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Optimal FOPID Control for the Exhaust Temperature System of a Gas Turbine

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Abstract. : In recent times, the application of fractional mathematics helps in modeling the mechanical and electrical properties of real systems. Fractional integrals and derivatives have found full attention in the control of dynamical systems when the controlled system and the controller is described by a set of fractional order differential equations. This paper elaborates the ability of grey wolf optimization (GWO) in optimizing the fractional order proportional integral derivative (FOPID) controller parameters to control the exhaust temperature of a gas turbine (GT). The maintenance and operation of GTs at optimum performance with minimum fuel stroke ratio is mandatory in the electricity production sector. The obtained results of the optimum values of FOPID based exhaust temperature controller are compared with those attained using the optimum values of the current existing 265 MW simple cycle, actual single-shaft heavy duty GT. The attained results are impressive in terms of enhancing the dynamic performance and decreasing the response time.

Keywords: Grey wolf optimization, fractional order proportional integral derivative, optimal control, load disturbances, Heavy-duty gas turbine, fuel stroke ratio, Inlet guide vans.

1. INTRODUCTION

Gas Turbines (GTs) inherently depict unique frequency response characteristics compared with other conventional synchronous generation technologies as the governor response does not entirely determine their active power output during frequency deviations of the power network [1]. Thus, GTs' dynamics have significant influence on the system stability during frequency events in power networks [2]. Aegidius Elling and Norwegian built the first gas turbine using rotary dynamic compressor and turbines in 1903 [3]. The first GTs based power station of 8 kW was credited because of this effort, which was further improved to produce about 33 kW at speed of 2000 rpm and exhaust gas temperature of 773 K instead of 673 K in Elling model in 1904. A practical GT was successfully built in 1905 by French company "Societe Anonyme des Turbomoteurs" when they assembled first practical GT [4]. At first, the design of this engine was built to provide its power according to a condition of constant pressure with efficiency of 3%. The fuel was the input of the machine and the useful shaft power was considered as the output of the machine. The engine had a centrifugal compressor of 20 or more stages and its efficiency was of less than 60% with pressure ratio of 4 and inlet temperature of 393°C approximately. The first ever gas turbine built with a single compressor operates at an inlet temperature of 550°C and speed of 3000 rpm to generate a power of 15400 kW. The compressor of the system was powered by 1100 kW at an ambient temperature of 20°C [5]. The gas turbine is used as the prime mover for the electricity generating system. Generally speaking, this power station is used as a combined with the conventional steam unit power station to produce limited amount of power. Combined Power Stations (CPSs) are used as peaking power plants in most countries. However, the systems of gas turbines are very complex, the operation of which at peak performance is necessary [6]. Moreover, the control and stability problems of the power system are critical considerations in the design and operation of modern power systems. In particular, during the past decade, where power generation has undergone several extremely significant changes, and the growth in interconnections and the use of new technologies are the main reasons of the complexity of power systems increasing continually [7].The main parameters which had made GTs to be popular in different power systems are their lower greenhouse emissions as well as the higher efficiency especially in the case of CPSs. Figure (1) indicates the cycle of an Industrial Heavy Duty Gas Turbine (HDGT).

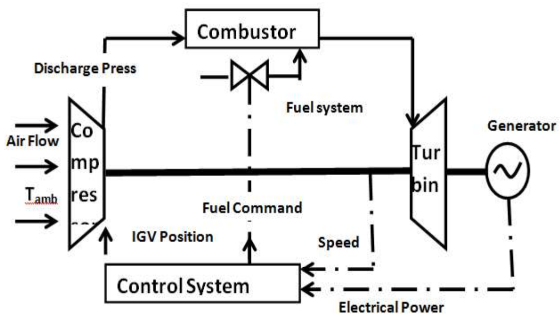

Fig.1. Simplified Schematic of Gas Turbine System Overview

The modular structure of the gas turbine controller gives it the advantage to be adapted for achieving various requirements at all operating conditions of GTs such as in simple-cycle, combined-cycle, single-fuel or dual-fuel operation modes. Several gas turbines modeling is based on different models. Among these models, the most applicable with high efficiency and fuel stroke ratio are the following [2]: (1) Rowen's Model. (2) GGOV1 Model. (3) IEEE Model. (4) CIGRE Model. (5) Frequency-Dependent (FD) Model. (6) Detailed Model. Rowen's and Vournas's model will be discussed briefly in this paper because it is considered the most commonly utilized model for this type of system studies due to its high efficiency in the field of power generation [3].

