Real-Time Optimization for an AVR System Using Enhanced Harris Hawk and IIoT

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Abstract: Recently, several research studies have used standard metaheuristic optimization algorithms rather than traditional algorithms and the Ziegler-Nichols (Z-N) method for tuning PID controller parameters. However, these studies have directly implemented these algorithms in order to configure the cascade control system one time. This paper presents a novel real-time monitoring and optimization architecture based on the Enhanced Harris Hawk Algorithm (EHHOA) and the Industrial Internet of Things (IIoT) for tuning the PID controller parameters for an Automatic Voltage Regulator (AVR) system. The EHHOA is based on a Chaotic map and an opposition-based learning technique that is linked to the IIoT layers. The proposed algorithm was implemented through Simulink in the MATLAB environment and it was compared with the Z-N method, the classical HHO/PID algorithm and the PSO/PID algorithm. The simulation results show that the proposed algorithm managed to enhance tuning with an insignificant difference in comparison with the other employed algorithms and EHHOA gave satisfactory results in adjusting the parameters of the PID controller, especially in IIoT real-time scenarios.

Keywords: EHHOA, PID controller, IIoT, PSO, HHO.

1. Introduction

Nowadays, real-time optimization and monitoring of an industrial control system are essential in the Fourth Industrial Revolution (4IR). Especially, the data exchange between various devices has become a primary component of operation processes in smart factories. The data exchange shows the state of production, the rate of energy consumption, the lack of materials, customer requests, and product quality, etc. (Lin et al., 2017). Consequently, the necessity of using modern technology such as Artificial Intelligence, Big Data, Machine-to-Machine (M2M) Communication and wireless technology was raised. Hence, the 4IR is a stable concept that represents a game-changer for the current production systems, because of the convergence between new automation technologies and information technology.

On the contrary, the AVR system (Karimi-Ghartemani et al., 2007; Sahib & Ahmed, 2016; Gaing, 2004; Li et al., 2017) is one of the major components in the field of industry 4.0 , which is used for the supply of a constant voltage circuit. However, A PID controller (Ang et al., 2005) is a type of control loop that can be used in a variety of industrial problem situations. It is utilized in industrial control systems to gain the mechanism feedback (Yu, 1999; Åström & Hägglund, 1995).

Most researchers had used the PID controller in the AVR system to control the stability of the terminal output voltage (Er & Sun, 2001). Many traditional PID tuning methods are applied, such as the (Z-N) (Ziegler & Nichols, 1942), Cohen-Coon (Cohen & Coon, 1953), IMC (Skogestad, 2003) etc. The Ziegler-Nichols is considered to be the most widely used method. Nonetheless, it does not provide the appropriate tuning for the PID controller because the output tends to largely overshoot.

Thus, various optimization algorithms, such as Genetic Algorithms (GA), and Swarm Optimization (SO) were utilized. These systems were improved in selecting the appropriate parameter values instead of the traditional methods.

Currently, SI-inspired optimization approaches have classical Particle Swarm Optimization (PSO) (Kennedy & Eberhart, 1995; Hu et al., 2011) and Ant Colony Optimization (ACO) (Socha & Dorigo, 2008). And, Artificial Bee Colony (ABC) (Karaboga, 2005), Bacterial Foraging algorithm (BFO) (Passino, 2002), Simulated Annealing (SA) (Lahcene et al., 2017), Sine Cosine Algorithm (SCA) (Ekinci et al., 2019), and Butterfly Optimization Algorithm (BOA) (Arora & Singh, 2015) have been developed.

PID optimization is the process of selecting the best settings for system parameters from a large number of options to optimize output or decrease error. Swarm algorithms are known to simulate swarm behaviour, as many creatures, such as fish, birds, bees, and ants, behave in groups. Individuals in the group may have limited potential, but the group as a whole has a strong vitality.

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AVR has received significant interest from researchers and scholars as they have applied various algorithms, Karimi-Ghartemani et al. (2007) were the first to use particle swarm optimization (PSO) in tunning the AVR system. Meanwhile, there are several studies focused on tuning PID controllers using standard swarm optimization algorithms through different systems which were compiled in (Zamani et al, 2009). Due to the development in industry and compactional techniques, Li et al. (2017) and Zamani et al. (2009) developed and redesigned circuits of a PID control system by using a similar standard PSO. With advances in the era of artificial intelligence and optimization techniques, Khan et al. (2019) applied Salp algorithm Based on Fractional Order PID (FOPID) Controller Order to the tuning parameters of related to the same system. Also, various optimization algorithms were applied in many industrial systems, Zhao et al. (2021) suggested a vehicle suspension tuning approach based on the PSO algorithm to optimize PID control settings, intending to evaluate the vehicle's ride comfort after the function that integrates vertical acceleration and suspension was installed.

Ekinci et al. (2020) proposed a novel approach that improves the selection of the DC motor parameters using PID controller Cruise control system. The cascade control system has been redesigned to improve system robustness, efficiency, and stability. It also presents a comparison of different analyzes between HHO / PID Control and other controls such as SCA/PID (Hekimoğlu, 2019), and GWO/PID (Agarwal et al., 2018).

Maghfiroh et al. (2021) have proposed a model for improving the selection of PID control parameters, using swarm optimization based on a DC motor to reach the best engine speed control and power control. Ribeiro et al. (2017) and Ferreira et al. (2016) used various optimization algorithms, such as optimize bacterial search, ant colony, bat algorithm and bee swarm optimizations to tune PID parameters. The motivation of this study is to outline, display and assess a stage tank tool for a SMAR training area. The optimization aim is to decrease integral errors and reduce transient response by lowering overshoot, settling time, and rising time of step response. After defining an objective function, the optimal controller settings may be assigned by minimizing the objective functions using real-coded EHHOA.

Based on the preceding overview of the continued advancement recorded in the industry and challenges in PID optimization tuning, the contributions of the proposed analysis are the following :

- Introducing a novel prototype of real-time optimization framework based on IIoT techniques to show the adaption of Optimization algorithms in factory.
- Introducing and applying a new version of Harris Hawk Optimization Algorithm (EHHOA-PID) which uses Chaotic map (CM) and opposition-based learning (OBL) techniques to improve the diversity of the population in classical HHO.
- Ensuring the dynamic response of the optimized PID parameters with comparison between popular swarm algorithms and traditional tuning methods.

