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Optimal Design of PID-Based Low-Pass Filter for Gas Turbine Using Intelligent Method

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ABSTRACT Due to the ever-increasing demands for electrical energy in industrial and domestic consumption, the use of gas turbines in power plants has great importance for the generation of electrical energy while taking less time. In this case, analyzing the role of gas turbines in the generation of electrical energy and their performance in the stability of power systems has special importance. Therefore, acquiring the suitable model for gas turbines and estimating various factors in modeling can consider as main part of power system stability. The purpose of this paper is originally a detailed dynamic modeling of a gas turbine based on the Rowen design and then controlling it to get most stability of power system by a new intelligent procedure. In next step, the most commonly accruing faults in gas turbine which can lead to control difficulty in power system are considered for analysis in the proposed simulation. Gas turbine in combined cycle power plant has ability for changing operation condition rapidly and more frequently. So its useful life is lesser than steam turbine. Gas turbine controller must increase its useful life because of high expenditure of gas turbine constructing. Damage mitigating control or life extend control is to design a controller to get better tradeoff between dynamic act and structural durability in a power system. Finally, the proposed interactive artificial bee colony method is employed to design a better controller and the design has been done under different working conditions to get the best results from proportional–integral–differential type controller parameters with low-pass filter compare to genetic algorithm and particle swarm optimization.

INDEX TERMS Stability analysis, IABC method, gas turbine, Rowen model.

I. INTRODUCTION

Gas turbine is a rotating machine based on the released energy of combustion gases. The common perception of gas turbine is the aircraft engine which is one of the most used types of gas turbines in engineering. Each gas turbine unit includes a compressor for air compressing, a combustion chamber to mix air and fuel and a turbine to convert the energy of hot and compressed gases into mechanical energy. Shorting speaking and as shown in Fig 1, some part of the generated mechanical energy in the turbine is used to spin the turbine and the rest energy depending on the usage of the gas turbine, it may spins the generator (turbo-generator) into the air (turbo-jet and turbo-fan) or directly (or later use the same way to change the pivot speed of the gearbox (turbo-charged, turbo-prop and turbo-fan). Gas turbine and its control system require the system identification and its process. Figure 1 shows the gas turbine configuration.

The main parts of gas turbine can be considered by a compressor, a combustion chamber and turbine itself. Owing to gas turbine working, the compressor gets air in lowest pressure while its output will be air flow with most pressure.

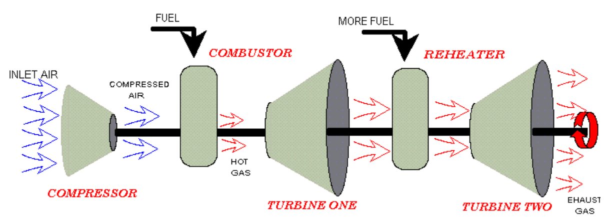

FIGURE 1. Gas turbine process.

Next, this air flow goes to the combustion chamber in order to mixed fuel combustion with air to increase air's temperature. In the last part, the mixed air and fuel is expended in turbine to supply mechanical power [1]–[9].

Several methods have been proposed for a model gas turbine; the Rowen and IEEE models are two of them which receive more consideration. The model which is proposed by IEEE is mostly based on thermodynamic relations while the Rowen model depends on the values obtained from tests. The Rowen model is suitable in those cases in which the identification of turbine functions by experiments is important [1], [2].

Wu [1] presented simplified models of gas turbine by Rowen which consider temperature control, the turbine's thermodynamic responses as well as load-frequency as a linear model [2]. Furthermore, the non-linear power system model of interconnected Automatic Generation Control (AGC) creates it not easy to guarantee system stability at all loading conditions with PID, classical integral or PI stabilizers being tuned at a particular loading state [4]. Several developments have been approved by fuzzy logic theory (FLC) and artificial neural network (ANN) stabilizer for better dynamic action in the interconnected AGC system [3]. FLC based on integral, Fuzzy based on PI stabilizer and Fuzzy based on PID stabilizer have been argued in [4]. However, none of papers presented in the past concerned with Fuzzy integral + double derivative stabilizer (FIDD) [5]. An adaptive neural controller for a class of nonlinear systems with unmodelded dynamics and immeasurable states is presented in [6]. In order to overcome the problems existing in a nonlinear triangular form, the consistency structure of virtual control signals and the variable partition technique are combined. According to the backstepping technique and the universal approximation property of the radial basis function (RBF) of neural networks, an adaptive neural output-feedback controller is developed. The semi-globally and uniformly ultimate boundedness of all signals within the closed-loop system is guaranteed by using the Lyapunov stability analysis. The state-feedback decentralized stabilization problem for interconnected nonlinear systems in the presence of unmodeled dynamics is taken into account in [7]. The functional relationship in affine form between the strong interconnected functions and error signals is established, which makes backstepping-based fuzzy control successfully generalizable to strong interconnected nonlinear systems. An adaptive decentralized control algorithm is developed by combining adaptive control with both backstepping design and the approximation property of fuzzy systems. Zhao *et al.* [8] propose an adaptive fuzzy hierarchical sliding-mode control method for a class of multiinput multioutput unknown nonlinear time-delay systems with input saturation. At first step, the system under study is transformed into an equivalent system. Subsequently, a set of adaptive fuzzy hierarchical sliding-mode controllers are designed for the new defined system based on sliding-mode control technology and the concept of hierarchical design, by using fuzzy systems to approximate uncertain functions and compensate input saturation. The problem of adaptive neural control of nonlower triangular nonlinear systems with unmodeled dynamics and dynamic disturbances is considered in [9]. The difficulties appeared in designing the unmodeled dynamics and nonlower triangular forms are dealed with a dynamic signal and a variable partition technique for the nonlinear functions of all state variables, respectively. It is shown that the proposed controller is able to ensure the semi-global boundedness of all signals of the resulting closed-loop system.

