ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Heat recovery steam generator (HRSG) three-element drum level control utilizing Fractional order PID and fuzzy controllers

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ARTICLE INFO

Article history:
Received 3 February 2020
Received in revised form 5 April 2021
Accepted 28 April 2021
Available online xxxx

Keywords:
Three-element
Level control
Fractional-order PID
HRSG
CCGT
Shrink and swell
ABC algorithm
Fuzzy logic control

ABSTRACT

Shrink and swell is a phenomenon that causes transient variability in water level once boiler load variation occurs. The leading cause of the swell effect is the steam demand changes and the actual arrangement of steam generating tubes in the boiler. Steam bubbles beneath HRSG drum water make the level control very difficult, particularly with significant disturbances in the input heat to HRSG. Plant shutdown may occur in some situations, and combined cycle plant efficiency is diminished. The recently applied control methods in industry are single-element and three-element control with PID controllers, but these methods are not well suited for substantial load changes. The main aim of this paper is to investigate the shrink and swell phenomenon inside HRSG power plants. In addition to the existing PID loops, two different standalone controllers, namely, the FOPID controller and fuzzy controller, are implemented with the HRSG model. Besides, Artificial Bee Colony (ABC) algorithm is used to tune FOPID efficiently. Based on overshoot, rise time, ISE, IAE, ITAE as performance measures, the comparison has been held between the three controllers. Simulations show that how the ABC optimization algorithm is efficient with PID, FOPID. It turns out that the proposed method is capable of improving system responses compared to the conventional optimal controller.

1. Introduction

From the U.S. Energy Information Administration (EIA) [1], the most efficient Energy conversion system to produce electrical and thermal energy is the combined cycle gas turbine (**CCGT**). The rise in efficiency merely is from the waste heat recovery section of the unit or heat recovery steam generator (HRSG). In 2016, GE company manufactured a CCGT with an efficiency of 62.22% - recorded in the Guinness World Records as the most efficient combined-cycle plant at that time [2]. As the name combined cycle implies, this type of power plant consists of a mixture of gas and steam power generation technologies. A CCGT is based on the simple premise that a gas turbine generates both power and hot exhaust gases. The hot gasses are used to create steam, and the steam runs a steam turbine to generate extra power. A CCGT uses both gas and steam turbines to generate near 50% more electricity than a traditional single-cycle plant from the same fuel [3,4].

As shown in Fig. 1, HRSG, which is the most critical component of the combined plant, incorporates Brayton and Rankine cycles [3]. To maximize the heat exchanged and improve the performance of the CCGT [5], HRSG must carefully be designed and controlled in different situations [5].

The HRSG works like a heat exchanger or a group of heat exchangers. The tubes are arranged in sections known as economizers, evaporators, superheaters. The economizer part is used to raise the temperature of demineralized water to meet the required drum saturation temperature, and then water is going to the drum, which is attached with evaporator tubes directly. As the hot exhaust gasses flow through the evaporator downcomer tubes, heat is absorbed, and steam is generated.

As shown in Fig. 2 of the drum and evaporator, the steam–water inside tubes reaches the steam drum where the moisture separators isolate the steam from the hot water. Separated water is continuously recirculated into the downcomers of the evaporator. HRSG drum has three basic functions: separation of water/steam, water storage for some time, and water treatment. The level control valve (LCV) controls the drum level at the desired value to compensate for water evaporating to steam. Saturated steam in the drum is sent to the superheater part to get a dry, high temperature and pressure steam to rotate the steam turbine.

Drum level is the most important control loop through HRSG and in case of improper control causes either shutdown for HRSG, or the Steam Turbine (ST) connected to HRSG. If the level goes too

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https://doi.org/10.1016/j.isatra.2021.04.035
0019-0578/

Please cite this article as: M.A. Elhosseini, A.s. El-din, H.A. Ali et al., Heat recovery steam generator (HRSG) three-element drum level control utilizing Fractional order PID and fuzzy controllers. ISA Transactions (2021), https://doi.org/10.1016/j.isatra.2021.04.035.

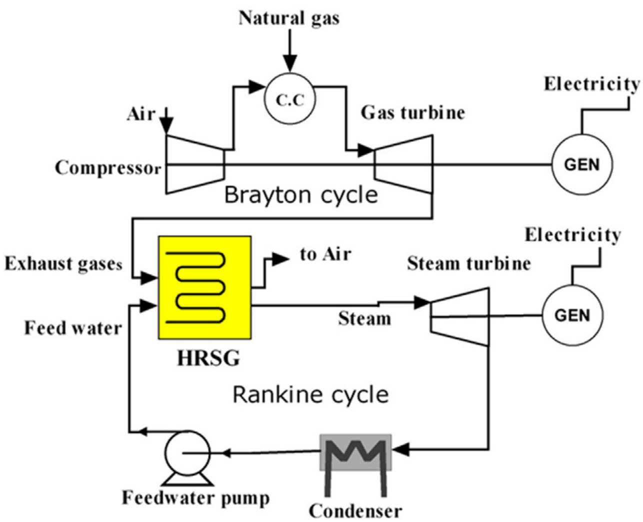

Fig. 1. Combined cycle power plant [2].

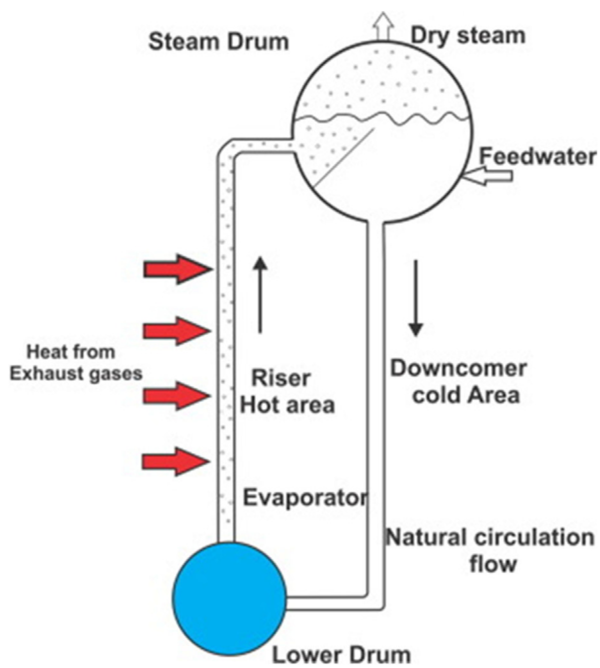

Fig. 2. HRSG drum layout [3].

high, water goes to the turbine and causes damages. If the level goes too low, HRSG becomes dry, and tubes are in danger.

The most used control algorithm is the three-element PID control circuit. The basic principle of PID is to minimize and correct the error regardless of whether this error is temporary or fixed. PID tuning in the industry is done once and with conventional or experimental tuning methods. PID tuning becomes very tedious and complicated when (1) dealing with MIMO systems, (2) dealing with more than one loop, and (3) it is not possible to benefit from operator expertise to tune the PID controller. Based on the data mentioned above, tuning PID with a heuristic algorithm such as ABC can better perform its performance.

FOPID control is more versatile with its five tuning parameters than traditional PID, and it also deals with higher-order systems and nonlinearities [6]. The integration order and the differentiation order are added to Kp, Ki, Kd of normal PID parameters. FOPID tuning is a difficult and complicated procedure, so it has a lot of different optimization techniques like Genetic algorithm (GA) as in [7] or PSO in [8] or ABC algorithm [9], or multi-objective bat algorithm (MOBA) in [10] or internal mode control (IMC) in [11].

The work done in [9] deals with optimization of an integer order-based and fractional order PID controller tuned by particle swarm optimization (PSO) and artificial bee colony (ABC) algorithms. The controller tuning algorithms' validity was tested with two systems with time delay and a nonminimum phase like drum level control. The optimal tuning process of the PID and FOPID controllers has been performed with three cost functions. The controller tuned by ABC gives better dynamic performances than controllers tuned by the PSO. ABC is robust under internal or external disturbances, as shown in papers [12,13].

With the advance in artificial intelligence techniques and complicated scenarios in power plant operation, a fuzzy logic level controller is investigated in many papers [14–18]. The fuzzy controller can be viewed as a way to acquire operators' operational experience that makes the system smarter and so fuzzy can achieve the desired response.