The remainder of this paper is organized as follows in order to meet the aforementioned goals. Section 2 provides an overview of the most important methods as well as a survey for the maximum paper application. Section 3 presents the proposed real-time architectural model using IIoT and introduces the EHHOA optimization algorithm. Section 4 is devoted to experimental simulation and quality, while Section 5 concludes this paper.

2. Materials and Methods

2.1 An overview of IIoT

Industrial Internet of Things (IIoT) is basically the communication between machines (M2M) and independent work based on the information exchanged with each other. It can also be applied to all industries and allows the network system to work with other systems to provide the necessary data and information, for example about any problems in the condition of equipment, etc. IIoT is an evolution of the classic term "Internet of Things" (Miller, 2018) that is based on the same principles but aims directly to connect machines in factories.

The architecture of the Internet of Things system consists of many servals of hardware and software. The first stage is by sensing to collect data through sensors (WSN Nodes). Then, data is sent using the edge node, and gateways and switched to the cloud intranet as it is shown in Figure 1. Therefore, a real-time model application can be applied using IoT instead of an independent tuning system that can be sent to the cascade control system by tuning the parameters of PID controller and variable reception of a response from different systems.

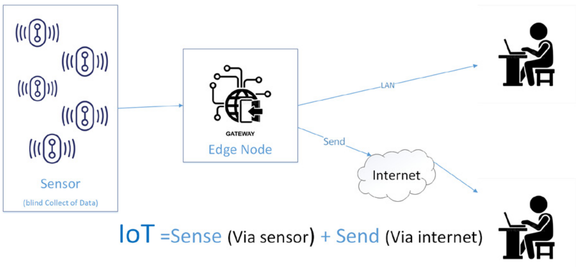

Figure 1. Internet of Things operation cycle

Despite advances in 4IR there are a lot of advantages of IIoT, some of which are listed below:

- Predictive & Proactive maintenance
- Real-Time Monitoring
- Asset/Resource Optimization
- Remote Diagnosis

In recent years, the trend of most business companies and factories has been to do business while developing the Internet of Things to get the latest technology in their business. As a result, new challenges and opportunities have emerged. It has been demonstrated that in the future, 72% of these companies may lose market share if they fail to embed a big data strategy. Some of the challenges faced by the IIoT (Chen et al., 2017) are illustrated in Figure 2.

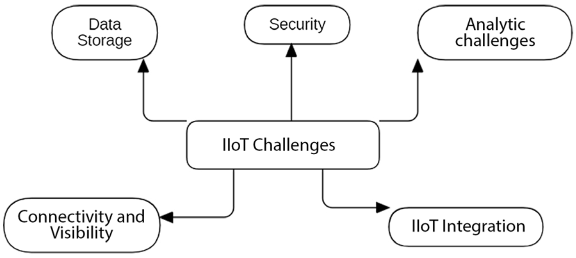

Figure 2. The main challenges in IIoT

2.2 An Overview of PID Control

A proportional-integral-derivative controller (PID controller) is a type of industrial control loop feedback system. The difference between the measured plant variable and the desired set-point is calculated by a PID controller as an "error" value. The controller adjusts the process control inputs in an attempt to reduce the fault. The basic construction of a closed-loop controller is shown in Figure 3, where R, E and Y are the reference, error, and controlled variables, respectively.

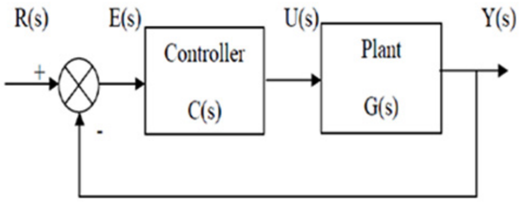

Figure 3. General diagram of the common feedback control system

$G(s)$ is the plant transfer function, and $C(s)$ is the PID controller transfer function.

$$C(s) = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

The PID controller's differential equation is as follows:

$$U(s) = K_p e(t) + T_i \int e(t)dt + T_d \times de(t)dt + P_0 \tag{2}$$

where K_p, K_i and K_d denote the proportionate, integration, and derivative gain, respectively. T_i stands for integral time. T_d stands for derivative time. The tracking error, which is the difference between the desired input value and the actual output, is represented by the variable $e(t)$.

2.3 An overview of Stranded Harris Hawk Optimization (HHO) Algorithm

Heidari et al. (2019) introduce a new proposed algorithm named Harris Hawk Optimization that simulates the behavior of hawk in cooperative treatment and chasing techniques. Hawk hunt their prey (rabbits) using a technique called "surprise pounce" which involves applying some approaches (tracing, approaching, and attacking). Harris Hawk optimization (HHO) algorithm quite simulates the hunting behaviour of an intelligent hunter desert bird attacks using one of the following attack mechanisms: with soft besiege, hard besiege with progressive rapid dives and soft besiege with progressive rapid dives.

Harris hawk hunting for prey, search in the optimization process pursuing prey while considering the discovery of the field attacks of the regions that offer a better solution, is considered an exploit (Passino, 2002).

Heidari et al. (2019) divide Hawk, a mathematical model, into 3 phases: exploration, the transition between exploration and exploitation, and exploitation. The population is randomly initialized first. Then, the next equation is used:

$$X(t+1)=\begin{cases} X_{rand}(t)-r_1\left|X_{rand}(t)-2r_2X(t)\right| & q\geq 0.5 \\ (X_{rabbit}-X_m(t))-r_3(l_b+r_4(u_b-l_b)) & q<0.5 \end{cases} \quad (3)$$

where t is the current iteration, r_1, r_2, r_3, r_4 and r_5 are random numbers, $X_{rabbit}(t)$ denotes the position of rabbit/prey and u_b, l_b denote the upper and lower bounds of variables.