All the mentioned models try to increase system stability under dynamic conditions. It is evident that by changing the task point, the designed controller does not have the desired efficiency anymore. This paper proposed a design for a controller for gas turbines by applying the real parameters of a power plant in a modified Rowen model and by using the improved algorithm of bee colony (IABC). Paying attention to the changes in exploration conditions at different work points, this paper proposed to design a resistant PID controller to improve the performance of the control loops of gas turbines. Therefore, the optimal adjustment of the parameters of the controller issue will change into the optimization of the controller under different exploitation conditions, which are a function of the speed and electric power of the generator. The stability issue is discussed from the transient and constant aspects. Four different controlling loops are considered for modelling: temperature, acceleration, frequency, and fuel system. It should be noted that in the gas turbine model, the actual parameters of a power plant are used. Evaluation of the results shows the suitable efficiency of the suggested algorithm of bee colony in the development of the gas turbine controller performance compared to the algorithm of the particle community.

Consequently, the optimal variables of Rowen's model in order to heavy operating gas turbines in dynamic reports are approximated by use of accessible working and performance input data. The main purpose of this paper is to create nearby into various components of the gas model and to define an effortless and comprehensive process to get the optimal variables out of straightforward physical laws, focusing particularly on intelligent model for students who are paying attention in simulations and dynamic models. Gas turbine variables are approximated using straightforward thermodynamic assumptions, follow-on in good association with representative values. Based on in-depth review of the available methods in the literature, the highlights of this article can be summarized as follows:

(i) A PID controller is proposed to damp proposed turbine model output with low-pass filter. The performance of various optimal PID controllers is compared together in terms of the sum of IATE and balanced robust performance criteria.

(ii) The standard ABC is modified by gravitational search law in order to obtain exploitation as well as exploration in solving the optimization problem. Choosing inappropriate adjusting variables can result in instability in the proposed turbine model. In order to overcome this problem, its variables must be adjusted accurately. Therefore, this model is converted to an optimization problem which will be solved in this study using the proposed IABC algorithm. In fact, to deal with the disadvantage of traditional algorithms in finding global optimum solutions, when system has too many optimization variables, an innovative ABC algorithm is suggested using interaction theory, called IABC. It is able to optimize the parameters of the gas turbine model.

(iii) Carrying out the proposed algorithm on a real test system to demonstrate its ability and reliability in optimization

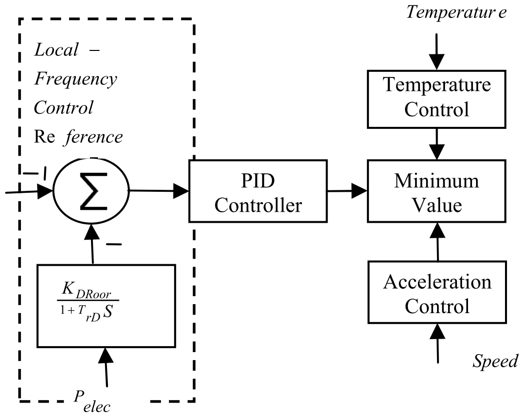

FIGURE 2. Control loops of gas turbine.

engineering problem. Because of the fact that most of the real systems are vulnerable to external disturbance, measurement noise and model uncertainty, robustness is also considered as an important criterion in controller design.

(iv) Dynamic modeling of a gas turbine based on the Rowen method is proposed and then controlling it to increase the efficiency of the system is done. It is not easy to implement the controller for higher order systems in practical engineering applications, because the order of the robust output feedback controller is much higher than that of the systemin order to deal with this problem, the structure specified approach is regarded to solve the robust optimal control problem from the suboptimal perspective.

The rest of this paper is organized as follows. Sections 2 to 7 provide the general formulation of the gas turbine and its control loop. Sections 8 and 9 introduce the proposed IABC optimization algorithm. Owing to get all potential of the proposed ABC optimization algorithm, a test system has been considered. Simulation results and comparison with previously-reported results are discussed in section 10. Lastly, the paper is concluded in Section 11.

II. TURBINE CONTROLLING LOOPS

Figure 2 shows the structure of the gas turbine controller which is composed of three factors: temperature, acceleration, and load–frequency [3], [4]. The transferring function of PID is given by

$$PID = K_p + \frac{K_i}{s} + \frac{K_d S}{(1 + T_d S)} \tag{1}$$

Where K_p, k_i and k_d are variable gains to optimally set the desired output. The sample range of optimized variables for these gains is [0.01-3]. Although construction of the ideal PID controller is impossible in practice, the application of low–pass filter at the entrance is of great importance in industrial PID controllers to remove noise. Therefore, in this paper, the function of derivation in PID controller is considered as $K_d S/(1 + T_d S)$ in three part of eq (1) which ($K_d \ll T_d$).

III. TEMPERATURE CONTROL LOOPS OF TURBINES

The temperature control expression controls the output temperature when it rises above the constant maximum. If a generator is in normal operating condition or the load demand of gas turbine increases, its output power operates according to the performance of the load–frequency controller. This increases the temperature above the maximum limit and the temperature controller will be necessary. In the temperature control loops operation the measured temperature will be compared to a reference temperature. After passing through a controlling PI, it will be compared with the minimum and maximum values and will be given to the fuel system [4], [5].

IV. TURBINE CONTROLLING LOOPS

The acceleration control loop is designed to control the fuel system in situations that the generator is enduring acceleration out of permissible range. This condition can occur during the start-up or the injection process. Acceleration control loops prevent high speed in gas turbines that can damage the shaft [10]–[14]. The proposed close-loop controller of the gas turbine consists of three main control loops: speed, start up and temperature. Owing to get the proposed modeling tests, the speed control, receives the most attention. The motive is that when the unit is launched it is not in line and in the temperature control mode, the governor does not respond to system frequency changes.

V. FREQUENCY-LOAD LOOP

With a change in the load, the speed rotation system of the generator will change according to the amount identified by its fixed inertial and the governor, which is guided by the speed rotation of the generator, will compare it with a reference speed. Therefore, by receiving change in speed rotation, it will modify the input power of the turbine to achieve the desired speed [4], [5]. Figure 3 shows the diagram of the gas turbine attending to temperature control, frequency–load, and acceleration control loops.

