$gbest_m$is the best particle among all the particles in the population [31].

4.3. Ant Colony Optimization (ACO)

Ant Colony Optimization is an evolutionary and heuristic algorithm that usually utilizes a graphical depiction to illustrate the solution, in addition, that it is invented to solve the combinatorial issues [11]. Merging the earlier information about the previous good solutions and upcoming information about the following solution is mainly the most important characteristic of the ACO algorithm. However, the algorithm starts by selecting the number of ants individually of which illustrates a potential answer to the desired optimization problem. Thereafter, the initial pheromone amount will be calculated by utilizing the below equation:

$$\tau_o = \frac{1}{\mathrm{Z_{min}}} \tag{14}$$

Equation (15) is to calculate the pheromone and visibility values for every decision variable.

$$\tau_{\mathrm{ij}} = \frac{1}{\tau_o}, \mathrm{V_{ij}} = \frac{1}{\mathrm{x_{ij}}}, i = 1,2, ., nv\ \ j = 1,2, ., npool \tag{15}$$

where x_{ij} is jth value of the design variable i, the complete number of the design variables in any optimization problem is donated by nv, and a value that can be selected for decision variable i is donated by *npool.* Second step is choosing the design variables that should be done by each ant in their colony. From the pool value is came after the first step. The probability computation that is represented in equation (16).

$$P_{ij}(t) \frac{\tau_{ij}(t)^\alpha \cdot v_{ij}^\beta}{\sum_{j \in allowed}^{ndiv} \tau_{ij}(t)^\alpha \cdot v_{ij}^\beta} \quad \forall\ i, j \tag{16}$$

where $P_{ij}(t)$ is the probability of ^{jth} value that is selected from the pool to have decision variable i, and t represents the assigning time for the previous decision variable. Third step happens while ending of each tour, a local update should be performed.

$$\tau_{\mathrm{ij}} = \zeta * \tau_{\mathrm{ij}} \tag{17}$$

The above equation is the mathematical representation for the previous step, where ζ is usually called local update coefficient and its value ranges between 0 and 1. Fourth step is for the next decision variable, by penalizing a candidate solution by utilizing the expression $Z_p = Z(1 + C)\varepsilon$ will occur when this candidate solution fails to satisfy the constraints. However , the Z_p in the previous expression represents the location and ε is the penalty coefficients. Fifth step is to we perform the global update by utilizing equation (18):

$$\tau(t+2)_{ij} = \rho \cdot \tau(t)_{ij} + \Delta\tau(t)_{ij} \tag{18}$$

Where ρ represents the constant between 0 and 1. Sixth step is to repeat steps 2-5 until the termination criterion matched which is basically chosen as the maximum number of iterations [11].

4.4. Artificial Bee Colony (ABC)

Swarm based, metaheuristic algorithm that was initiated by Karaboga in 2005. The algorithm consists of three groups which are Employed bees, onlooker bees and scout bees. Employed bees are directly linked to food sources (solution). Onlooker bees' job is to observe the employed bee's food sources and use a fitness values utilizing the information they acquired from employed bees. Scout bees on the other hand objective is to search for new possible solutions [32]. In terms of either PID or FOPID. For instance, in FOPID controller, the employed bees are a possible solution that carry the values of the five parameters $K_p, K_i,\ K_D, \mu\ and\ \lambda$. Unless there is no change in the system response employed bees become scout bees and they start looking for better values that achieve better system response.

5. METHODOLOGY

The systematic literature review covers metaheuristics optimization methods used in last decade for tuning both PID and FOPID controller gains, in which it will focus on the most three utilized algorithms. The systematic literature review has been made by following the exact methodology that is stated in Charters and Kitchenham [33].

5.1. Objectives and Research Questions (RQs)

The goal of this systematic literature review is to identify the advantages and benefits of utilizing different evolutionary algorithms to optimize the tuning of both PID and FOPID controller gains. The research methodology that is adopted in this paper depends on giving the answers to some important questions. These questions are as follows:

RQ1: What are the recent optimization methods employed in the selected research papers, and what is the most meta-heuristic algorithm applied in each problem?

The desire of this question is to know the trend optimization algorithms utilized in dealing with the tuning of the PID controller gains.

RQ2: In those research papers, what problems have been optimized?

The desire of this question is to explain different kinds of tuning both PID and FOPID controllers' fields.

RQ3: What is the most meta-heuristic algorithm applied in each problem?