The following equation is used to determine x_m.

$$X_m(t)=\frac{1}{T}\sum_{i=1}^{T}x_i(t) \quad (4)$$

where T refers to the maximum iteration number. The next stage is the transition between exploration and exploitation. To model the energy of the prey the following equation is used:

$$E=2E_0\left(1-\frac{t}{T}\right) \quad (5)$$

where E and E_0 are the prey energy and its initial value, respectively. Note that exploration happens if $E\geq 1$. Otherwise, exploitation happens. There are 4 different scenarios for attacks:

Soft besiege: $r\geq 0.5, |E|\geq 0.5$. The following equation is used:

$$X(t+1)=\Delta X(t)-E\left|X_{rabbit}-X(t)\right| \quad (6)$$

$$\Delta X(t)=X_{rabbit}(t)-X(t) \quad (7)$$

where ΔX represents the difference between the prey's previous and current position.

Hard besiege: $r\geq 0.5, |E|<0.5$. The following equation is used:

$$X(t+1)=X_{rabbit}(t)-E\left|\Delta X(t)\right| \quad (8)$$

Soft besiege with rapid divide $r<0.5, |E|\geq 0.5$. The following equation is used to model escaping pattern where LF refers to Levy flight:

$$X(t+1)=\begin{cases} X_{rabbit}(t)-E\left|JX_{rabbit}-X(t)\right| & F(Y)<F(X(t)) \\ Z=Y+S\times LF(D) & F(Z)<F(X(t)) \end{cases} \quad (9)$$

Hard besiege with rapid divide $r<0.5, |E|<0.5$. The following equation is used:

$$X(t+1)=\begin{cases} X_{rabbit}(t)-E\left|JX_{rabbit}-X_m(t)\right| & F(Y)<F(X(t)) \\ Z=Y+S\times LF(D) & F(Z)<F(X(t)) \end{cases} \quad (10)$$

Also, many scholars have proposed modifications and improvements in using Harris Hawk in optimization. For example, the elite opposite-based learning (EOBL) technique, Sihwail et al. (2020) developed a novel search mechanism to improve HHO. By integrating Opposition-Based Learning (OBL), a Chaotic Local Search (CLS) technique, and a self-adaptive strategy, Hussien & Amin (2022) presented IHHO algorithms to improve algorithm resilience and convergence acceleration. In Chemoinformatics, Houssein et al. (2020) presented CHHO-CS, a hybrid method that combines Harris Hawk with chaotic maps and cuckoo search (CS) for drug design and discovery. Kaveh et al. (2022) proposed novel algorithms for structural optimization called ICHHO based on hybridizing HHO using a competitive imperialist algorithm.

All of these studies have shown that HHO is an excellent investment. As a result, Section 3 of this paper focuses on HHO in order to increase the controllability of the cascade control system. this paper proposes a novel approach based on IIoT to improve the performance of real-time self-tuning PID controllers for AVR systems (EHHOA).

3. The Proposed Model

Despite the attempts of many researchers to automatically adjust the PID control parameters using various swarm optimization algorithms, there is still a gap in improving the results with improved optimizations connected with online server and the use of a new IIoT technique to achieve a real-time optimization in tuning any control system. In this section, a new real-time optimization architecture using a new version of Harris Hawk algorithms is described in detail.

3.1 Enhanced Harris Hawk Optimization Algorithm (EHHOA)

The original HHO suffers from local optima and a slow convergence curve whereas applying works on more intricate system optimization. As a result, this paper introduces the Enhanced HHO (EHHOA), a novel form of HHO that improves the diversity of the population using Chaotic Map (CM) and Opposition-Based Learning Techniques (OBL). Figure 4 displays a comprehensive flow chart of the EHHOA operations as intended.

Chaos is a random phenomenon that exists in almost all non-linear and deterministic systems as it is very sensitive especially to the initial values. Many chaotic maps existed in literature such as