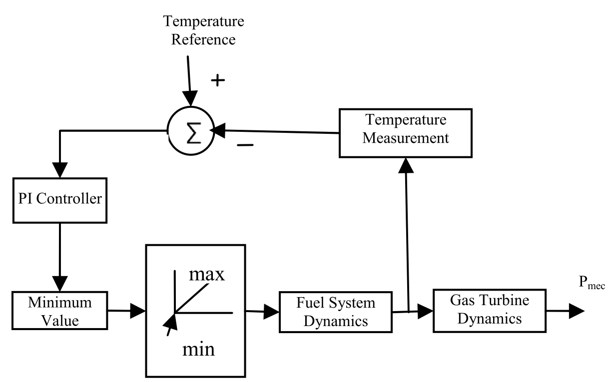

FIGURE 3. Temperature control loop.

VI. FUEL SYSTEM CONTROLLING LOOP

The gas turbine fuel system is of two types: gas fuel system, and liquid fuel system. This paper used gas fuel turbine

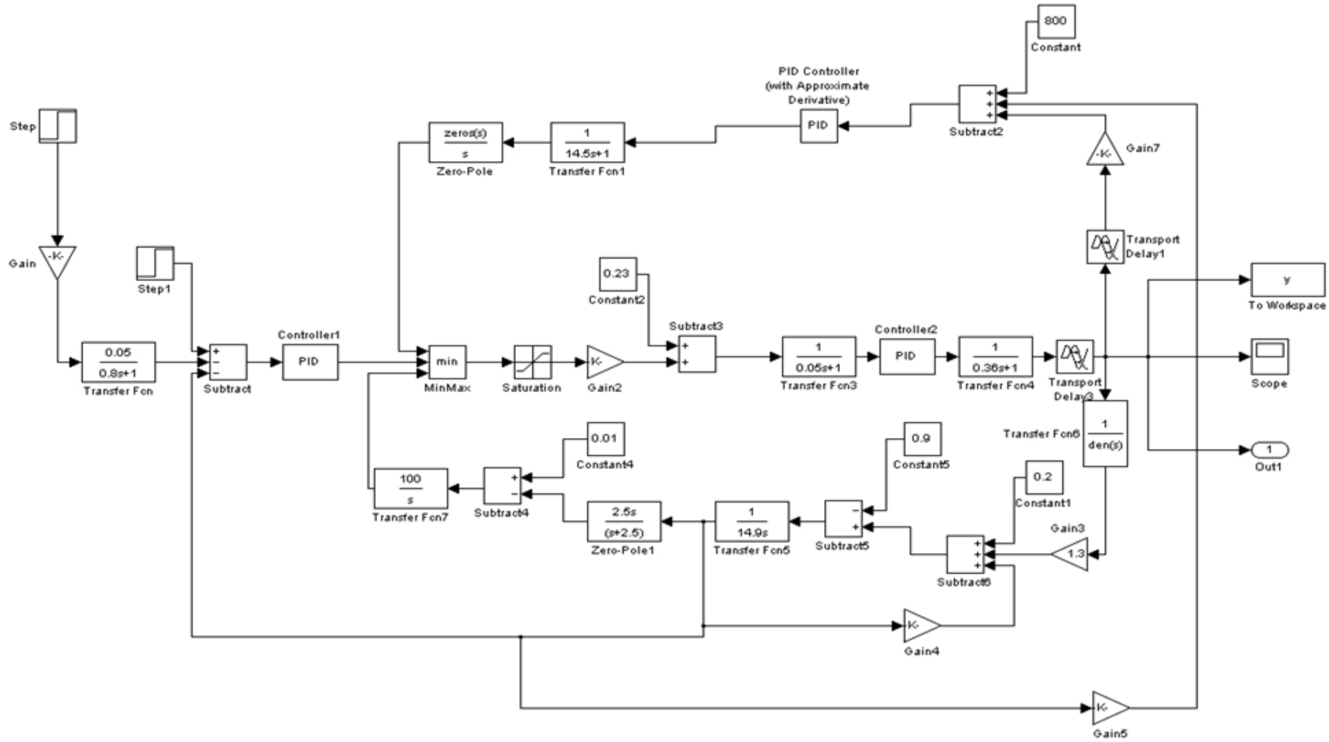

FIGURE 4. **Gas turbine diagram.**

for dynamic modelling of the fuel system controllers of gas turbines. The position of the valve will be changed by a transformer whose core is attached to the valve; also, the external voltage will change according to the changes in the valve position.

The main part in this system is the valve which controls gas. It will open and close according to the command of the gas fuel system. This will be done by a controlling loop. This controlling loop consists of a proportional–integral which compares the real position of the gas controlling valve with the command signals. Then an appropriate signal will be applied to open and close the valve [10]. A simulation diagram in MATLAB software is shown Fig 4.

The main frequency control is the response to the frequency deviation. In this regard, the total production must be balanced in demand at all times:

$$P_G = P_D \tag{2}$$

where P_G denotes the generated power and P_D refer to the power demand by the active loads in the power system, including losses. Kinetic energy of all rotating masses (i.e. motors and generators) in the system is given by:

$$E_{rot} = 0.5\, J\omega^2 \tag{3}$$

where J refer to the total moment of inertia and ω denotes the angular frequency. Unbalance values between P_G and P_D leads to changes in kinetic energy

$$\frac{d}{dt}\left(E_{rot}\right) = P_G - P_D \tag{4}$$

$$\frac{d}{dt}\left(\frac{1}{2}J\omega^2\right) = P_G - P_D \tag{5}$$

By derivating with value to t, the formulation is rewritten by:

$$\frac{d\omega}{dt} = \frac{P_G - P_D}{J\omega} \tag{6}$$

The amount of inertia is usually defined by the circumferential constant H [10]:

$$H = \frac{= \textit{Kinetic energy at rated speed}}{\textit{total base power}} \tag{7}$$

The inertia constant H becomes:

$$H = \frac{0.5\, J\omega_0^2}{S_b} \tag{8}$$

Shorting speaking, at last, when spoken in each unit, the frequency f and the angular frequency ω are equal, one gets:

$$\frac{df}{dt} = \frac{f_0}{2H}\left(P_{Gpu} - P_{Dpu}\right) \tag{9}$$

VII. SPEED CONTROL

The controls of governer can be developed to droop or isochronous governor by fine-tuning the given variables W, X, Y and Z which shown in Fig 5.