This paper's main goal is to experiment with different controllers such as PID and FOPID tuned with the ABC algorithm and fuzzy controller to reach the optimum response during heat change disturbances. The final controller should be efficient and maintain safe, stable operation during transients and normal operation of the power plant.

The main contributions of this paper are:

- Discussing the shrink/swell phenomenon of drum level
- Adapt the general HRSG model to the Talkha station and calculate mass, volume, and other real system dimensions.
- Simulating the HRSG model with a Three-element PID controller from the Talkha plant.
- Discover how optimization algorithms can enhance PID controller response
  By tuning it with the ABC algorithm.
- Presenting two new recent three-element controllers using FOPID and fuzzy logic.
- The application of ABC optimization algorithm to set the Membership function (MF) parameters of Fuzzy Logic.
- Conducting comparative analysis between PID, FOPID and the Fuzzy logic controllers.

The rest of this paper is arranged as follows: Section 2 depicts the basics and equations of the HRSG model inside MATLAB. Section 3 covers PID Three element control's related work, and Section 4 outlines the proposed FOPID, ABC algorithm, and Fuzzy controllers. Section 5 covers the computer results and simulation and finally the conclusion section.

2. HRSG mathematical model

The HRSG raw model has illustrated inside paper [19], and the work on Talkha HRSG model shown in detail in paper [20] with explanations, model parameters calculation such as mass and volume of drum-riser, downcomer calculation, and values, etc. The HRSG model has four equations illustrated in Fig. 3. Symbols of the model are shown in Table 1.

$$\frac{dp}{dt} = \frac{1}{e_{22}}\left[Q + q_f h_f - q_s h_s - e_{21}\frac{dV_{wt}}{dt}\right] \quad (1)$$

$$\frac{dV_{wt}}{dt} = \frac{1}{e_{11}}\left[q_f - q_s - e_{12}\frac{dp}{dt}\right] \quad (2)$$

$$\frac{d\alpha_r}{dt} = \frac{1}{e_{33}}\left[Q - \alpha_r h_c q_{dc} - e_{32}\frac{dp}{dt}\right] \quad (3)$$

$$\frac{dV_{sd}}{dt} = \frac{1}{e_{44}}\left[\frac{\rho_s}{T_d}\left(V_{sd}^0 - V_{sd}\right) + \frac{h_f - h_w}{h_c}q_f - e_{42}\frac{dp}{dt} - e_{43}\frac{d\alpha_r}{dt}\right] \quad (4)$$

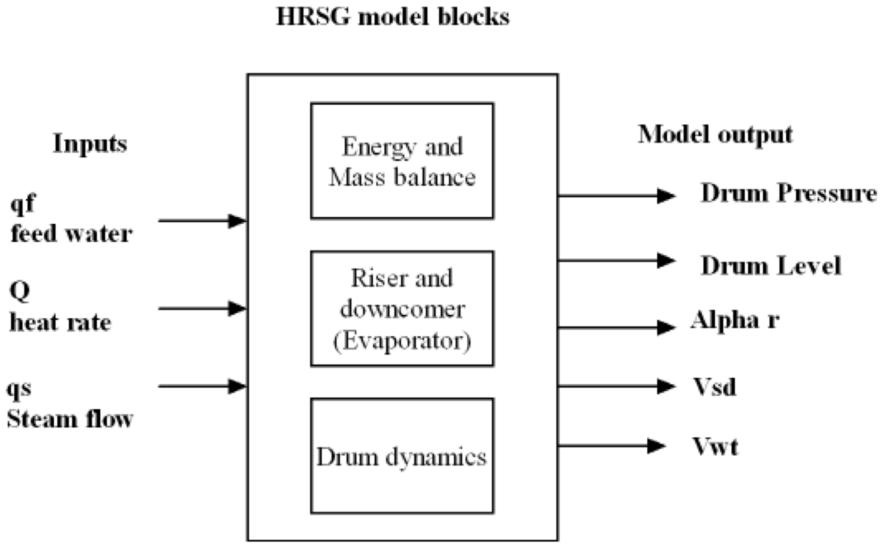

Fig. 3. HRSG mathematical model parts.

Table 1
List of symbols of HRSG model.

Symbol	Definition
Q	Gas turbine load (MW)
q_f	Flow of Feedwater (kg/s)
q_s	Flow of Steam (kg/s)
q_{dc}	Downcomer flow rate of evaporator (kg/s)
q_r	Riser flow (evaporator) (kg/s)
α_r-alpha r	Steam mass quality in riser
h_f	Feedwater specific enthalpy (kJ/kg)
h_s	Steam specific enthalpy (kJ/kg)
h_c	Condensation enthalpy (kJ/kg)
h_w	Drum water specific enthalpy (kJ/kg)
v_{sd}	Steam volume beneath water in drum (m^3)
V_{sd0}	Hypothetical volume of steam with no condensation in drum (m^3)
T_d	Residence time of steam in drum (s)
V_{wt}	Water volume (m^3)
V_{st}	Steam volume (m^3)
ρ_w	Water density (kg/m^3)
ρ_s	Steam density (kg/m^3)
β	Empirical coefficient

Table 2
Real plant parameters and initial conditions of HRSG model.

Parameter	Value (medium load)
Drum volume	45 m^3
Drum area	24 m^2
Drum mass	8860 kg
Pressure of steam	78 bars
Water volume	50 m^3
Steam quality	0.1
Volume of steam in drum	9 m^3
Drum normal level	0.0 mm
Heat input	93.177 MW
Feedwater	60.9 kg/s
Steam flow	60.9 kg/s
Downcomer flow	615 kg/s

where e_{11} to e_{44} parameters are listed in reference [19] and [20].

Some HRSG model real parameters values and initial conditions of the model are shown in Table 2. These parameters are needed at the start of the model simulation in MATLAB /Simulink environment like feedwater flow, steam flow, heat input, and other model specs.

One of the main problems of the Talkha HRSG model is the lack of information or details of thermodynamic properties of the HRSG in power plant manuals, so a lot of experiments and searches are needed with the real plant. The experiments were run using MATLAB Simulink 2018 on a personal computer with an i5 −2.5 GHZ processor and 4 GB RAM, and the author recommend using a more powerful computer to run the simulation faster as optimization of PID and FOPID process and fuzzy logic control is computationally expensive.

3. Related work

The simplest but least effective form of control is one-element level control [21] When the produced steam is minimal. The three-element level control shown in Fig. 4 is the second control mode of drum level, and the transfer process from one-element to three-element is done automatically in the control system when HRSG operates efficiently and generates a significant amount of steam flow. Three-element control uses feedwater flow, level error, and output steam flow to control the feedwater control valve. The three-element control system provides tighter drum level control with fluctuating steam load and when the system is suffering from fluctuating feedwater pressure or flow, as shown in papers [22–24].

Drum level control techniques have a challenge called Shrink /Swell. Shrink and swell refer to a mess-like phenomenon that happened when we open a shaken-up bottle of soda. In HRSG, when the drum pressure drops, some water down in the tubes flashes, and those steam bubbles lift water in the tubes above them up into the drum, increasing the drum level even although the total water mass in the HRSG drum and tubes falls as illustrated in paper [25,26]. Then, when the process stabilizes, and the steam bubbles either burst or enter the drum, the tubes rapidly replenish from the drum lowering the level. The effect is asymmetrical in the condition when drum pressure rises.

Also, HRSG, in reality, is connected to a gas turbine (GT), which its load is subjected to load change as a result of frequency change in the power grid. Wind and solar power generated are profoundly impacted by climate occasions and may slope up or down unexpectedly, so it affects the whole power grid, including combined cycle plants [27]. If the combustion chamber inside the GT has unstable fire or flame, its load can decrease rapidly and affect the attached HRSG drum level. Three-element control is solution to this problem, but it is limited to small load changes with low swell/shrink effect impact on the level as in [23].