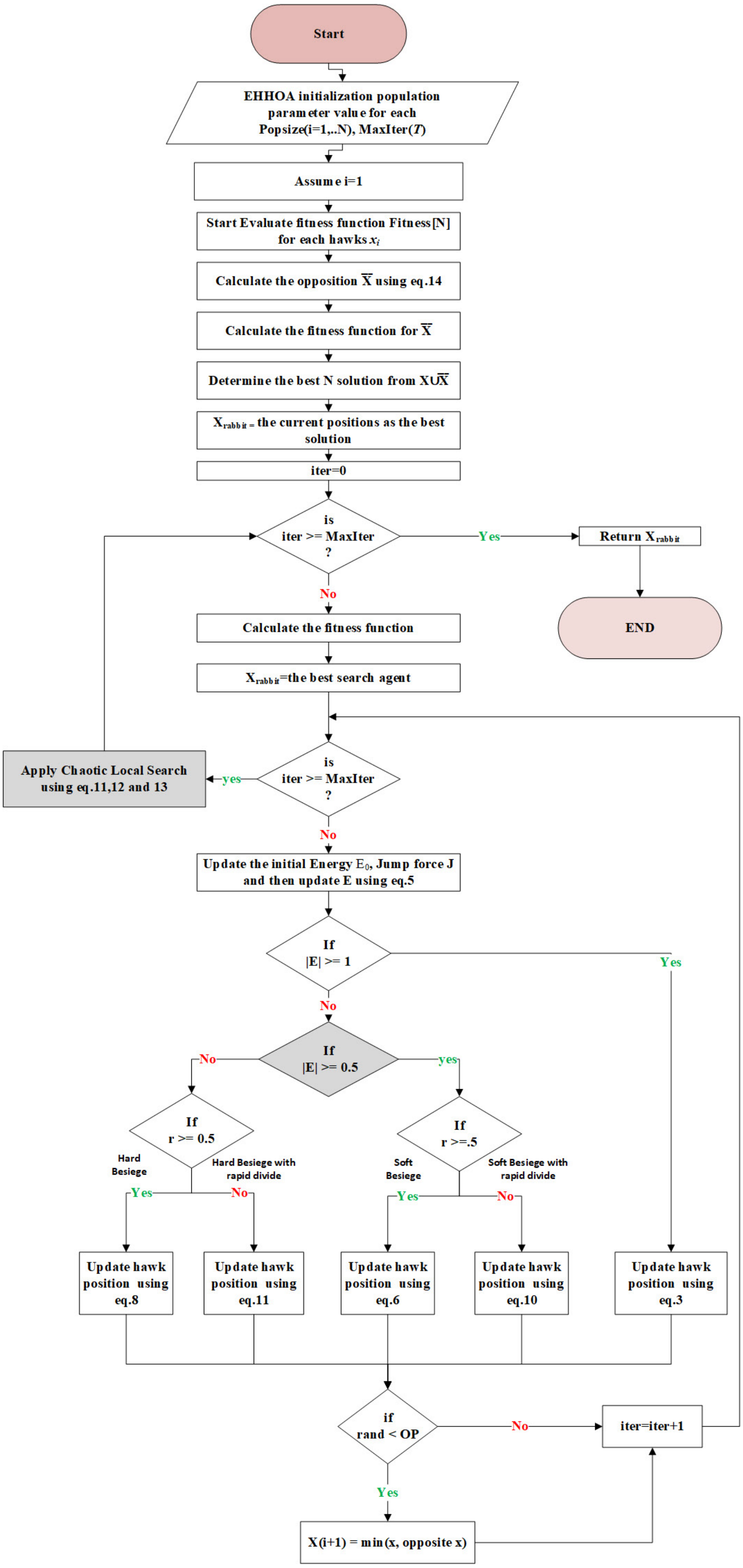

Figure 4. Enhanced Harris Hawks Optimization Algorithm (EHHOA) process flowchart

Sine, Circle, Piecewise, Logistic, etc. Here, the logistic map is used for creating a chaotic sequence.

$$O^{s+1} = CO^{s}(1-O^{s}) \tag{11}$$

The initial values can be set for the initial parameters: $c = 4, O^{s} = rand(0,1)$, and $C_1 \neq 0.25, 0.5$ and 0.75. Chaotic Map technique can be implanted in HHO as follows:

$$C_s = (1-\mu)*T + \mu C_i' \tag{12}$$

where C_s denotes the optimum solution and T denotes the goal position and could be calculated using the formula:

$$\mu = \frac{MaX_{Iter} - Curr_{Iter} + 1}{MaX_{Iter}}, \tag{13}$$

where Max_{Iter} refers to the Maximum number of iterations in process and $Curr_{Iter}$ is the current iteration. Opposition-Based Learning was introduced by Tizhoosh, which calculates the fitness of each individual, computes its corresponding solution and transfers the better of them to the next iteration. OBL can be calculated using

$$\overline{X} = u_b + l_b - x, \tag{14}$$

where $x = (x_1, x_2, ..., x_d)$ and l_b and u_b denote the lower bound and upper bound, respectively. Finally, the current solution is currently being implemented by $\overline{x}$ if $f(\overline{x}) \leq f(x)$.

Algorithm 1: Pseudo code Enhanced Harris Hawk Optimization Algorithm

```
Initialize population parameters $Popsize(x_i)$, i=1,2,..N , $Max_{Iter}(T), l_b, u_b$ and Dim
Assume $i = 1$
  Start evaluate fitness function $Fitness[N]$ for each hawk $x_i$
Calculate the opposition $X \to \overline{X}$ using Eq.14 and calculate fitness function
Determine the best N solution from $X \cup \overline{X}$
$X_{rabbit}$ = the current positions as the best solution
Set $Iter = 0$
While ($Iter \leq Max_{Iter}$) do
  calculate the fitness function for each hawk $x_i$
  $X_{rabbit}$ =the best search agent
  for each hawk ( $x_i$ ) do
    Update the initial Energy $E_0$, jump force $J$ and then update $E$ using Eq.5
    if ( $|E| \geq 1$ ) then
      Update hawk position using Eq.3
    end if
    if ( $r \geq 0.5$ and |E| ≥ 0.5 ) then
      Update hawk position by Eq.6
    else if ( $r \geq 0.5$ and |E| < 0.5 ) then
      Update hawk position by Eq.8
    else if ( $r < 0.5$ and |E| ≥ 0.5 ) then
      Update hawk position by Eq.10
    Else
      Update hawk position by Eq.11
    End if
  End for
  if ( $rand < OP$ ) then
    Calculate $\overline{X}_{i+1}$ and its fitness
    $X_{i+1} = \overline{X}_{i+1}$ if $f(\overline{X}_{i+1}) < f(X_{i+1})$
  End if
End while
Update $X_{rabbit}$
Apply Chaotic Local Search using eq.11,12 and 13
Return $X_{rabbit}$
End
```

3.2 The Proposed Real-Time System Architecture of Tuning PID Control Using IIoT

The proposed model is based on how to use EHHOA optimization algorithms to automatically increase the performance of a real-time self-tuning PID controller for the AVR system to the cascade control system. Figure 5 illustrates the proposed architecture of the IIoT-enabled PID system in which users can control and display feedback for system operations using the IIoT layers. The proposed real-time optimization architecture consists of two levels namely the supervisory level and control level. At supervisory level the user can control the system by giving the setpoint value and duration time of process using the Graphical User Interface (GUI), it can also find an Internet protocol layer that can access and make encryption/decryption over the Internet.

By connecting it to "CC3200" kit, which is directly interfaced with the cascade control system, the control level, on the contrary, can implement system tuning. Model predictive control is used to correct time delays connected with Internet connection, such as feed-forward and feedback, so that the proposed optimization algorithm will select the value of K_i, K_p and K_d to cascade control all of these values that connected online broker server to manage feedback and control which fulfills the principle of real-time optimization.

This section will implement the PID control model based on the Enhanced Harris Hawk compared with Harris Hawk (Heidari et al., 2019) and PSO (Gaing, 2004; Zamani et al., 2009) parameter tuning.