As shown in Fig. 5, the activation signal for the frequency of the comparison is the reference values in each single signal and the speedometer signal measured from the block of the PM coordinate device.

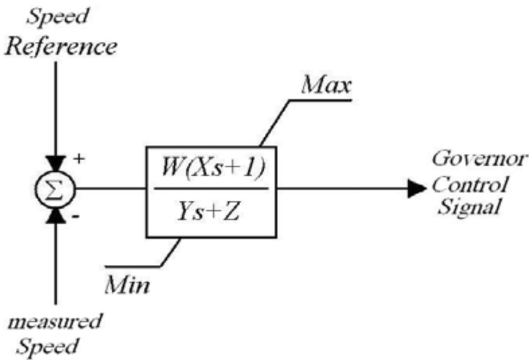

FIGURE 5. Speed control blocK.

VIII. DESCRIPTION OF THE IMPROVED IABC ALGORITHM

A. STANDARD ALGORITHM OF ABC

The algorithms not based on Froman are generally based on the behaviour of honeybees. The algorithm of an artificial bees' colony is a technique for solving optimization issues, which is based on the behaviour of honeybees in nature. In this method, each bee tries to get the best answer according to the laws of probability by direct cooperation and sharing information. In nature, each colony is composed of three groups: worker bees, food–source, and non-worker bees. The maximum duty of each hive is done by worker bees which include: raising children, caring for the queen and male bees, cleaning the hive, regulating hive temperature, gathering nectar, pollination, etc. Non-worker bees are divided into two groups of scouts and spectator. Scout bees search the surrounding environment for new food sources, and spectator bees wait in the hive for information from worker bees. Honeybees use a complex system for information about the location and quality of foods outside their hives. The relationship between bees takes place according to a ceremony which is called dancing. This communicating language is based on continuous movements of the bees. This dance, called rotational dance, is composed of information regarding the location and quality of food sources. In this type of dance, the number of rotations shows the distance and the duration of dance shows the quality of food sources. After seeing the dance, the spectator bees choose the best sources of food. The algorithm of the artificial bees' colony is based on the number of rotations and the movement of spectator bees toward the sources with stable quality [16], [17]. At first, a number of food sources are chosen randomly (primary answers); then scout worker bees move toward these sources and evaluate the amount and quality of each source; then they go back to the hives and give their information to spectator bees. Then each bee moves toward the location and decides to stay in that location or move to the next source, based on the type of the flower and the amount of its nectar. When the source is finished, they move to a new food source found by the scout bees. This process is continued until all needs of the hive are met [17].

The codec process of this algorithm is shown in the following steps:

1. Initial amount as primary answers of X_{ij}
2. Calculating primary answers in target function
3. Primary replication cycle = 1
4. Finding new answers based on finding new food sources V_{ij} next to X_{ij}, which $i = 1, 2, 3 \ldots SN$, $j = 1, 2, 3 \ldots D$, then there are $(X_1, X_2 \ldots X_i \ldots X_{SN})$ and $X_i = (x_{i1}, x_{i2} \ldots x_{iD})$) and D is the number of dimension of optimization problem. SN is number of onlooker bee. The following equation is used for finding new answers:

$$v_{ij} = x_{ij} + \phi_{ij}\,(x_{ij} - x_{k,j}) \tag{10}$$

   where k is the obtained answer in the neighbourhood of i and Φ is a random number between $(-1, 1)$.
5. Selecting the best source or the best answer between X_{ij} and V_{ij}
6. Calculating the probable amount for X_{ij} based on the following formula:

$$P_i = \frac{fit_i}{\sum_{i=1}^{SN} fit_i} \tag{11}$$

   In fact, it use the following formula to calculate the suitable answers:

$$fit_i = \left\{ \begin{array}{ll} \dfrac{1}{1+f_i} & f_i \geq 0 \\ 1 + abs(f_i) & f_i \langle 0 \end{array} \right\} \tag{12}$$

   The answers for P_i are between $(-1, 1)$.
7. Providing new answers (new sources) V_i based on spectator bees from X_i answers and determining the probability.
8. Selecting the best answers (the bees that eat more than others) between X_{ij} and V_{ij}.
9. Determining the corrupted sources and replacing them with random sources provided by scout bees by using the following formula:

$$x_{ij} = \min_j + rand(0, 1) \times (\max_j - \min_j) \tag{13}$$

10. Saving the best answer (qualified power supply) which has been achieved until this step.
11. Cycle = Cycle + 1

Repeating all the previous steps until achieving the condition needed for ending the program.

B. IMPROVED IABC ALGORITHM

However, ABC has been succeeded in finding the best answer to the optimization problem, but only considers the relationship between the queen and the chosen honey by the rule roll selection. This factor is generated randomly. Therefore, it is not able to use full capacity. To cope with this shortage, the interaction theory is proposed in this paper. In our theory, the $F(\theta_i)$ and $F(\theta_k)$ plays role of masses in space (to coincide with Newton laws), in fact, they are fitness amount of the employed bee that selected bee using the roulette wheel selection and the randomly chosen employed honey bee, correspondingly. So as to surmount this lack, the Newtonian law of universal gravitation is employed. In the standard IABC optimization algorithm the equation (14) is considered to indicate the global gravities between selected selections using the selection of roulette wheels and observer bees.

$$p_i = fit_i/(\sum_{n=1}^{SN} fit_i) \tag{14}$$

The mutual power between two things m_1, and m_2 is as below. Figure 6 shows the mutual interaction of these forces.