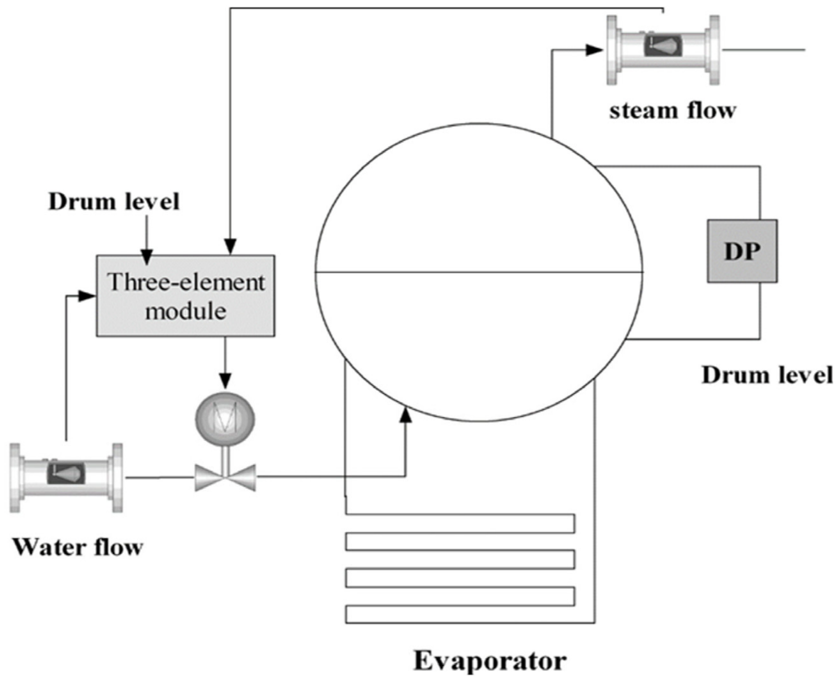

Fig. 4. Three element drum level control scheme [4].

The highest priority among HRSG control loops is maintaining the water level in the steam drum near the predefined setpoint (SP). The liquid level must remain low enough to allow steam and high enough volume to ensure that water is present at the drum and each steam-producing pipe in the HRSG. Usually, these criteria result in a limited level range wherein the liquid must be stored. As shown in Fig. 5, the structure of the 3-element level control is shown; the first is the level or main or master loop; the second is the flow loop or the secondary or slave loop. PID1 corrects the level error, and then the output is summed up with HRSG generated steam flow in the feedforward block, and the output represents the flow loop SP (PID2) that controls the LCV opening ratio.

The flow loop in three-element control will compensate for any flow disruptions before affecting the drum level and reduce the swell effect during boiler load rate changes [7]. The flow loop may have a deadband value of error to maintain the LCV lifetime and stop oscillations. The level loop has zero value of deadband, and this has been shown in the control valves of different drums in the Talkha-power plant.

All control systems require normalization between the real process units and the control loop units. The drum level's normalization values are process value (PV) gain, PV bias, SP gain, and SP bias for every loop. Typical HRSG drum level range varies between −1098 to 1110 mm, and the control valve range is between 0 and 100%, so we need to normalize the values of the level setpoint and process value.

PID control technique has some drawbacks, such as it becomes complicated to use with MIMO systems, difficult to tune more than one loop, and it is not possible to benefit from operator expertise to tune the PID controller [28]. Non-minimum phase systems like boiler level are considered a threat to the PID controller's working theory in some conditions. Conventional methods used to tune PID result in poor performance with making the derivative equal to zero. For the validation of PID controllers, we use the ABC algorithm to tune it at different load steps to achieve the best performance and less error.

4. Proposed controllers

The Three-element level configuration is very popular for controlling drum levels in the boiler or HRSG power plants. We use the same configuration in HRSG drum level control and change the level controller loop vital in the 3-element with FOPID or Fuzzy controller to overcome swell effect with the load rate change.

4.1. Three-element ABC-FOPID

There has been increasing literature on FOPID controllers [11, 29–31] and their applications on process control in recent years. The fractional-order integrator and derivative can achieve better response and results than classical PID with proper tuning based on metaheuristics [31].

The general form of the fractional-order PID (FOPID) is ($PI^{\lambda}D^{\mu}$). It consists of five parameters; the k_p, k_i, k_d, and the two additives are the integration fractional order (λ), and the derivative fractional order (μ), and the equation of FOPID is shown in Eq. (5). Classical PID controller is a particular case of the fractional PID controller in which the values of λ and μ are unity.

$$\text{FOPID controller equation: } C = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \quad (5)$$

Previous research findings into FOPI have been inconsistent and contradictory. FOPI controller does not significantly improve performance compared to classical PI, in some cases, leading the oscillating regimes. One study by Mircea Dulau [29] examined the FOPI controller performance over classical PID; it states that in some cases, it is leading the oscillating regimes and does not provide significantly improved performance compared to classical PI. Besides, the practical implementation schemes are very complicated and suggest that FOPID controllers should be checked and researched well before the operation.

The Authors experiment with the FOPID controllers using the FOMCON toolbar [32] that can be installed on MATLAB/Simulink. In the FOPID drum level controller, we replace the PI level controller with the FOPID controller only, and the feedforward gain

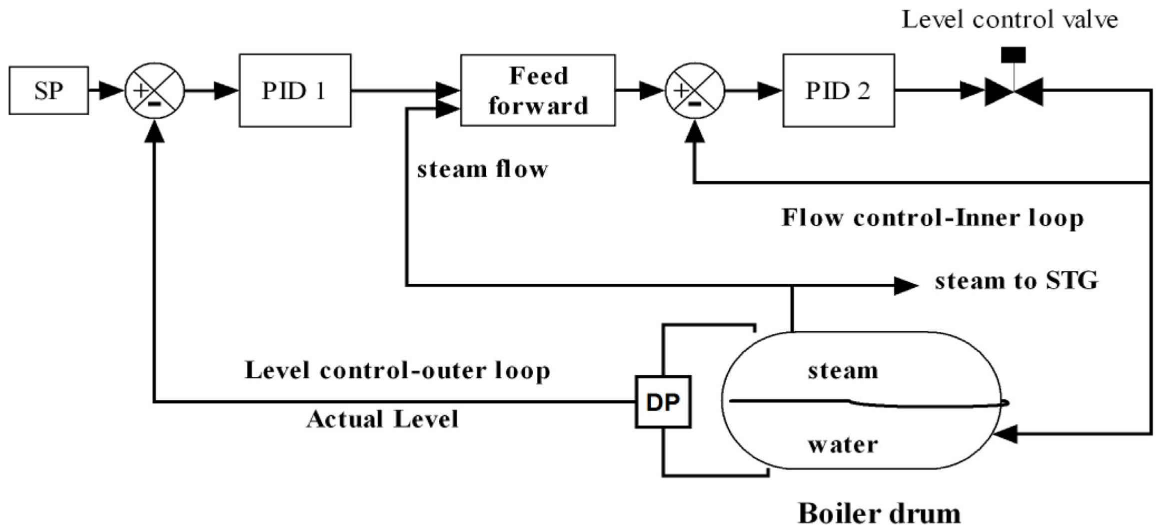

Fig. 5. Three-element PID structure of the drum.

Table 3
Initial conditions of the FOPID-ABC tuning.

Parameter	Value	
Fitness function	IAE (error)	
Number of variables	5	
	Kp,	[1 50],
	ki,	[0 5],
Variables ranges	*kd*,	[0 3]
	λ,	[0 5],
	μ	[0 2]
Max iterations	70	
Colony size	20	
Onlooker bees	20	
Abandonment limit	(0.5∗var∗pop)	

or flow loop is the same. Then the authors tune the five parameters of FOPID with the ABC algorithm, and parameters and response will be presented in the simulation section.

The artificial bee colony algorithm, as demonstrated in [12, 13,33–35], summaries the working of bees inside the colony. The colony consists of three different types of bees. Employed, onlooker, and scout bees. Employed forager is a bee that carries information about the food source. Onlooker is a bee that chooses a food source through employed foragers information. Scout is a bee that searches and explore surrounding nests for a new food source.

In the ABC tuning algorithm of FOPID tuning, employed foragers (FOPID parameters) collect information regarding food sources (IAE of the HRSG level curve). They then share their information with onlooker bees. Onlooker decides to employ itself at the most profitable food source (the minimum IAE of drum level) for nectar suction. Scouts bee perform a random search process for investigating new food sources. The food source position is considered the solution, while the amount of nectar is defined as the solution's profitability. The number of food sources equals the number of employed bees.