2. Rowen'sModel

This model appeared in Rowen's paper [8]. It entails a simplified mathematical model for heavy-duty gas turbines. In Rowen's model, the following assumptions were presented: (i) It is a heavy-duty gas turbine operated in a simple cycle with no heat recovery. (ii) Relatively constant speed is maintained between 95%–107% of the rated speed. (iii) It operates at an ambient temperature of 15° C and an ambient pressure of 101.325 kpa.In 1992, Rowen extended the original model as in [9] to include inlet guid vans (IGVs) and their effect on the gas turbine dynamics, especially the exhaust temperature as the original model has a constant amount of air for any power load due to the absent of IGVs which give the ability to control fire and exhaust temperature when the gas turbine is at the combined cycle mode as shown in Figure2. The model has been utilized to investigate the impacts of the governor on system operation. It was derived from and validated against the actual operation data and found to be adequate for real-life implementation. It is shown in Figure.2 in a simplified block diagram format. Rowen's model consists of a set of algebraic equations describing the steady-state characteristics of the gas turbine thermodynamics, simple time delays, and a few related controls, including the temperature control, governor, and acceleration control. The extended Rowen's model is enabled more accurate modeling of a gas turbine operation installed as part of a Combined Cycle Gas Turbine (CCGT). Therefore, it is considered the starting point and backbone for the development of most CCGT models in recent years [10]-[11]. The extended Rowen's model [3] is enabled more accurate modeling of a gas turbine operation installed as part of a CCGT. Therefore, it is considered the starting point and backbone for the development of most CCGT models in recent years such as [8]-[9]. As shown in Figure (3), dynamics of the gas turbine in Rowen model is mainly made of the function blocks F1, F2 and simple time delays. There is a transport delay associated with gases in the turbine and exhaust system that must be included before any temperature calculations. The temperature of the exhaust gases from the turbine is then determined as an output for block F1. The characteristics of F1 can be assumed to be linearly dependent on speed (N) and fuel flow (WF). A short time delay is also incorporated in the fuel system to take into account the time delay associated with the combustion reaction (CR). The torque in the turbine is then calculated using block F2. In the restricted operating range of this model, the gas turbine torque (TRQD) is linear with respect to fuel flow and turbine speed. The mechanical power output of the gas turbine (PMG) is the product of the torque by the speed. An additional first-order lag associated with the compressor discharge volume (TCD) is incorporated before the turbine torque being calculated. Terminologies used throughout the block diagrams are kept in the per-unit system, except for temperatures. As illustrated in [8], Rowen's model is based on heavy-duty gas turbine, simple cycle, single-shaft, generator drive only. In extended Rowen's model (Rowen-II), the gas turbine had been equipped with modulating IGVs and hence assumed to be a part of a CCPP. It is easy to conclude that there are two main function blocks in Rowen's models, such that block (F1) is to calculate the exhaust temperature (T_X), while the block (F2) is to calculate the output torque of the gas turbine (TRQ_D). The governing equations for each block are described below [12, 13].

$$\mathrm{T_X} = \mathrm{T_R} - 700(1 - \mathrm{W_F}) + 550(1 - \mathrm{N}) \qquad (1)$$

where T_R Turbine rated exhaust temperature (°F). W_F Mass fuel flow (pu). N is turbine rotor speed (pu).

The governing equation of $\boldsymbol{F_2}$ is given as[8, 14, 15]:

$$TRQ_D = 1.3(W_F - 0.23) + 0.5(1 - N) \qquad (2)$$

The governing equation of F_3 is given as [14, 16]

$$W_X = N\frac{519}{T_A + 460}(Ligv)^{0.257} \qquad (3)$$

Where

Ligv Inlet guide vane position (pu).

$\boldsymbol{T_A}$ Ambient temperature (°F).