$$F_{12} = G\frac{m_1 m_2}{r_{21}^2}\hat{r_{21}} \tag{15}$$

$$\hat{r_{21}} = (r_2 - r_1)/(|r_2 - r_1|) \tag{16}$$

where, m_1, m_2,r_{21}, $\hat{r_{21}}$, F_{12} and G denotes mass of the item 1 and item 2, the division between the items, the unit vector described with equation (15), the gravitational force heads from the item 1 to the item 2 and the universal gravitational value, correspondingly. It shows the following formulation in a related mode for bees based on their ability [18]:

$$F_{ik_j} = G\frac{F(\theta_i)\times F(\theta_k)}{(\theta_{kj}-\theta_{ij})^2}\cdot\frac{\theta_{kj}-\theta_{ij}}{|\theta_{kj}-\theta_{ij}|} \tag{17}$$

$$x_{ij}(t+1) = \theta_{ij}(t) + F_{ik_j}\cdot[\theta_{ij}(t)-\theta_{kj}(t)] \tag{18}$$

where, $F_{ik}\cdot[\theta_i - \theta_k]$ denotes the universal gravitation laws among the employed bee, which is hand-picked by the onlooker bee, and more than one employed bees. F_{ik} denotes the factor controlling in the roulette wheel selection. By developing and considering the gravitation between the picked employed bee and n chosen employed bees, resulting are:

$$x_{ij}(t+1) = \theta_{ij}(t) + \sum_{k=1}^{n}\tilde{F}_{ik_j}\cdot[\theta_{ij}(t)-\theta_{kj}(t)] \tag{19}$$

where, $\tilde{F}_{ik_j}$ refer to the normalized gravitation force function. $k \in \{1,2,\ldots,BN\}$ and $j \in \{1,2,\ldots,D\}$ denotes randomly chosen indexes and x_i, t and θ_k are the place of the i^{th} onlooker bee, the generation number and the randomly chosen employed bee, respectively. D denotes the number of dimension of optimization problem. BN denotes number of onlooker bee. In fact, in the improved algorithm, the aggregation of standard particles, instead of randomly selected particles, is the reason that causes a high increase in the efficiency of this algorithm. The movement of scout bees: If the efficient amount of the function is not corrected in the next repetitions of the algorithm, this situation is called the limit and those sources are called abandoned sources. Worker bees start to replace new sources with abandoned ones. The movement of these bees is as below:

Placement: If the amount of food found in the next steps be better than previous ones, these amounts will be saved in the bees' memories.

The end of the programme: The programme will be continued until the end of all repetitions. If it reach a satisfactory amount, then the programme is finished, otherwise it will go to the second step. Figure 7 shows the flowchart of the proposed algorithm.

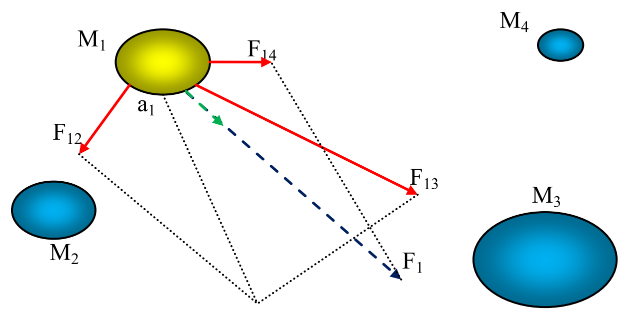

FIGURE 6. The way that things enter power into each other mutually.

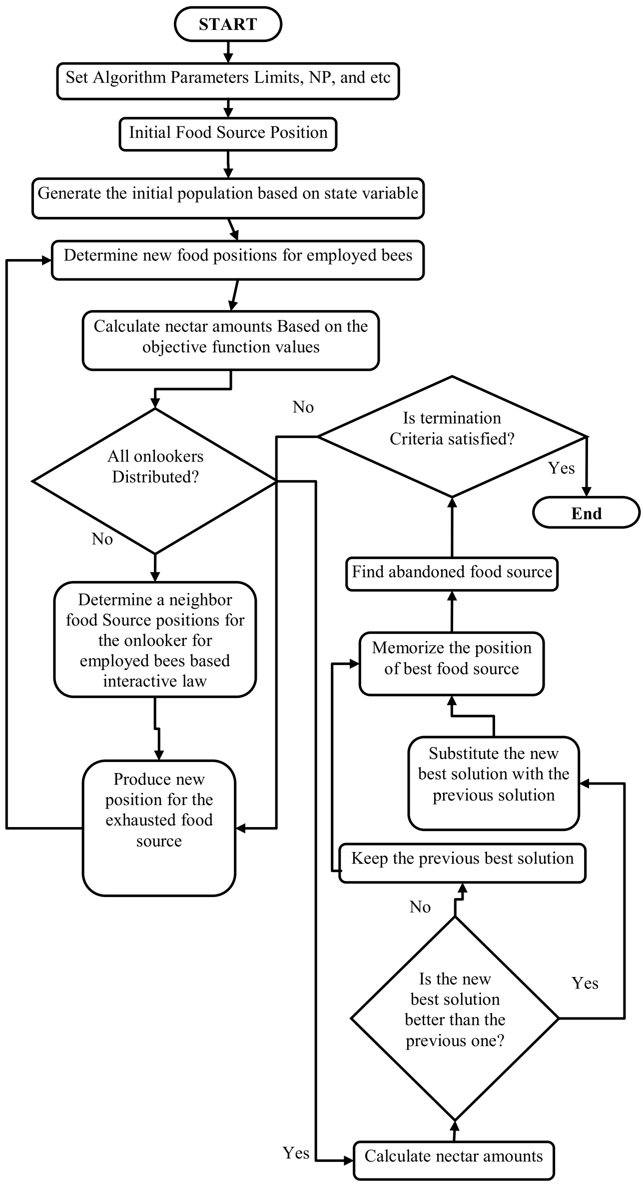

FIGURE 7. Flowchart of the proposed algorithm.