3.3 Implementation of EHHOA with PID Control Model

In order to implement the suggested optimization algorithm EHHOA, some parameters must be selected, which determine the ability of an algorithm to converge at a global minimum or maximum. The number of search agents, the number of iterations, and the number of variables are all input parameters for various algorithms. The basic settings for each algorithm are shown in Table 1.

Table 1. Initialize the parameters of the proposed EHHOA algorithm

Parameter	Value
Number of hawks (POPU. size)	50
Maximum number of iterations	50
Constant of levy flight function β	1.5
Dimension of optimization problem (D)	3
Lower bound for [K_i, K_p, K_d]	[0.001, 0.001, 0.001]
Upper bound for [K_i, K_p, K_d]	[5,5,5]
Chaotic initial parameter (C)	4

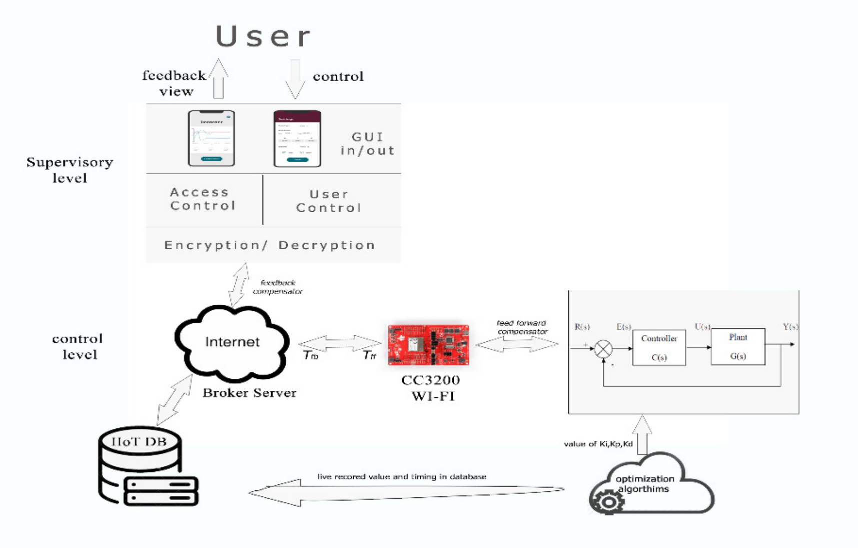

Figure 5. Outline of the proposed new real-time model for the cascade control system

The architecture of the proposed algorithm model is shown in Figure 6.

The enhanced Harris Hawk algorithm (EHHOA) was independently run 50 times. The obtained EHHOA-based PID controller parameters are: K_i = .87635, Kp = .56776 and Kd = .65356 and that as they are illustrate in Table2 after successful finalization of the optimization process.

The model was designed using MATLAB@2013 using Simulink models, and the system block design shown in Figure 7 and in Figure 8 there is a sub-system to block which contains the transfer function for the AVR system.

4. Experimental Results

This section contains a block diagram for the AVR system, as well as the optimization method for the PID controller's K_p, K_i, and K_d parameters, as well as the PID controller's implementation and testing findings, in addition to several techniques for evaluating performance criteria.

The MATLAB 2013a/Simulink environment software package was loaded on a PC with an Intel® i5 2.50 GHz processor and 16.00 GB of RAM, and the simulations of transient response and robustness analysis for HHO, PSO, Z-N, and EHHOA were carried out.

In Figure 9 there's a display of a comparison of the obtained findings and step response with various optimization strategies available in the literature, highlighting the benefits of the proposed EHHOA/PID tuning optimization algorithm. The Z-N/PID tuning method is, in fact, the most direct. Nevertheless, it causes overshoot, especially system time delay. The system response of the HHO/PID also has little overshot which is better than in the case of the Z-N method. In addition, PSO/PID system response provided quick system