The desire of this question is to explain different kinds of tuning PID controller fields that have been optimized.

RQ4: What is the most efficient algorithm that supports the tuning of the PID and FOPID controller gains, and why?

Determine which algorithm is the most efficient one in this problem is desire of this question.

5.2. Search Strategy

This phase recognizes the keywords utilized in collecting the associated papers, consequently, answering the desired research questions.

5.2.1. Search terms and exclusion criteria

First stage in search strategy phase is to set search terms, which they are: ("GA" OR "ACO" OR "PSO" OR "ABC" OR "Optimization" OR "Metaheuristic") AND ("Tuning PID Controller" OR "Tuning FOPID Controller" OR "PID Controller" OR " FOPID") AND ("PID" OR "FOPID").

5.2.2. Resources, periods, and documentation

The following digital libraries and online resources are utilized to find out all related papers, by utilizing the aforementioned search terms and identifying years from 2010 to 2020 in order to indicate the search strategy phase: IEEE Explorer, Springer, Google Scholar, Science Direct, ACM Digital Library, Elsevier, Semantics Scholar and Research Gate.

300 papers were found in the first round, these papers identified to conferences and journals. By evaluating the papers through the RQs, the papers were filtered.

5.2.3. Choosing the initial study

By utilizing the inclusion and exclusion criteria, the filtration process of the papers was done. Starting with the inclusion criteria were characterized by the following, including papers that talk about the tuning of the PID or FOPID controllers, papers that compare among different optimization algorithms and papers that published between 2010 to 2020. On the contrary, exclusion criteria were performed by the following, excluding papers that analysed multi-objective optimization methods, papers that not consisting of any optimization techniques.

5.2.4. Quality Assessment Rules (QARs) evaluation

The selected papers were assessed by quality evaluation rules questions to decide how these papers area reasonable, and firmly identified with the research topic in this section.

QAR 1: Does the paper clearly describe its objective?

QAR 2: Does the paper define the PID controller gains?

QAR 3: Does the paper clearly describe the utilized algorithms?

QAR 4: Does the paper describe the problem that needs to be optimized?

QAR6: Are the results shown clearly?

All questions carry 1 mark, if the paper "fully answered," the QAR question the score=1, if the paper answered, " above the average" the score equals to 0.75 if it answered, " the average" then its score equals to 0.5, if " below the average" the score of it is 0.25 and finally of the paper doesn't answer the QAR at all "not answered" the score of it is 0. The papers included in this review are the papers that scored the average mark and above (>=3.5), while the papers scored below the average will be excluded. 62 articles were selected after applying the filtration process in this systematic literature review (SLR) [34- 95].

5.2.5. Data Extraction and synthesizing

In this step, more study of the chosen papers is done in order to extract and explore the required information that answered the defined four research questions earlier.

Based on the answers to the research questions, the collection of all the chosen papers to contrast and summarized all the extracted information is done. Based on [31] synthesizing the data can be narrative, qualitative, and quantitative. Narrative procedures are followed for extraction of the information from RQ1 and RQ2.while RQ3, RQ4 and RQ5 are quantitative.

6. RESULTS AND DISCUSSION

In this phase, an illustration and discussion of the extracted results from the chosen articles will be presented. In this section, the stated four research questions RQs will be answered in detail from the 62 selected papers that are mainly talking about the tuning of both PID and FOPID controllers. The papers included in this systematic literature survey have a score of 3.5 or above by evaluating them according to the QARs [34-95].

6.1. What are the recent optimization methods employed in the selected research papers?

During research in the previously mentioned libraries, in the selected range, it is found that there are many evolutionary algorithms that are utilized to enhance the tuning of both PID and FOPID controller gains.

In terms of PID controller, Figure 4 depicts the percentage of each optimization algorithm utilized. These algorithms are mainly the most implemented algorithms in this tuning PID controller parameters. In addition, it is obvious from the figure that GA, PSO, ACO are the most three algorithms used among the others.