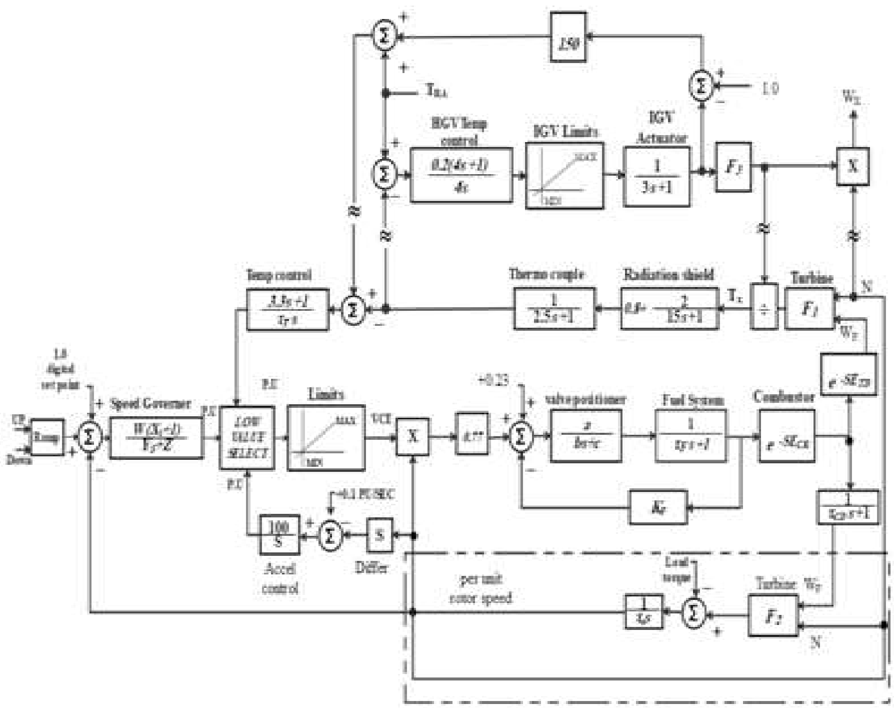

Fig2. Rowen's Model with IGV[9, 16]

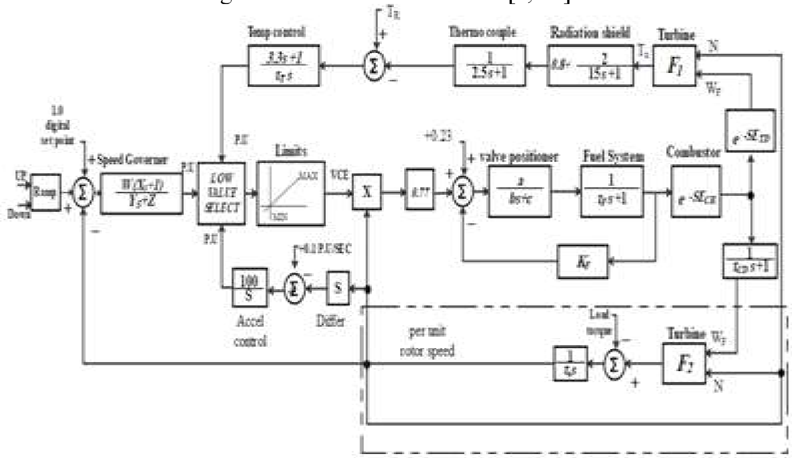

Fig3: Rowen's Model with constant IGV [8, 16]

3.Case Study of 265 MW HDGT

A 265 MW simple cycle, single-shaft HDGT and its available operational and performance data are presented and studied for deriving the parameters of Rowen's model for HDGT. The nominal data of the selected HDGT for modeling are listed in Table (1). The standard conditions used by the gas turbine industryare: (i) Ambient temperature (***T_A***) 15 ºC / 59 ºF. (ii) Ambient pressure (***P_A***) 1.013 bar / 14.7psia. (iii) Relative humidity (***Φ***)60%. These conditions are established according to the International Standards Organization (ISO) [9, 17, 18, 19].

Table (1): Design Specifications of an Actual Single-Shaft HDGT[18]

Parameter	***Symbol***	***Unit***	***Value***
Electrical power	P_{GT}	MW	265.4
Nominal frequency	*F*	Hz	50
Turbine speed	*N*	rpm	3000
Cycle efficiency (simple cycle)	η	%	38.49
Cycle efficiency (combined cycle)	$\eta_{combined}$	%	~ 58
Compressor type	17-stages axial		
Compressor pressure ratio	*CPR*	bar	17.29
Compressor inlet air mass flow	W_A	kg/sec	651.1
Combustor type	Annular		
Primary operating fuel	Natural gas		
Fuel mass flow	W_F	kg/sec	13.9
The lower heating value of fuel	*LHV*	kJ/kg	50012
Turbine type	4-stages axial		
Turbine diffuser exhaust mass flow	W_X	kg/sec	664.8
Turbine diffuser exhaust temperature (as a set point)	*TET*	^{o}C	585.6

As shown in Figure (4), the values of the frequency-load and temperature control blocks are based on [9], for simulation purposes. The range of the typical values which are usually used for HDGT dynamic models and all obtained values of the controller's parameters are given in [9, 11,14, 19] .

A fraction order proportional integral derivative (FOPID) controller will be used to control the exhaust temperature of a gas turbine alternative to the existing temperature control system (PI controller) of HDGT.