IX. THE PROPOSED IDEA OF CONTROLLING

PID control is one of the most successful areas in the software, and is a great alternative to the usual control of the method, when the process is very complex for analysis with typical techniques. This is because in almost all components of the industry and science, such as power systems, effortless to operate and familiar engineers. It ought to be noted that the momentary actions of the power system depends in particular on the control of the PID control variables owing to the direct and flow control lines. On the other hand, normally employed methods for optimal tuning profit PIDs are able of identifying or determining a global optimum for achieving the optimal level of system action owing to the complexity operating conditions of power systems, and they may be boring and computation time consuming.

The function used in this paper is based on minimizing the integral obtained from the multiplication of time and the absolute amount of output power of the turbine (ITAE). This target function is defined as expression (20):

$$ITAE = \int_{0}^{t_{sim}} t \cdot \Delta Pm(t)dt \tag{20}$$

By taking the uncertainties into account in designing controllers, the target function $f_{init.}$ will be assumed between 2.0 to 1 according to the electric power of the generator and simultaneously speed will be calculated as being between 2.0 to 6.0 per unit. The simulated target function $f_{init.}$ will be shown with 0.1 or $f_{init.}^{p}$ in response to the above changes. The target function is the average of the target function in response to all uncertainties.

The final target function of the proposed PID controller will be shown as below:

$$fitness = Mean\left\{f_{init.}^{p}(P, W)\right\} \tag{21}$$

ABC improved algorithm is used to optimize target function (21) in designing parameters of PID controllers. Fig. 8 shows the block diagram of proposed method based tuned PID controller to solve the proposed problem.

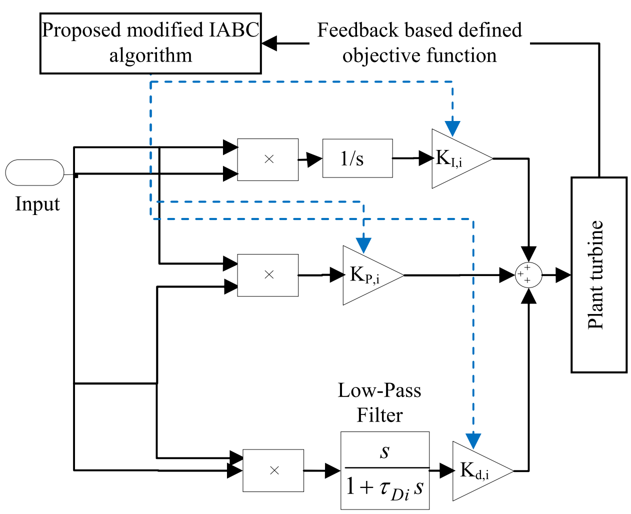

FIGURE 8. Structure of the proposed IABC-PID control strategy.

TABLE 1. Optimized values for PID parameters for load-frequency loop.

K_d	K_I	K_P	Algorithm
1.6035	0.7478	2.1626	IABC
1.2021	0.8042	2.1216	PSO
1.2065	0.6929	2.1011	GA

TABLE 2. Optimized values for PI parameters for load-frequency loop.

K_I	K_P	Algorithm
1.6521	0.4824	IABC
1.2863	0.5746	PSO
0.9656	0.6928	GA

The optimal PID tuning parameters problem can be formulated as the following constrained optimization problem, where the constraints are the PID parameters bounds. The optimization Problem can be stated as:

$$\begin{aligned} K_P^{\min} &\leq K_P \leq K_P^{\max} \\ K_I^{\min} &\leq K_I \leq K_I^{\max} \\ K_d^{\min} &\leq K_d \leq K_d^{\max} \end{aligned} \tag{22}$$

Typical ranges of the optimized parameters i.e. K_p, K_I and K_d are [0, 5].

X. DESIGNING PID CONTROLLER FOR CONTROLLING LOOPS

In this part, the proposed PID controller and PI are suggested respectively for load, temperature, and fuel system controlling loops by using the proposed algorithm in gas turbines whose information is provided in [15]. After applying the algorithm on target function (21), a controller has been designed for different operating points, paying attention to the uncertainties [19], [20]. The results of designing the proposed PID and PI controllers, load, frequency, temperature, and fuel system controllers are shown in Tables (1) and (2).

XI. SIMULATION RESULTS

The performance of the proposed controllers, which are based on the improved ABC algorithm, will be investigated to evaluate their performance. In this section, the proposed controllers of load–frequency, temperature, and fuel system of gas turbines (whose information is provided in [15]) will be tested to show their resistance performance, and then the results will be compared with those controllers which are based on the colony of the particles. In this comparison, the performance of the system will be investigated regarding changes in loading condition and changes in generator electric power in load–frequency controlling loop for 20 per cent. The performance of the time factor of controllers will be simulated by using the model proposed in Section 2. For this purpose, the exploitation points provided in Table (3) are used considering the changes in the amounts of the generator's electric power and turbine speed. The simulation results of given operating points regarding ascending changes 2/0 in turbine mechanical torque are shown in Figures 9–12. According to the simulation results, it is observed that all three proposed controllers are able to stop the oscillations or to stabilize the system at all operating points. As you can see,

TABLE 3. Operating pints to evaluate gas turbines.

	Power (pu)	Turbine speed
Case No	P	W
1	0.2	0.5
2	1	0.3
3	0.6	0.3
4	0.7	0.4

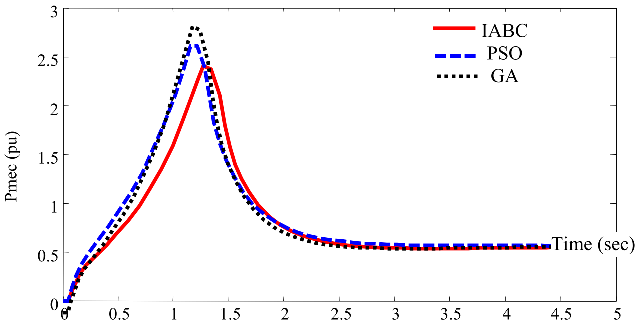

FIGURE 9. Operating point No.1: line (IABC), dash (PSO) and dots (GA).