The parameter settings and ranges of the FOPID are listed below in Table 3. Most of these settings are based on the operator experience. Besides, the authors try to widen the range to search for the optimal setting of FOPID constants. The pseudocode of the ABC algorithm is listed in Fig. 6.

4.2. Fuzzy three-element level controller

The Fuzzy Logic controller consists of four essential parts: fuzzification interface, information and decision-making base, inference engine, and defuzzification interface [36]. Each of these parts plays a diverse part within the control system and affects controller performance and the entire system behavior.

Fuzzification works by transforming numerical data from clearly defined input values to linguistic terms, or fuzzification changes the classical sets of input to fuzzy sets. The information base gives fundamental data for all the fuzzy controller components, so it contains rules and membership functions (MFs) for fuzzy reasoning. Such information can be collected and delivered by humans. The fuzzy inference engine, called logical decision-making, is the controller's brain. It can simulate the process of decision-making of humans. At the end of the inference step, the result is a fuzzified value representing a meaning, not a value, so it should be de-fuzzified to have a crisp output value.

When designing fuzzy HRSG level controls, there are two scenarios concerning load rate. The first scenario is the load or heat increase. When the HRSG heat input increases, the drum level increases suddenly, then it decreases sharply as HRSG adapts itself to the new Heat change. The outer level controller decreases its output even though the total amount of water inside the drum is the same. The level rises due to bubbles formation with heat, so after the transient has passed the level decreases more. The second scenario is a reduction in load or temperature. As the HRSG heat input decreases, the drum level decreases suddenly then it increases again. The level controller increases its output to increase flow and level as result even though this is a transient state of level. The swell or increase and the shrink or decrease are proportional to the amount of heat added or removed.

Fuzzy detects and treats these conditions well to minimize their effects on the plant operation and avoid severity conditions. Fuzzy also offers level smooth transition at different load rates and level errors. Fuzzy controllers include more than one decision-making input and can have several outputs, as well — this is a significant advantage compared to PID controllers. Fuzzy controller inputs are error level, load rate, rate of change of error, and feedwater valve is the output. The fuzzy logic controller performance depends heavily on many parameters: the number of rules, how many MF are in each input, MF types such as triangle, trapezoidal, Gaussian, and parameter settings and ranges used for proper MF.

Algorithm 1: ABC Pseudo-code

```
Input Set function parameters (Fitness function, no of variables, min, max of variables);
 Set ABC setting (population size(cs), generations(gen), Limit(L));
Output: Solutions or food source Position
Declare No of employed bees = no of onlooker bees = population size (cs) ;
Initialize food source or solutions with eq. (4.2);
Calculate fit, probability of solutions libraries;
cycle=1;
while cycle < gen do
    for I = 1 to cs do // Employed Bee Phase
        Generate random solution (Vi) with equ.(4.3);
        if (f(Vi) < f(Xi) then
            Replace Xi by Vi;
            Counter(i)=0;
        else
            Counter(i)=counter(i) + 1;
        end
    end
    Calculate probability of all solutions with equ. (4.5);
    for i = 1 to CS do // Onlooker Bee Phase
        Select solutions based on probability (Xi);
        Apply random neighbor search (Vi) with equ (4.3);
        if (f(Vi) < f(Xi)) then
            Replace Xi by Vi;
            Counter(i)=0;
        else
            Counter(i)=counter(i) + 1;
        end
    end
    Calculate solution fitness, probability ;
    Memorize best solution so far;
    Determine the abandoned using limit value ; // scout bee phase
    ;
    Replace solution with max counter (exceed the limit value) using equ(4.2);
    gen =gen +1;
end
```

Fig. 6. ABC pseudocode.

Through simulating HRSG, Trial and Error, and experience gained through research interested in previous studies of Fuzzy level control [18], it is used to set the appropriate values, types, and number of MFs based on system response parameters like overshoot, settling time and steady-state error. The first input is load rate MF as in Fig. 7 is divided into seven values: High down, Medium down, Low down, Zero, Low up, Medium up, and High up.

The second input is level error MF has shown in Fig. 8 and is divided into six values: positive high (PH), positive medium (PM), positive low (PL), zero, Negative low (NL), Negative medium (NM), Negative High (NH). The third input is the Error change shown in Fig. 9 and is divided into three MFs: positive, negative, and zero. The Fuzzy controller has one output for the feedwater control valve, as shown in Fig. 10, and it is divided into seven MFs: open small, open medium, open high, stable(zero), close low, close medium, and close wide. Triangular MF gives the lowest rise time among other MFs such as trapezoidal, Gaussian, which is consistent with the study [37–39].

When the level error is positive, it means that the drum level is lower than the setpoint, and when the error is negative, it means that the level is higher than the setpoint. The load rate is considered an input to the fuzzy controller because we observe that heat change affects the drum level stability and can affect HRSG operation. Furthermore, this is integrated in a fuzzy system to make this important drum-level control process more robust at different scenarios during power plant operation. The error and error rate are used in the most conventional fuzzy control system.

MF ranges of load rate are set to [−30 30], level error [−30 30] scaled, derror [−3 3] scaled, and the output MF range are from [−0.8 0.8] scaled.

The rules listed in Table 4 considered the swell effect, which occurred with the introduction of a sudden large amount of heat into HRSG and delaying the level controller's action, and they even take a counteraction to reduce its effect on drum level. Rules also tackle the shrinking effect, reduce its amount, and quickly stabilize the process. The error change of level is applied inside FIS rules when there is a steady load, resulting in a minimum steady-state error. Fuzzy functions as a PID derivative action using the input of the error change of level. Rules cover a large range of input values suitable to different load changes during normal or transient conditions.

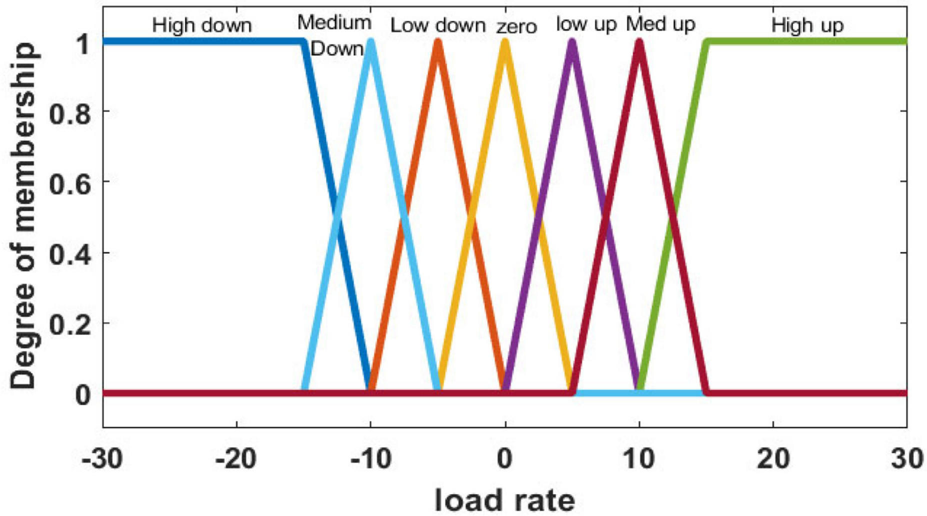

Fig. 7. Fuzzy level load rate input membership function.

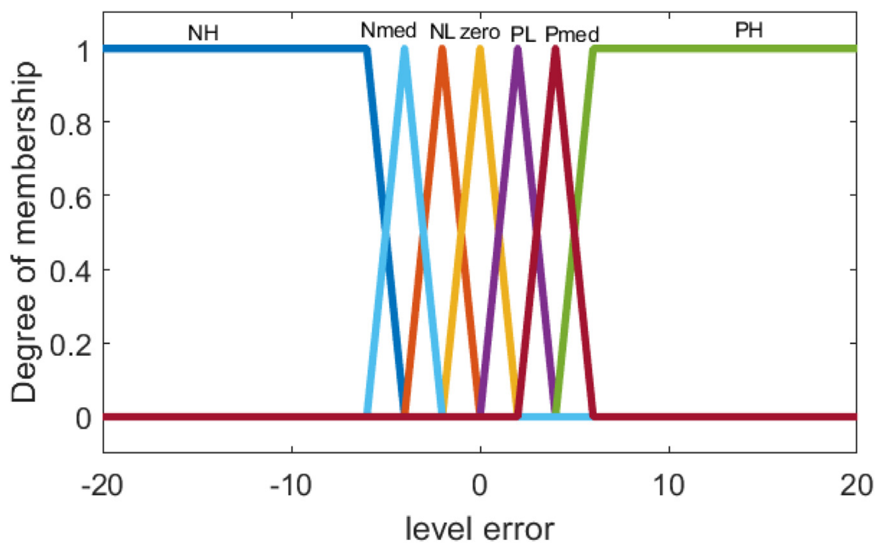

Fig. 8. Level error fuzzy input MF.