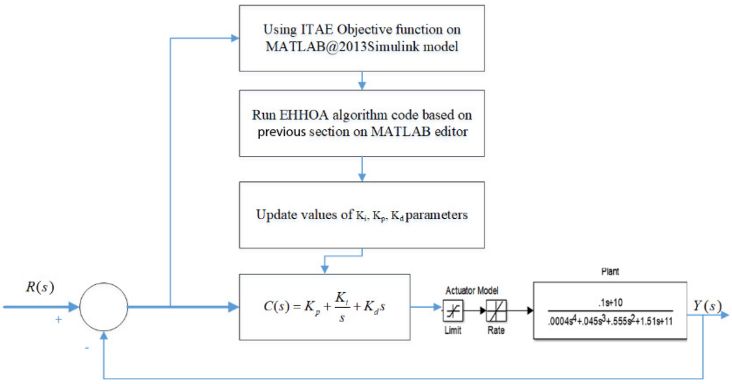

Figure 6. Implementation of the EHHOA/PID model architecture for the AVR System

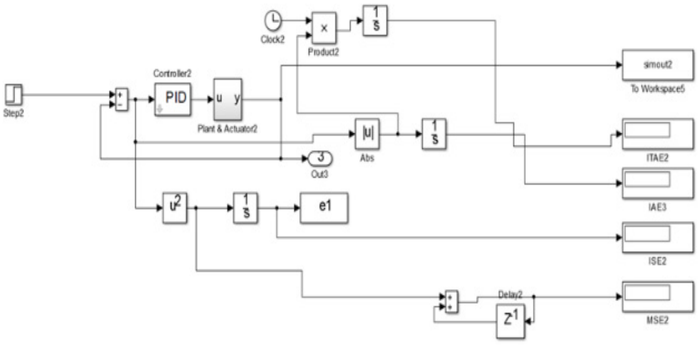

Figure 7. System Block Diagram from MATLAB/Simulink

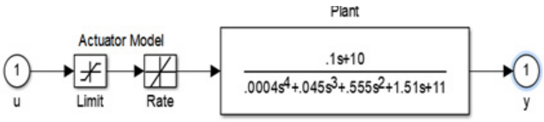

Figure 8. Diagram of the transfer function for a sub-system of AVR

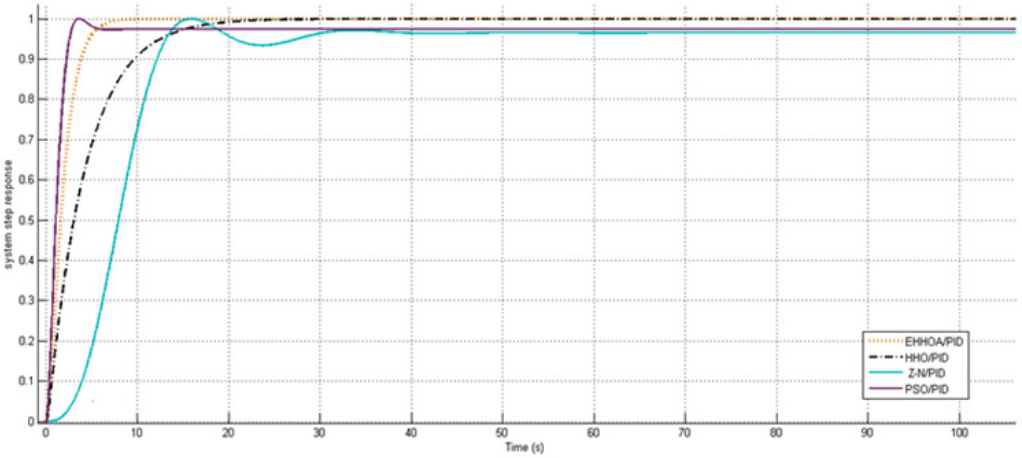

Figure 9. Comparison of step responses for various tuning optimization algorithms

stability and is better in the rise time as well as settling time, but cannot achieve optimal desired point and has peak overshoot.

Therefore, the simulation results show that the curve of the proposed EHHOA/PID algorithm is the best one for system response and is the real-time system achieved for the desired point.

To compute performance index statistics results for all runs, EHHOA and other comparative approaches were run independently for 50 times. Furthermore, the majority of researches employ four key error criteria to represent system performance: Integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time square error (ITSE). Table 2 illustrates the results obtained by these methods with regard to the overall performance of any system in the control unit and the time domain specifications as a quantitative measure. The gain parameters of the employed controllers are also included in Table 2.

Figures 10 to 13 show the bar plots for the percentage overshoot, rise time, settling time, and steady-state error for the four above-mentioned system optimization strategies.

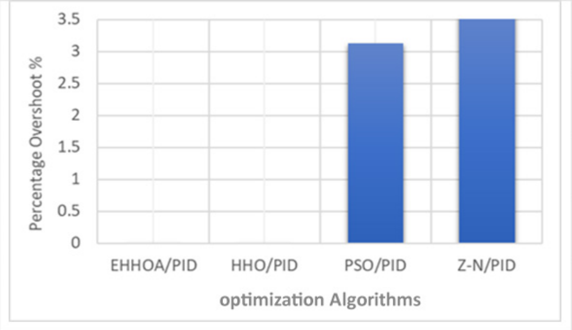

Figure 10. Overshoot Percentage chart for the employed optimization approaches

Table 2. Average values measurements for standard performance using the PID controllers tuned by various algorithms and the proposed algorithm

Methods/Performance Index			IAE	ITAE	ISE	ITSE
Z-N/PID tunning method	K_i	4.6978	704	3.512e+04	3.767e+05	1770.98
	K_p	1.9098				
	K_d	1.3847				
PSO/PID	K_i	1.8898	150	1.565e+02	1.002+06	54.909
	K_p	1.1453				
	K_d	.98754				
HHO/PID	K_i	1.0688	94.46	4712	6925	89.24
	K_p	.0504				
	K_d	.6300				
EHHOA/PID	K_i	.87635	7.113	36.02	313.8	5.153
	K_p	.56776				
	K_d	.65356				

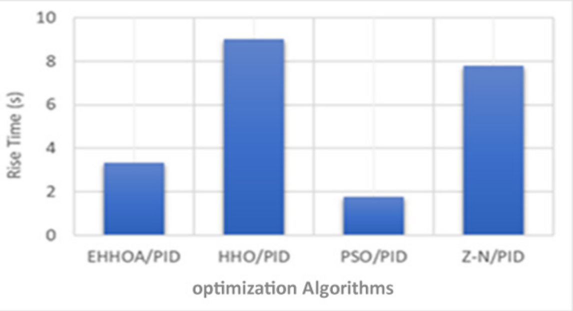

Figure 11. Rise Time chart for the employed optimization approaches

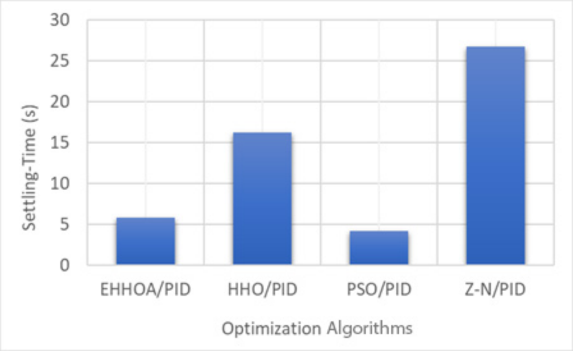

Figure 12. Settling Time chart for the employed optimization approaches

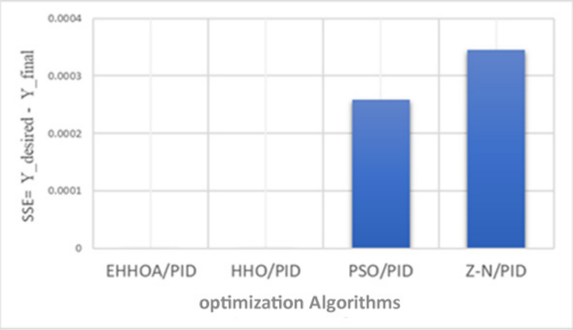

Figure 13. Steady State Error chart for the employed optimization approaches

A time domain definition is demonstrated in Table 3 based on the statistical findings produced by tuning PID controllers using various techniques. The approach based on EHHOA is clearly faster, it has a lower overshoot, and has a shorter settling time than any of the other employed methods. With the EHHOA-based technique, the response speed and control effect were significantly enhanced.