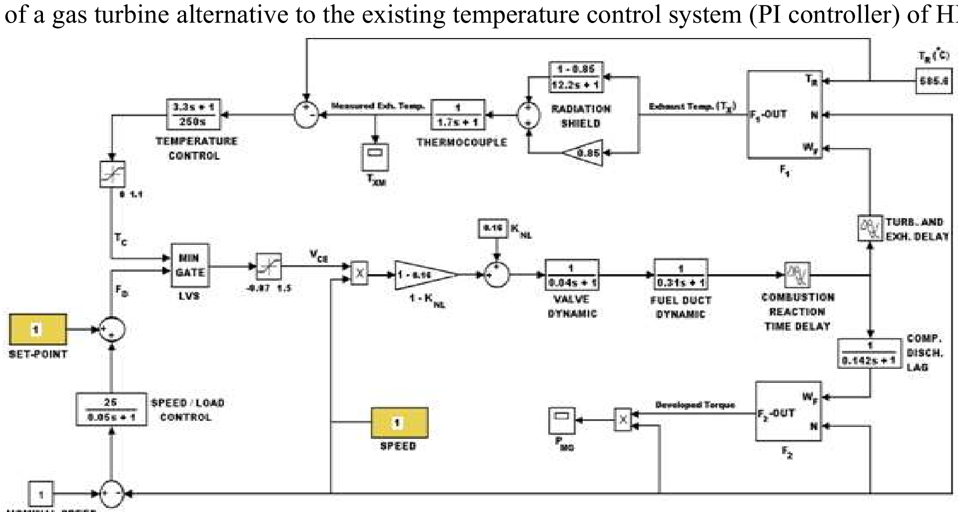

Fig4: 265MW HDGT Model for Dynamic Studies

4. FOPID Controller:

Fractional order proportional-integral-derivative (FOPID) controller can be considered the suitable controller to deal with fast output sampling (FOS), as a generalization of PID controller. The FOPID controller has more flexibility because it has more parameters to be tuned. In the literature, the authors have employed many optimization techniques to optimize the parameters of FOPID [20-25]. For the standard model (NM: normal mode) more than one evaluation index are defined and used for parameters optimization. The development for the internal model control (IMC) and the design procedure of IMC-FOPID is similar to the classical PID[26].

The classical PID controller is described in the form

$$G_{PID}(s) = K_P + \frac{K_i}{s} + K_d s \quad (4)$$

FOPID controller which can be considered as a generalization of the classical PID controller with a similarstructure with the classical PID controller which can bedescribed in the form

$$G_c(s) = K_P + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \quad (5)$$

Where λ and μ can take any values within the range (0, 2) [27] and the tuning of FOPID parameters are obtained using GWO algorithm.

5. GWO ALGORITHM

The GWO is a meta-heuristic algorithm proposed by Mirjalili et al. in 2014 [28], which imitates the social manners of grey wolves. These wolves live in a group contains 5-12 members. In this group, the strict dominance hierarchy is practiced where the group has a leader named alpha (α), supported by secondary ones named beta (β), which aid α in decision-making. The rest members of the group are named δ and ω as

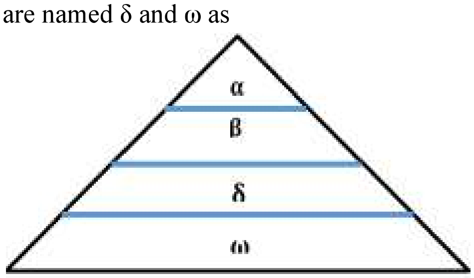

Fig.5 Grey wolf hierarchy

The procedure of hunting the food by the grey wolves is looking for the food, surrounding the food, hunting, and attacking the food. The arithmetic model of surrounding the food is written asfollows[28]:

$$\overrightarrow{D} = \left|\vec{C}.\overrightarrow{X_{Pi}} - \overrightarrow{X_i}\right| \quad (6)$$

$$\vec{X}_{i+1} = \vec{X}_{Pi} - \vec{A}.\vec{D} \quad (7)$$

where X_i is the place of the grey wolf, X_{pi} is the place of the food, D is the distance, A and C are vectors calculated as following [28]:

$$\vec{a} = 2 - 2 \times \frac{t}{Max_{iter}} \quad (8)$$

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \overrightarrow{a} \quad (9)$$

$$\vec{C} = 2.\vec{r}_2 \quad (10)$$

The analogy between the hunting mechanism of GWO and optimal control design can be introduced as follow: The fitness function or objective function (J) is defined as:

$$J = \int_0^{T_{final}} t * [|(\Delta T_{X_1})| + |(\Delta T_{X_2})| + |(\Delta P_{tie})|]dt \quad (11)$$

Where, T_{final} is the final simulation time, ΔT_X is the change in exhaust temperature and ΔP_{tie} is the power loading deviation.