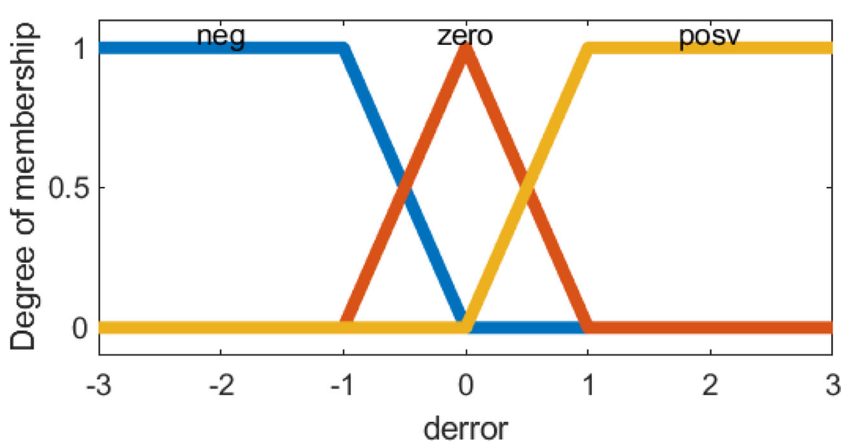

Fig. 9. Error rate fuzzy input MF.

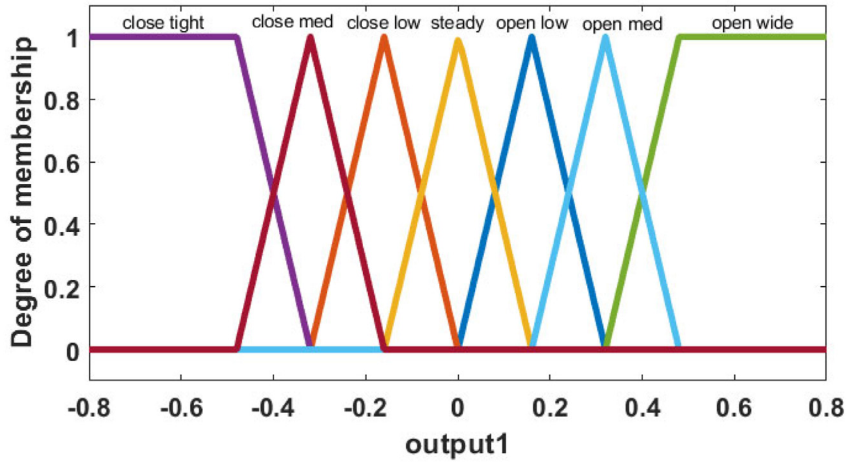

Fig. 10. Valve output membership function.

Table 4
Fuzzy rules and output of the controller.

		Load rate (input 1)						
		HDOWN	MDOWN	LDOWN	ZERO	LUP	MEDUP	HUP
Level error (input 2)	PH	OPNMED	OPNMED	OPNMED		OPNMED	OPNMED	OPNMED
	PM	OPNMED	OPNMED	OPNLOW		OPNLOW	OPNLOW	OPNLOW
	PL	STEADY	OPNLOW	OPNLOW		STEADY	STEADY	OPNLOW
	Z	STEADY	STEADY	STEADY		STEADY	STEADY	OPNLOW
	NL	STEADY	STEADY	STEADY		STEADY	STEADY	CLSLOW
	NM	STEADY	STEADY	STEADY		CLSLOW	STEADY	CLSLOW
	NH	CLSLOW	CLSLOW	CLSLOW		CLSMED	CLSLOW	CLSMED

Table 5
Fuzzy rules and output in case of steady load rate condition.

		Error change (input 3)		
		Positive	Zero	Positive
Level error (input 2)	NH	Close med	Close med	Close tight
	NM	Close med	Close med	Close med
	NL	Steady	Close low	Close low
	Zero	Open low	Steady	Steady
	PL	Open low	Open low	Steady
	PM	Open med	Open med	Open low
	PH	Open wide	Open wide	Open med

Rules cover many input values and are suitable for different load changes during normal or transients. Generally, the number of rules in a fuzzy logic controller relates to the number of inputs and outputs and the number of membership functions.

Rules in the steady-state load condition or zero load rate includes a third input (error rate) in determining the output of the control valve, and some of them are shown below, and Table 5 lists the entire states of input two and input 3 with the corresponding output like: like:

- If the load rate is ZERO and level error is PH, and Error rate is POSV, then the output is OPEN WIDE.

In general, the number of rules in the fuzzy logic controller is defined according to the number of inputs, output variables, and membership functions [38].

4.3. ABC Fuzzy controller

The ABC algorithm is used to tune the gains of inputs to the fuzzy level system like level error, error rate, and feedforward. The ABC algorithm is also used to tune Membership functions for the fuzzy three-element controller for input like level error or outputs like valve output of the optimized Fuzzy controller.

Table 6

Parameter	Value
Fitness function	IAE (error)
Number of variables	26
Variables ranges	Trapezoidal or triangle dimensions
Max iterations	30
Colony size	10
Onlooker bees	10
Abandonment limit	(0.5∗var∗pop)

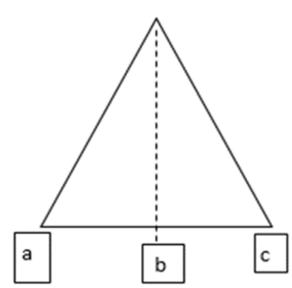

Fig. 11. Triangular Membership function parameters used in optimization.

With many experiments and changing the fitness function of the algorithm to be adapted with different Membership functions, it was found that level error MF dimensions such as positive high (PH) or positive med (PMed), or pos low (PL) can be enhanced with optimization and the cost function of error as will be seen in simulation and results part. Every membership function has three parameters to describe it in the case of triangular shape, as shown in Fig. 11, and four parameters in the case of trapezoidal MF. These values have ranges that can be changed, so the system's control decision and output. The ABC fuzzy three-element controller is shown in Fig. 12.

Table 7
Optimal values of fuzzy Level input MF and gains.

MF	NH	NM	NL	Zero	PL	PM	PH	Klevel	Kerrror rate	kforward
Val.	−44 −33.9 −11.5 −7.9	−10 −7.7 −4.9	−4.1 −1.42 −0.76	−0.61 0.3 0.62	0.82 1.4 3.3	4.9 5.33 7.3	8.29 19.3 37 46	5.08	1.0294	0.88

Table 8
Three-element PID controller parameters.

Three-Element PID	Level loop		Flow loop (fixed)
Parameter	PI 1 from plant	PID 1 tuned by ABC	PI 2 Flow
Proportional	5	49.9	0.1
Integral	0.02	0.102	1/20
Derivative	0	1.3	0

Table 9
FOPID controller parameters.

	FOPID from ABC	Range
Proportional	49.2193	[1 50]
Integral	4.8473	[0 5]
Derivative	2.6424	[0 3]
Order of integration λ	0.0174	[0 5]
Order of differentiation	0.9851	[0 2]

To evaluate the performance of the controller, it is necessary to define a fitness function. Our controller's target is to obtain a minimum Integral absolute error with load rise or decrease over time. The hyperparameter settings of ABC algorithm are listed in Table 6

The result of optimization of the fuzzy controller with ABC technique for level input MF is shown in Fig. 13, and the values of linguistic variables inside level MF are shown in Table 7 besides the values of required gains inside the controller. It was noted that this trapezoidal MF is useful for NH, PH than triangular MF and produces less error with optimization.