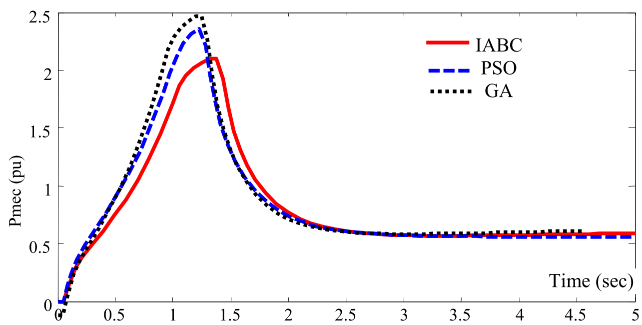

FIGURE 10. Operating point No.2: line (IABC), dash (PSO) and dots (GA).

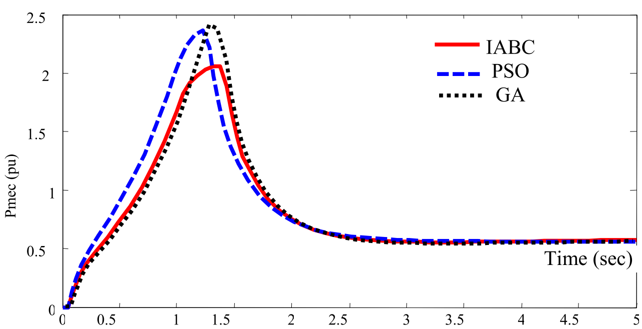

FIGURE 11. Operating point No.3: line (IABC), dash (PSO) and dots (GA).

although those controllers based on the PSO algorithm cause a high reduction in oscillation limits, in this case the oscillation limit will stop later. But the controller based on improved ABC algorithm has a favourable performance. Compared to the controllers based on the PSO algorithm, it has reduced oscillation limit well.

The FD evaluating criteria will be introduced under the following equation to evaluate the resistance of the controllers:

$$FD = (2 \times OS)^2 + (T_s)^2 \tag{23}$$

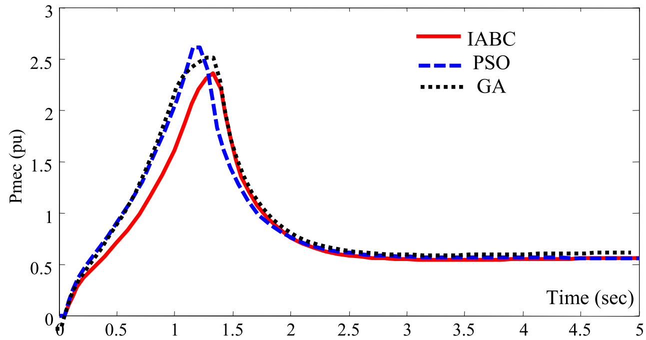

FIGURE 12. Operating point No.4: line (IABC), dash (PSO) and dots (GA).

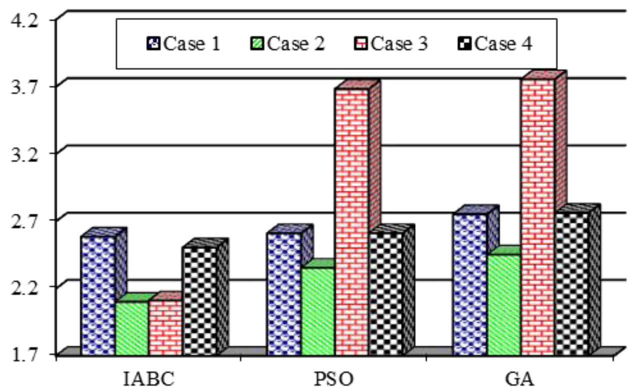

FIGURE 13. Changes of the amount of overshoot for obtained algorithms.

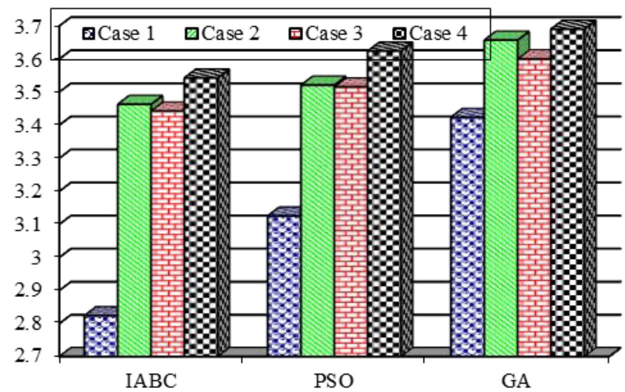

FIGURE 14. Changes of stop–time for obtained algorithms.

In these equations, the maximum overshoot (OS), stop–time (TS), and deviations of mechanical power of turbine are presumed to evaluate FD. The numerical results of the performance for all given operating points are shown in Figures 13–16. It is observed that the values of the performance indexes for those controllers which are based on ABC are smaller compared to GA. This shows that maximum overshoot (OS), stop–time (TS), and deviations of the mechanical power of turbine have reduced largely with the proposed method.

In view of the fact that initial population is generated by random numbers in case of stochastic simulation techniques, therefore, the randomness model is inherent property of these

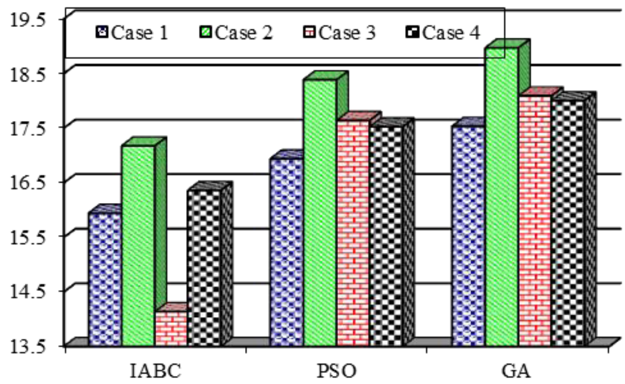

FIGURE 15. Changes of deviations of FD for obtained algorithms.