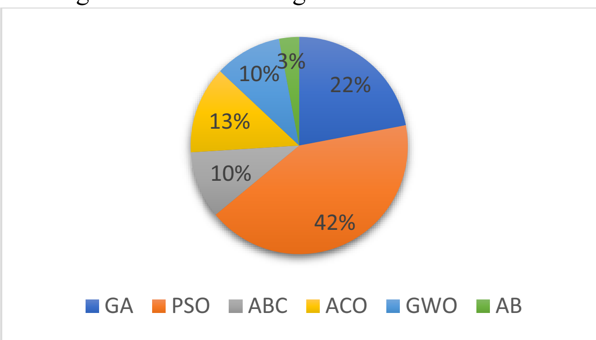

Figure 4 Recent used algorithms for tuning PID

On the other hand, 10 recent algorithms were surveyed in the collected papers in light of tuning FOPID controller gains. The following Figure 5 showcases the overall distribution of utilized methods according to number of articles. It can be noted that PSO, GA, ACO and ABC are the most preferred methods in the collected papers.

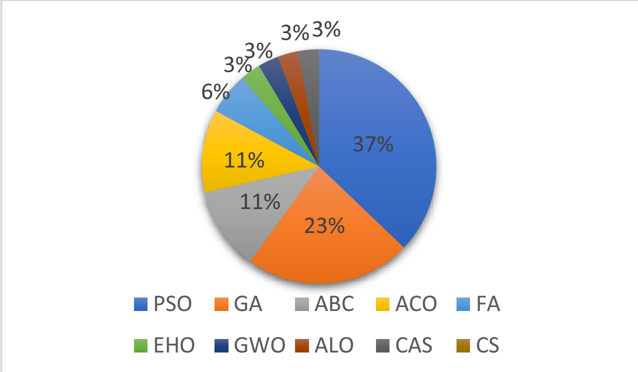

Figure 5 Recent used algorithms for tuning FOPID

6.2. What is the problem that optimized in the selected research papers?

There are many problems that the tuning of both PID and FOPID controllers' gains utilized in, Figure 6 shows the number of articles based on the used problems in tuning PID controller. While Figure 7 demonstrate the problems that utilized in tuning FOPID controller parameters.

5.2.1. Inverted Pendulum

The inverted pendulum has been considered as one of the common causes of a multi-variable, coupled, non-linear, and exceptionally unstable system. Any pendulum that has a mass above its pivot point can be considered as an inverted pendulum. Based on the inverted pendulum characteristics, the system must be actively balanced by locating the pivot point horizontally which acts as feedback to the system [96].

5.2.2. Automatic Voltage Regulator (AVR)

In any electric power gird, voltage level should be within the accepted range based on the international standards. The. Maintaining a constant voltage level is a big challenge in the power system analysis. To keep a constant voltage in the power system, a voltage regulator is a must in the power system. Recently, the AVR system is usually useful to the power generation units, this will allow us to solve a lot of control problems. The PID controller is utilized for the AVR framework with a normal gain promoter and has the controller gains identical to the tuning parameters of PID [97].

5.2.3. DC Motor

DC motors are torque transductors that are utilized to producing the mechanical energy by transforming electric energy.

Consequently, they are usually utilized in the industries. On the motor shaft, the essential torque for the movement is developed there, which has directly proportional to the armature current and the field flux. However, Electric motor frameworks are necessary for the modernistic industries. By utilizing the feedback controller allows us to control the speed, motion, or both servo motors [98].

5.2.4. Magnetic Levitation System (MLS)

Naturally, unstable systems, magnetic levitation systems "Maglev" are widely used applications in modern technology. From standard application such as the ferromagnetic levitated ball, magnetic bearing which are used in electrical machines to support the rotation of the shaft, to much modern applications like high-speed magnetic levitated trains. Maglev systems are very important as they eliminate friction and need of lubrication [99]. These systems are non-linear open loop unstable systems that requires the aid of a controller to stabilize them around a point called equilibrium point.

5.2.5. Load Frequency Control (LFC)

Load Frequency Control is one of the most important issues alongside Automatic Generation Control in power system design. Interconnected system might witness changes in nominal system frequency to other areas which may result in unwanted effects. Thus, there is a need for a controller to achieve balance between total generation and total demand in these interconnected systems. Such controller will provide Load Frequency Control. In other words, it must ensure zero steady state error while frequency deviation occurrences. The controller must also maintain an acceptable overshoot, settling time on the tie line power deviation [100].

The two figures below depict the number of papers based on the used problems in tuning both PID and FOPID respectively.