5. Computer results and simulation

PID and FOPID in the three-element controller are tuned according to overshoot, rise time, error, and steady-state properties of the system. We increase the range of the parameters and do experiments until we have these ranges, and it was found that FOPID derivative order above the value of 2 results in undesired oscillations. According to the operator and testing experience, the most suited ranges for these PID and FOPID are listed in Tables 8, 9. The cost function with iteration number for example is shown in Fig. 14 for FOPID tuning.

Using the Talkha HRSG plant's parameters in Egypt, we simulate the HRSG model developed in the MATLAB/Simulink context. We apply 12, +20, −20 MW that represent medium and large step change of the heat input to HRSG and observe various level controllers' responses. These load rate values are chosen carefully to judge and observe the system's response under normal and high input rates. A step change occurred at 150 s when three controllers are stabilized. Figs. 15–18 show the step response of HRSG with a medium and high load rate.

We observe from Fig. 15 that including the derivative part of PID in optimization, the final controller has less overshoot, small rise and settling time, and small error values than PI of the plant. We can see that the ABC algorithm makes the PID controller more efficient, and performance is fine compared to the exist (PI) in Talkha plant. The controller performance is far better with fast rise time, settling time, and less overshoot with step change.

Table 10
Performance indices of three-level controllers in case of +12 MW step.

	PID	FOPID	Fuzzy-ABC
Rise time (s)	40	40	42
Overshoot	3%	3%	3.8%
Settling time (s)	50	50	50
Peak value	22.6	22	23
Steady-state error	0	0	3
ISE	1223	1219	1242
IAE	240	237	245
ITAE	8.519 e3	8.291 e3	10e3

Table 11
Performance indices of three level controllers in case of +20 MW step.

	PID	FOPID	Fuzzy-ABC
Rise time (s)	40	40	42
Overshoot	6%	6%	6.7%
Settling time (s)	70	70	70
Peak value	39.5	39	43
Steady-state error	0	0	3.5
ISE	1257	1252	1283
IAE	258	255	263
ITAE	1.15 e4	1.134 e4	1.37 e4

Table 12
Performance indices of three-level controllers in case of −20 MW step.

	PID	FOPID	Fuzzy-ABC
Steady state error	0	0	3.5
ISE	1270	1264	1320
IAE	278.6	272.6	279
ITAE	1.57e4	1.47e4	1.647e4

We compare the two fuzzy three-element controllers' performance, the manual tuning one, and our approach of ABC optimized fuzzy tuning. As shown in Fig. 16, the ABC fuzzy controller is somewhat better related to overshoot and IAE, ISE, ITAE and Manual tuning behaves close to ABC fuzzy due to many experiments done in fuzzy tuning of the system.

From Figs. 17–19 and performance Tables 10–12 we can conclude that:

- ABC algorithm makes PID controller more efficient, and its performance is better than the plant PI controller in the simulation of the system at steady state and disturbance.
- The Three-element controller using FOPID performance does not have the expected major improvement, and the difference with PID three-element controller is a little bit.
- The author believes that PID is still desired and has the advantage in a three-element loop with optimization.
- Fuzzy logic controllers with the design and experienced rules behave like the optimized PID or FOPID using inputs and experienced rules.

The second case illustrated to study and observe swell/shrink of level is applying negative or decreased load input to HRSG model. We apply a high down rate with a 20 MW step, and the response of the three optimized controllers is illustrated in Fig. 19, and Table 11 shows the performance measures.

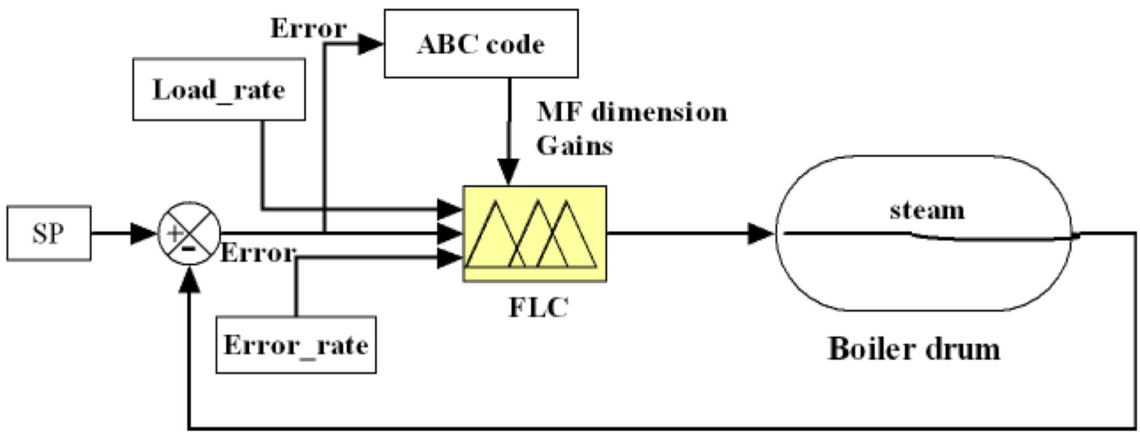

Fig. 12. Structure of three-element fuzzy with ABC technique.

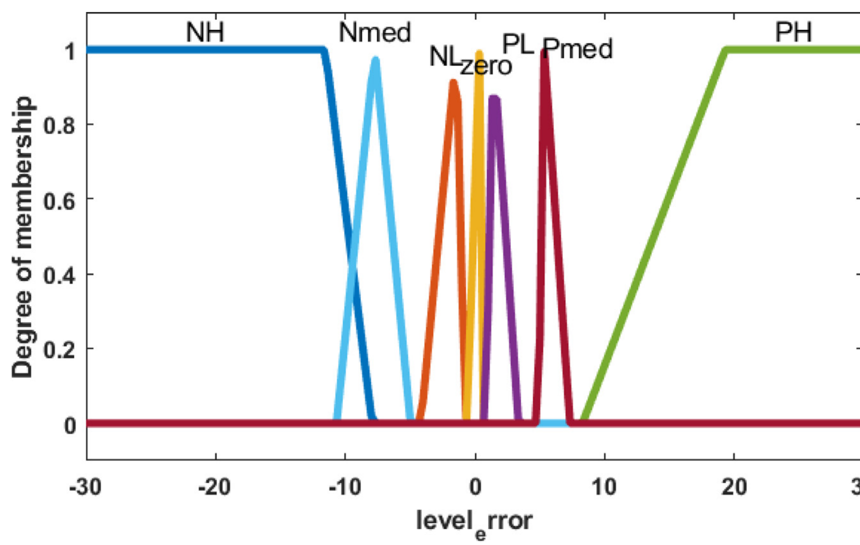

Fig. 13. Optimal membership functions for level error using ABC.

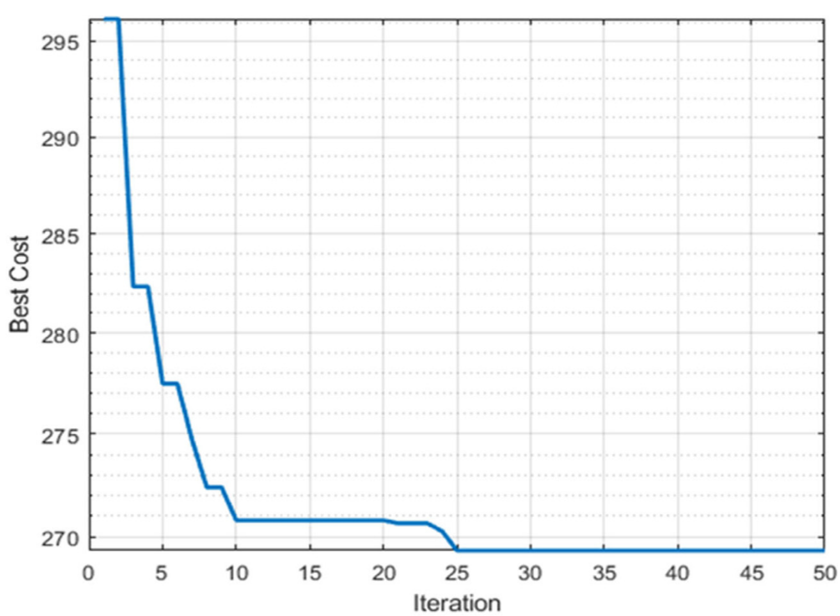

Fig. 14. The cost function (Level error) for ABC tuning of FOPID.