Table 3 shows that the EHHOA-based controller has a better overall time-domain performance. Performance comparisons with numerous current techniques were done utilizing transient response analysis and robustness analysis in order to verify the efficiency of the proposed EHHOA/PID controller. As it can be seen in Table 3, the PSO/PID, HHO/PID, and Z-N/PID approaches were chosen for this comparison.

The simulation results for the stability and efficient performance show that the EHHOA/PID controller is a better tuning method than the HHO/PID, PSO/PID and Z-N/PID controllers compared to cascade control system. Robustness analysis is related to a system's ability to sustain changes in its parameters. The uncertainties related to the AVR component system time constant are analysed. (T_{sensor},$T_{Ampilfier}$,$T_{generator}$,$T_{Exciter}$). A 50-percent variance in the rating values of the given time constants with a step size of 25% is created to attain the purpose of optimization. The related step response curves are shown in Figures 14 to 17.

To ensure the real-time response for system stability and robustness, control must be tested on a multi-sequential set-point, consequently such a system was tested on 3 different points as it is shown in Figure 18 in comparison with the standard Harris Hawk and Z-N algorithms. The results of the simulation and performance analysis show that the EHHOA/PID controller is a better tuning method than the HHO/PID and Z-N/PID controllers.

It's necessary to evaluate the results of the proposed EHHOA/PID algorithm in terms of stability and of dynamic performances in real-time control exploitation in comparison with the various traditional algorithms.

Table 3. Time domain specifications generated by tuning PID controllers using various algorithms

Time/Specification domain	Z-N/PID tuning method	PSO/PID algorithm	HHO/PID algorithm	EHHOA/PID (proposed)
Overshoot (%)	3.5778	3.1236	No Overshoot	No Overshoot
Rise time (s)	7.794	1.772	9.021	3.339
Peak time (s)	15.864	3.645	No peak	No peak
Settling time (s)	26.683	4.202	16.234	5.854
Steady state error	.0345	.0259	0	0