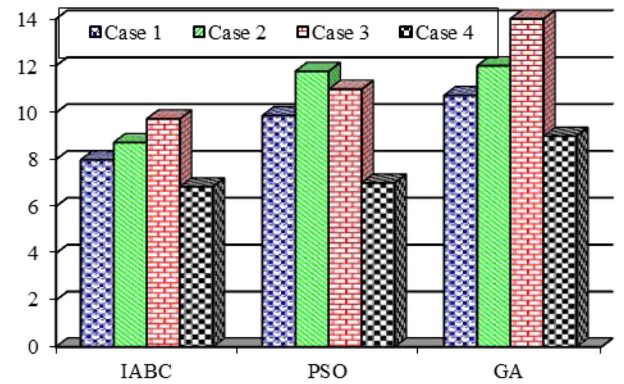

FIGURE 16. Comparison based on ITAE index for all operating condition in Table 3.

TABLE 4. Frequency of convergence for turbine system out of 100.

Method	0-10	10-50	50-100	100-200	200-500	500-1000	1000-2000
IABC	14	71	14	1	0	0	0
PSO	0	11	24	36	14	8	7
GA	0	7	14	8	41	21	9

techniques. For this reason the operation of stochastic search methods are judged out of a number of trials.

Numerous trials with different initial populations have been carried out to test the consistency of the proposed algorithm. In order to analysis the computational mistake and standard deviation (SD) of the proposed technique, many simulations are done considering number of trial runs and its distribution.

The variation of frequency out of 100 independent trials with is shown in Table 4. It can be seen that the proposed technique is robust and most consistent in producing lower loss.

XII. CONCLUSION

In this paper, a proposal is presented for designing PID controllers considering low–pass filters for load–frequency, and temperature controller of gas turbines, which is based on the improved ABC algorithm which called Interactive Artificial Bee Colony (IABC). In designing the proposed PID controllers, changes of operating point are considered, which are shown in the system's parameters which can guarantee the final simulation results in other operating conditions. Here the simulation of gas turbine based on documents of power-plant as real test system and its role in the stability of the system is investigated. In this regard, the controllers designing issue is turned into optimization under different operating conditions and the optimized parameters of controllers are adjusted by IABC algorithm, which is a strong method in optimizing in exploration and exploitation. The figures and tables results of simulation show that the designed controller using the IABC algorithm has better performance compared to PSO and GA algorithm. Implementations of simple PID controllers have been done to show the dynamic performance variations of the gas turbine process cycle. Thus, in the future works, the Gas Turbine Power Plant (GTP) model in this paper project should be integrated with power generator model of GTP simulator where moment of rotor inertia, mechanical and generator efficiency are considered. The simulation results show that the proposed controller has better results in operation conditions and fuel consumption saving compared to classical controller.

Based on the obtained results, the proposed model can be used to discuss the stability and its effect on low frequency. Also optimization intelligence models adopted with fuzzy theory can be used to set optimization parameters.

APPENDIX

A. INTRODUCION OF PSO AND GA

1) PARTICLE SWARM OPTIMIZATION (PSO)

The PSO is a population-based random-search algorithm presented by Eberhart and Kennedy [21]. If we consider each particle as a bird, then in the PSO algorithm we have a group of birds flying in the problem space to find the answer. The position of each bird is a probable answer to the problem. Each bird is assigned two position vector (Xi) and velocity (vi). In the n-dimensional search space, these two vectors can be represented as $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$ and $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$ in most of its components. During the flight, each bird exchanges with other birds and thus optimizes its movement path. There are several models for optimizing the bird group, but the most common one is the gbest model, which uses the entire population as a neighborhood for birds in the search area. In each replication, the best particle (gbest) shares its information with the rest of the particle. Each particle adjusts its position according to the position of the best gbest and its best experience (pbest) according to the following relationships:

$$v_i^{t+1} = wv_i^t + c_1 r_1 (pbest_i^t - x_i^t) + c_2 r_2 (gbest^t - x_i^t)$$
$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

c_1 and c2 are called acceleration coefficients and determine the impact degree of the best member of the group and personal experience.

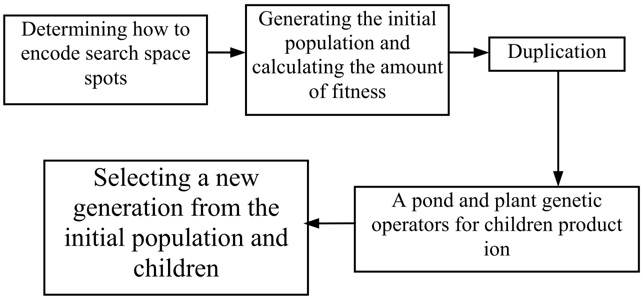

FIGURE 17. Basic principles and concepts of using Genetic Algorithm and its components.

r_1 and r_2 are two random numbers created in the interval [1 and 0]. W is the weight of inertia, and models the dependence of the bird on its predecessor. Inertia weight usually decreases linearly during the execution of the algorithm:

$$w(k) = w_{\max} - \frac{w_{\max} - w_{\min}}{Max \cdot iter} \times t$$

Where Max.iter represents the maximum number of repetitions (stop criteria) and t repeated counters. In this paper, we put $c_1 = 1/5$, $c_2 = 0.4$ $w_{\min} = 0.4$ and $w_{\max} = 0.9$.

2) GENETIC ALGORITHM (GA)

The genetic algorithm starts simultaneously with a series of data (points) and follows some of the optimal points in parallel so that the probability of being involved in local optimizations is greater than that of the points as is shown in Figure 17. It should be noted that this point is separate from the choice of several initial points in terms of mathematical methods and the continuation of each one separately. Because in this method, information are exchanged between the points and they take advantage of each other to get the optimal response. While selecting a few initial startups for mathematical methods are only a few solutions of separate path.

The important point to be noted is that random selection in the genetic algorithm is not a simple random choice, but rather a directional selection. In this way, the genetic algorithm uses this random selection as a tool to guide the search operation and, by utilizing historical information in each repetition, improves the target function. Figure 16, in brief, illustrates the main part of the implementation of the genetic algorithm. For further details refer to [22].

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