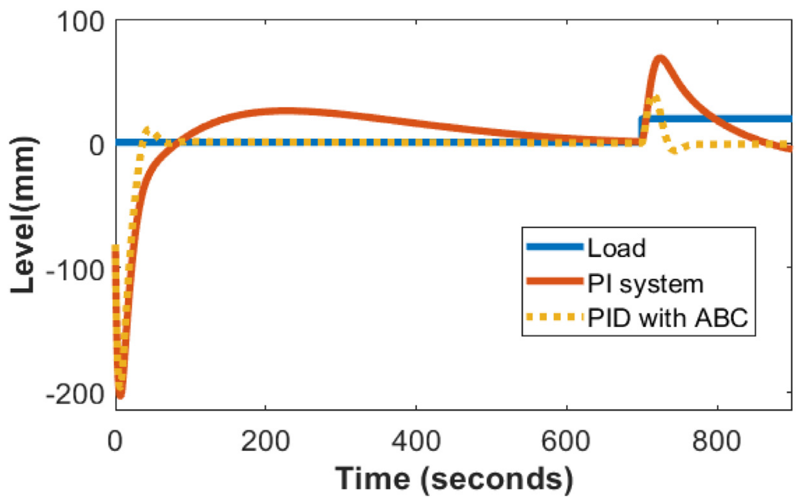

Fig. 15. High load Step response (20) for PI, PID tuned with the ABC controllers.

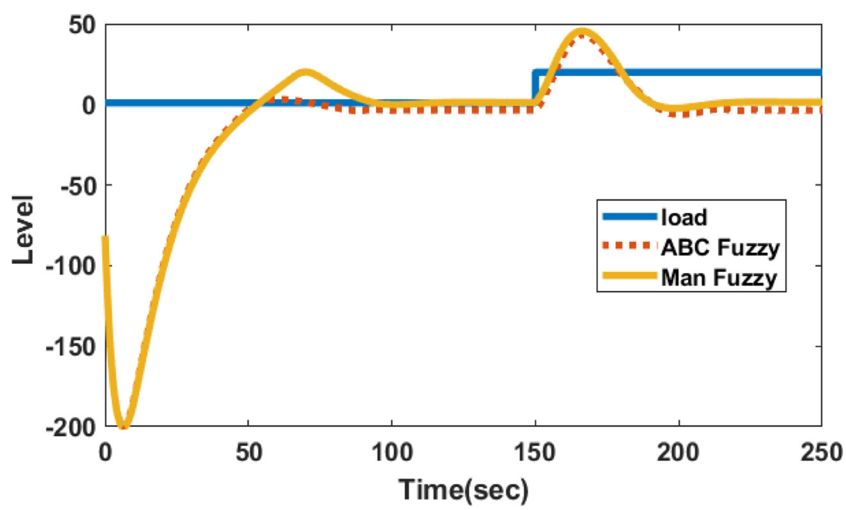

Fig. 16. High load Step response (20) for Fuzzy and Fuzzy tuned with the ABC.

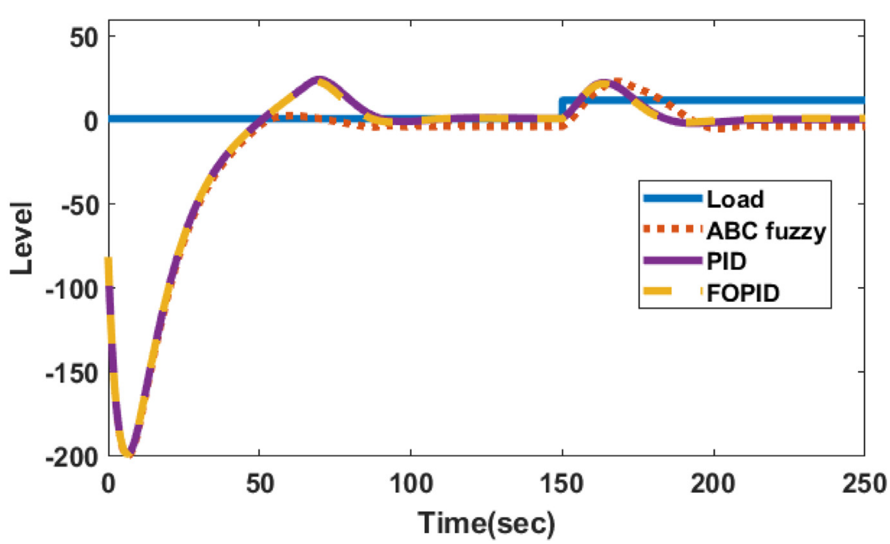

Fig. 17. PID, FOPID, and fuzzy level response with 12 step input in load input.

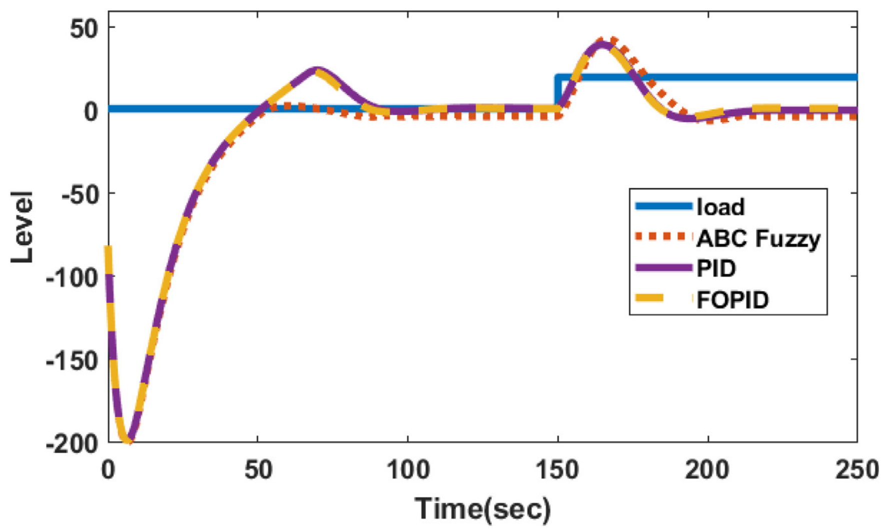

Fig. 18. PID, FOPID, and fuzzy level response with 20 step input load input.

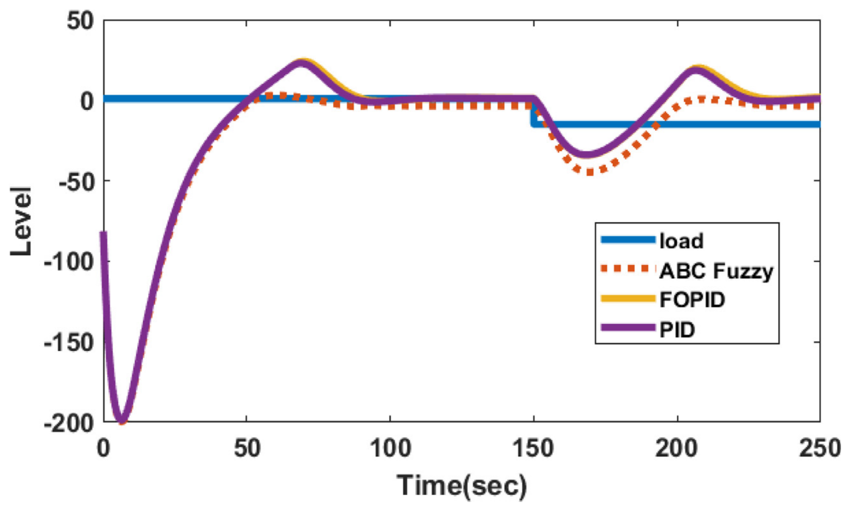

Fig. 19. PID, FOPID, and ABC fuzzy level response with −20 step load down.

6. Conclusion

Through this research in HRSG, that is, the plant drum level control loop, we discover how HRSG drum level is very important in combined cycle power plants; we observe some practical consideration of PID controller parameters in this loop like deadband parameter and K_p, K_i, K_d values and other control settings through simulating the loop in MATLAB.