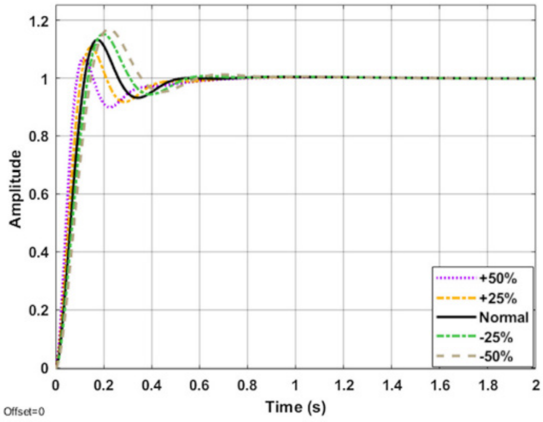

Figure 14. Step response curves for TA from -50 to 50%

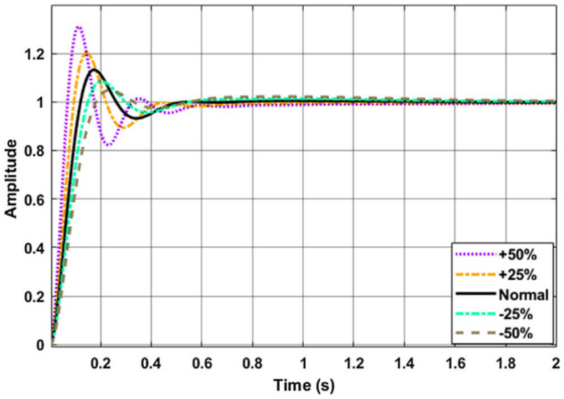

Figure 16. Step response curves for TG from -50 to 50%

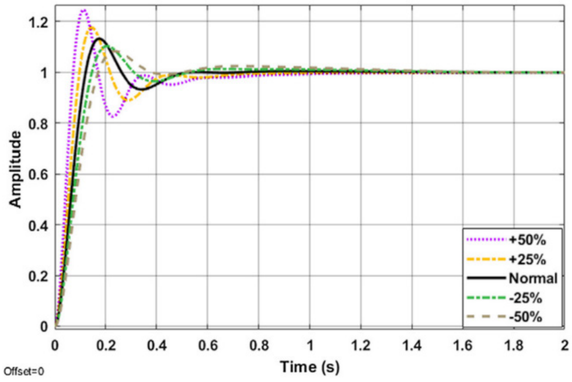

Figure 15. Step response curves for TE from -50 to 50%

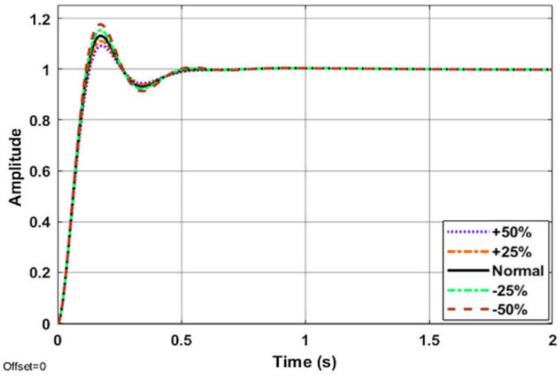

Figure 17. Step response curves for Ts from -50 to 50%

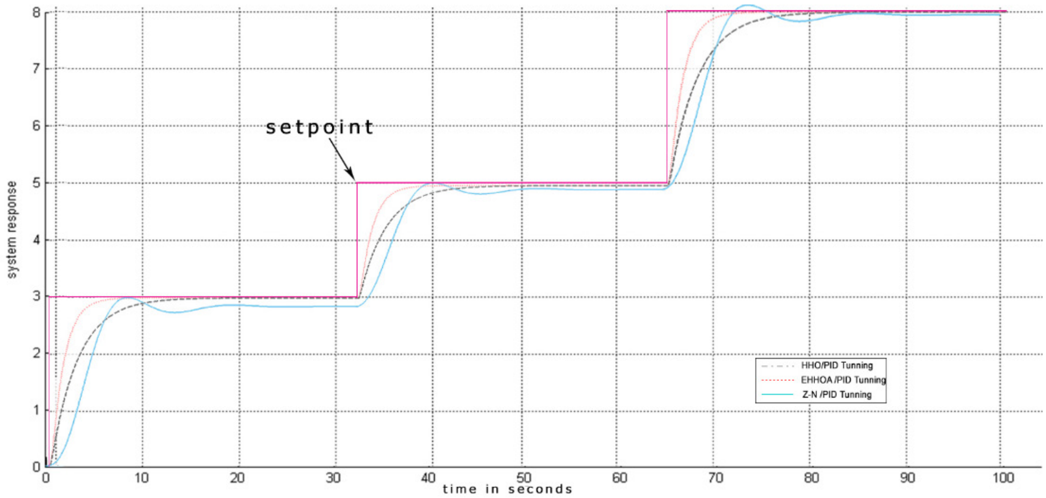

Figure 18. Performance analysis of Z-N/PID, EHHOA/PID and HHO/PID tuning at various operating points

Table 4 shows the optimal solution results of the proposed algorithm and other algorithms in real-time optimization. The performance of the proposed algorithm was evaluated for 12 benchmark problems chosen from literature. The simulation results for the proposed algorithm and the three other algorithms demonstrated the effectiveness of the proposed algorithms in real-time for benchmark optimization.

5. Conclusion

One of the most important challenges in the Fourth Industrial Revolution industry field is data and the continuous development using modern technology. From this perspective, the Enhanced Harris Hawk optimization algorithm and IIoT techniques were applied to the most used component of an AVR system. This paper presents

Table 4. The optimal solution results for the proposed algorithm and the other three algorithms

ID	Algorithm	Best	Worst	Median	Average	STD
F1	**Z-N/PID**	308.2456	1496.136	3267.126	3267.126	4246.822
	PSO/PID	2122580.2	3303439.2	5118398	51183981	44448371
	HHO/PID	21225803	3136.197	3615.217	3515.217	3694.592
	EHHOA/PID	946.67259	3944.208	3944.208	4320.079	2587.169
F2	**Z-N/PID**	0	0	0	0	0
	PSO/PID	0	0	0	0	0
	HHO/PID	0	0	0	0	0
	EHHOA/PID	0	0	0	0	0
F3	**Z-N/PID**	300	300	300	300	3.19E-07
	PSO/PID	2108.9402	22578.087	3992.327	6016.056	5175.158
	HHO/PID	2108.934	553.0946	336.0311	351.9874	60.95221
	EHHOA/PID	300.00026	300.0135	300	300.0009	0.00305
F4	**Z-N/PID**	400.2762	406.4312	403.7745	403.0263	2.158708
	PSO/PID	407.7791	563.3884	411.8474	445.8044	53.72375
	HHO/PID	407.7791	406.155	405.1933	404.7927	1.218841
	EHHOA/PID	404.19418	408.2303	405.7141	405.2344	1.761902
F5	**Z-N/PID**	525.869	577.6307	534.326	539.4732	18.60687
	PSO/PID	541.7889	586.5452	552.5374	555.4925	16.46151
	HHO/PID	541.7889	521.8991	511.4803	512.518	5.314397
	EHHOA/PID	523.39745	565.6667	536.3159	536.7357	14.41524
F6	**Z-N/PID**	604.1243	631.77	610.5965	612.658	9.789651
	PSO/PID	632.4178	669.2541	638.3776	639.1642	12.69702
	HHO/PID	632.4178	600.0397	600.0018	600.0039	0.008619
	EHHOA/PID	606.89526	664.2668	624.1763	623.7979	17.04332
F7	**Z-N/PID**	750.0333	800.2865	763.4635	764.1849	16.53892
	PSO/PID	772.9736	847.5869	793.4636	792.6721	23.35112
	HHO/PID	772.9736	740.8953	725.2596	726.0932	9.138484
	EHHOA/PID	744.14382	825.2143	772.1789	770.9763	27.35464
F8	**Z-N/PID**	820.8941	864.6718	828.8537	831.873	12.90815
	PSO/PID	835.4478	894.0145	842.7488	845.4111	15.93723
	HHO/PID	835.4478	822.884	811.4466	812.7699	5.127114
	EHHOA/PID	825.86888	867.6564	831.1175	836.8516	15.70172
F9	**Z-N/PID**	933.0708	2050.989	1106.709	1227.608	344.9987
	PSO/PID	1068.03	2003.276	1244.185	1324.466	302.6735
	HHO/PID	1068.03	900.9107	900	900.0955	0.245944
	EHHOA/PID	961.34396	1969.029	1110.379	1176.302	284.5671
F10	**Z-N/PID**	1898.049	2448.151	2062.364	2047.175	221.7145
	PSO/PID	022.64	2867.226	2242.572	2204.926	396.7856
	HHO/PID	2022.64	2027.393	1501.675	1535.13	251.2706
	EHHOA/PID	1698.2082	2713.746	2149.467	2081.553	392.1674
F11	**Z-N/PID**	1130.47	1326.676	1142.507	1170.421	57.90485
	PSO/PID	1164.94	1388.425	1230.57	1245.814	79.42272
	HHO/PID	1164.94	1123.327	1106.585	1107.871	5.072009
	EHHOA/PID	1137.9006	1236.306	1163.346	1164.88	34.34812
F12	**Z-N/PID**	6797.742	62694.31	13409.94	20867.36	18432.64
	PSO/PID	245965.6	13451165	1329347	4009393	4284488
	HHO/PID	245965.6	892221	18180.07	84984.78	207174.6
	EHHOA/PID	9863.9141	61694.72	18109.56	25057.7	19056.18

a novel real-time monitoring and optimization architecture based on Enhanced-Harris Hawk Algorithm and Industrial Internet of Things to tune PID controller parameters for an AVR system. The results of the analysis carried out in this paper are presented in the included Tables and Figures. The simulation results obtained for EHHOA-PID confirmed its superior performance and effectiveness in comparison with the other three algorithms employed.

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