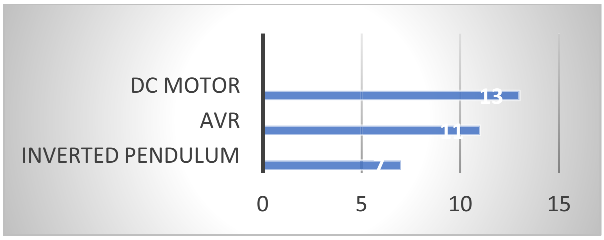

Figure 6 Articles based on used problems (PID)

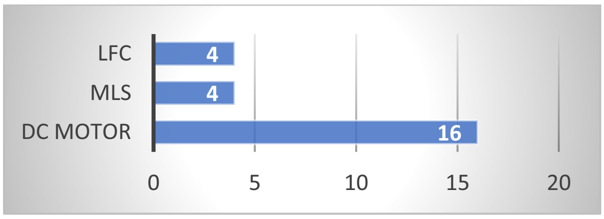

Figure 7 Articles based on used problems (FOPID)

6.3. What is the most meta-heuristic algorithm applied in each problem in PID/FOPID?

Figure 8 demonstrates the percentage of the algorithms used in the PID controller applications. As illustrated from the Figure 8, the genetic algorithm (GA) is the most utilized algorithm in the DC motor problem, while the particle swarm optimization is the most utilized algorithm in the AVR problem. However, in the inverted pendulum problem, both GA and PSO are the most utilized algorithms.

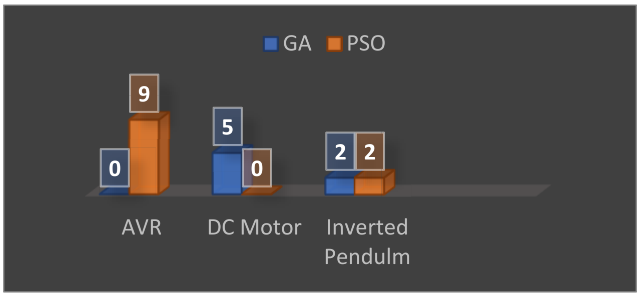

Figure 8 Most used algorithm in each problem (PID)

While Figure 9 showcases the number of algorithms used in most tackled problems in terms of FOPID . It is worthy to point out that PSO was the most utilized in both DC motor and LFC. GA comes in second place. For magnetic levitation systems a variation of algorithms was utilized in addition to the ones mentioned in Figure 9, such as firefly method. The figure intends to survey the most popular algorithms with the most popular applications.

Figure 9 Most used algorithm in each problem (FOPID)

6.4. What is the most efficient algorithm that supports the tuning of the PID and FOPID controller gains?

After examining the chosen papers, it is established that the best algorithm that utilized to optimize the tuning of both controller gains is the PSO, which is also measured as the maximum utilized evolutionary algorithm in optimizing both controller gains among the others. The main reason behind that is the PSO has the highest consistency and exactness as it looks completely in the search space and communicates with all other particles which increase effectiveness. In addition, the PID and FOPID values that has been measured by PSO is the nearest to the auto tuned value [12].
However, ACO has high accuracy but less consistency which makes it less effective than the PSO. To conclude, the PSO has the highest accuracy in finding the controllers gains followed by ACO and then the GA.

7. LIMITATIONS AND REVIEW EVALUATION

This systematic literature survey is limited only to the journal as well as conference papers in the field of tuning PID controller gains between 2010 and 2020. This search has begun by finding many papers related to the topic, but these papers are filtered to reach a limited number of papers because these limited papers are the only papers that match the research questions and quality assessment rules, among all selected papers. In addition to the previous limitation, while doing this SLR, it was found that there are new algorithms that are presented in 2021, these algorithms use two algorithms simultaneously, but including these algorithms requires more time as performing this SLR is restricted to a limited time. Nonetheless, including the aforementioned papers would have enhanced the SLR conclusion.

7. CONCLUSION AND FUTURE WORK

In recent years, tuning PID and FOPID controllers' gains has become usable by many authors. Therefore, many novel controller problems have been proposed and solved using various metaheuristics techniques. It can be concluded that there are mainly four metaheuristic algorithms that are mostly used in enhancing the tuning process. In addition, in both cases, PSO was the most applied and efficient technique amongst others.

For the future work, including a comparison between the most efficient output and statistics for every algorithm when it is applied to any problem in the tuning of PID and FOPID controllers' gains could be done. Moreover, such new techniques proposed in 2021 could be included also, because these algorithms can enhance and make this SLR more generic. Moreover, new algorithms especially the hybrid ones like GWO-PSO come across very efficient, consequently, there might be change of direction in with utilizing more hybrid while tuning either PID or FOPID controllers.

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