The shrink or the swell effect is a complicated phenomenon inside the HRSG drum due to the evaporation and steam bubbles inside water. This phenomenon increases with different things like load change, pressure change, and the existing PID controller in Talkha does not deal with this greatly. On the other hand, we use a small load rate of the plant with PI controllers to avoid this.

ABC algorithm is a good learning algorithm and reaches the optimum solutions quickly, and we can tune the PID or FOPID or fuzzy parameters concerning error or overshoot or settling time and save the time required to tune controllers manually and obtain the best results. The response of the process is improved, as seen in the HRSG model simulation curves in steady state and during disturbances.

FOPID needs advanced algorithms to tune it efficiently, so with the ABC algorithm, the controller is tuned efficiently, which appears in the response. FOPID gives the superior response among controllers but FOPID controller has the disadvantage of complexity in its mathematics when included in commercial controller systems.

FOPID controller gives the best results in different error indices, but this does not make it the best controller to use. The results suggest that the ABC optimization technique can be used in tuning of PID controllers, and the optimized controller outperforms recent controller. The fuzzy controller can be used with complicated processes like level of drum, and manual tuning is great related to system response. The proposed ABC fuzzy controller has somewhat better results than the manual fuzzy system and can be experimented with other MFs and rules in the future. Every proposed system has advantages and disadvantages that must be taken into account when choosing it in reality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] U. E. I. administration, How electricity is generated. 2019, [Online]. Available: https://www.eia.gov/energyexplained/electricity/how-electricity-is-generated.php, [Accessed 2019].
[2] company G. Combined cycle power plant: how it works, [Online]. Available: https://www.ge.com/power/resources/knowledge-base/combined-cycle-power-plant-how-it-works.
[3] combined cycle power plants, [Online]. Available: https://www.wartsila.com/energy/learn-more/technical-comparisons/combined-cycle-plant-for-power-generation-introduction].
[4] Kehlhofer R, Hannemann F, Stirnimann F, Rukes B. Combined Cycle Gas and Steam Turbine Power Plants. Pennwell; 2009.
[5] Manassaldi JI, Mussati GF, Scenna NJ. Optimal synthesis and design of heat recovery steam generation(HRSG) via mathematical programming. Energy 2011.
[6] Shah P, Agashe S. Review of fractional PID controllers. Mechatronics 2016;38:29–41, Elsevier.
[7] Tabari MY, Kamyad AV. Design optimal fractional PID controller for DC motor with genetic algorithm. Int J Sci Eng Res (IJSER) 2012;3(12).
[8] Pan I, Das S. Fractional order controller tuning using swarm and evolutionary algrothims. In: Intelligent Fractional Order Systems and Control. Springer; 2013, p. 87–131.
[9] Bingul Z, Karahan O. Comparison of PID and FOPID controllers tuned by PSO and ABC algorithms for unstable and integrating systems with time dela. Optim Control Appl Methods 2018;39(4):1431–50.
[10] Chaib L, Choucha A, Arif S. Optimal design and tuning of novel fractional order PID power system stabilizer using using a new metaheuristic bat algorithm. Ain Shams Eng J 2015;8(2):113–25.
[11] Edet E, Katebi R. On fractional-order PID controllers. IFAC-PapersOnLine 2018;51(4):739–44.
[12] El-Sherbiny A, Elhosseini MA, Haikal AY. A new ABC variant for solving inverse kinematics problem in 5 DOF robot arm. Appl Soft Comput 2018;73:24–38.
[13] Saad E, Elhosseini M, Haikal AY. Culture-based artificial bee colony with heritage mechanism for optimization of wireless sensors network. Appl Soft Comput 2019;79:59–73.
[14] Thomas AC, Hote YV, Saxena S. Comparative analysis of cascade fuzzy logic controllers for boiler water level control. In: 2014 Annual IEEE India Conference (INDICON), Pune, India, 2014:.
[15] Gowthaman E, Saravanan S, Naveenbalu K, Aravind S, Naveen S. Performance analysis of hybrid fuzzy-PID controller action on boiler drum level control. In: 2016 Online International Conference on Green Engineering and Technologies (IC-GET) 2016 Nov 19 (pp. 1-6). IEEE.
[16] Qingsong M, Qi W, Hongling W. Design of fuzzy controller for liquid level control system based on MATLAB/RTW. In: Proceedings of 2013 2nd International Conference on Measurement, Information and Control, Harbin, china, 2013:.
[17] Wei-jie Y, Yong-xin L. Boiler drum level controlled by fuzzy self-adapting PID. In: 2009 Asia-Pacific Conference on Computational Intelligence and Industrial Applications (PACIIA), Wuhan, China, 2009:.
[18] Chaudhury S. Fuzzy approach to boiler drum level control. 2008.
[19] Aström KJ, Bell RD. Drum-boiler dynamics. Automatica 2000;36(3):363–78.
[20] s. El-din A, A.El-hosseini M, Ali HA. Modelling and practical studying of heat recovery steam generator (HRSG) drum dynamics and approach point effect on control valves. Ain Shams Eng J 2018;9(4):3187–96.
[21] Lindsley R. Power-Plant Control and Instrumentation. London: The institution of Electrical Engineers; 2000.
[22] Chakraborty SK, Manna N, Dey S. Importance of three-elements boiler drum level control and its installation in power plant. In: IJICS. 2014.
[23] Lawrence I, Lawrence I. Overcoming the shrink-and-swell effect in water level control strategy on industrial boiler-drum. Stand Sci Res Essays 2013;(1):019–24.
[24] Amarnath Kumaran A, Ponni Bala M, Sivaraman V. Three element boiler drum level control using cascade controller. Int. J. Res. Appl. Sci. Eng. Technol. 2018;6(3):2835–9.
[25] Iacob M, Andreescu G-D. Plants, drum-boiler control system employing shrink and swell effect remission in thermal power. In: 3rd ICUMT. 2011.
[26] Houtz AD. Controlguru.com. 2019, [Online]. Available: https://controlguru.com/dynamic-shrinkswell-and-boiler-level-control/. [Accessed 2019].
[27] El-guindy A, Han D, Althoff M. Formal analysis of drum-boiler units to maximize the load-following capabilities of power plants. IEEE Trans Power Syst 2016;31(6):4691–702.
[28] Shakya R, Rajanwal K, Dinkar S, Patel S. Design and simulation of PD, PID and fuzzy logic controller for industrial application. Int J Inform Comput Technol 2014;4:363–8.
[29] Dulau M, Gligor A, Dulau T-M. Fractional order controllers versus integer order controllers. Proc Eng 2017;538–45.
[30] Khalfa B, Abdelfateh C. Optimal tuning of fractional order PID controllers using PSO algorithm. In: IFAC Conference. 2017.
[31] Shah P, Agashe S. Design and optimization of fractional PID controller for higher order control system. In: International Conference of IEEE ICART. 2013.
[32] Tepljakov A, Petlenkov E, Belikov J. FOMCON: Fractional-order modeling and control toolbox for MATLAB. In: Proceedings of the 18th International Conference Mixed Design of Integrated Circuits and Systems - MIXDES 2011, Gliwice, Poland, 2011:.
[33] Kang F, Li J, Ma Z. Rosenbrock artificial bee colony algorithm for accurate global optimization of numerical functions. Inform Sci 2011;181(16):3508–31.
[34] Abedinia O, Wyns B, Ghasemi A. Robust fuzzy PSS design using ABC. In 10th International Conference on Environment and Electrical Engineering, Rome, 2011:.
[35] Litake SR, Mukherji P. Integration of fuzzy logic and ABC algorithm for optimized network selection in heterogeneous wireless environment. Int J Sens Wirel Commun Control 2020;10(2):248–61.
[36] Mendel J. Fuzzy logic systems for engineering applications. Proc IEEE 1995;83(3):345–77.
[37] Pedrycz W. Why triangular membership functions? Fuzzy Sets and Systems 1994;64(1):21–30.
[38] Sadiq AA, Bakare GA, Anene EC, Mamman HB. A fuzzy-based speed control of DC motor using combined armature voltage and field current. IFAC Proc Vol 2013;46(20):387–92.
[39] M.Ali OA, Y.Ali A, Sumit BS. Comparison between the effects of different types of membership functions on fuzzy logic controller performance. Int J Emerg Eng Res Technol (IJEERT) 2015;3(3):76–83.