The problem constraints are the controller parameters' boundaries which can be presented as follows:

$$K_{p,min} \le K_p \le K_{p,max}, K_{I,min} \le K_I \le K_{I,max}, K_{D,min} \le K_D \le K_{D,max}$$

$$\lambda_{min} \le \lambda \le \lambda_{p,max}, \mu_{min} \le \mu \le \mu_{max}$$

Where, $K_{PID,min}$, $K_{PID,max}$, μ_{min}, μ_{max}, λ_{min}, λ_{max} are the minimum and maximum values of the PID-controller parameters.Hence, the optimal design of FOPID controller problem can be achieved by minimizing J under these constraints.

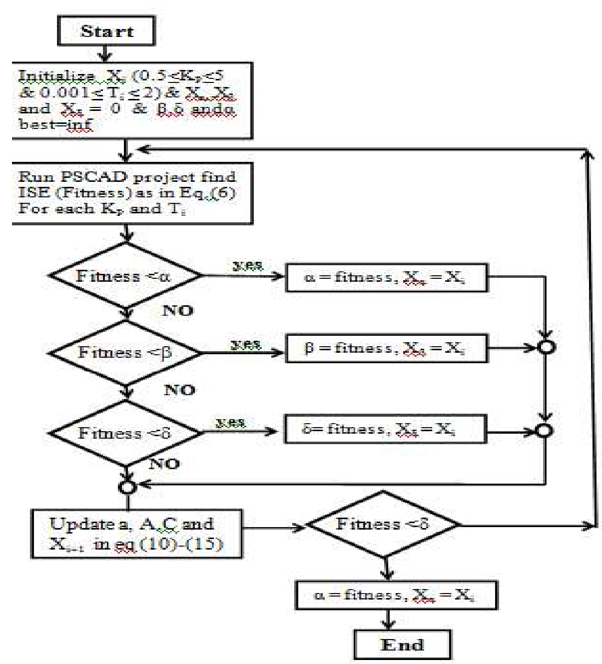

Fig.6.Flowchart of the GWO Algorithm [21]

where r_1 and r_2 are random numbers between [0, 1]. The parameter is a variable that is linearly reduced from 2 to 0, while the iterations increased. The process of looking for the food position (the optimum solution) could be attained by diverging the search entities when$|A| > 1$. The process of getting the food could be attained by the convergence of the search entities when$|A| < 1$. A entity lead the hunting with β and δ entities support as in equations from (13)to(15) [28].So, it can be considered as a simulation for the way of the algorithm to find the optimum solution like where the group has a leader named alpha (α), supported by secondary ones named beta (β) which considered the set points of the analyzing data, and the positions and distance between them and its vectors which expressed as D is the distance, A and C are vectors calculated effect on the controller decision also, these distances express the main guide for optimal selection. Figure.6 shows the flowchart of the GWO algorithm. Like other meta-heuristic algorithms, the GWO algorithm can be disposed to stagnate in a local minimum but the parameters A and C can help the GWO algorithm to avoid stagnation.

$$\vec{D}_{\propto} = \left|\vec{C}_1.\vec{X}_{\propto i} - \vec{X}_i\right| ,\ \vec{D}_{\beta} = \left|\vec{C}_2.\vec{X}_{\beta i} - \vec{X}_i\right|$$

$$\vec{D}_{\delta} = \left|\vec{C}_3.\vec{X}_{\delta i} - \vec{X}_i\right| \quad (13)$$

$$\vec{X}_1 = \vec{X}_{\propto i} - \vec{A}_1.\vec{D}_{\propto}\vec{X}_2 = \vec{X}_{\beta i} - \vec{A}_2.\vec{D}_{\beta}$$

$$\vec{X}_3 = \vec{X}_{\delta i} - \vec{A}_3.\vec{D}_{\delta} \quad (14)$$

$$\vec{X}_{i+1} = \frac{\vec{X}_1+\vec{X}_2+\vec{X}_3}{3} \quad (15)$$

6. RESULTS AND DISCUSSION

Here, the performances of both the GWO-FOPID and the existing temperature control system (PI controller) of HDGT to control the exhaust temperature of a gas turbine are compared. The performance criteria used in evaluating the FOPID controller parameters in the GWO tuning method are the ITSE, ISE, ITAE, IAE (includes Integral time absolute error (ITAE), Integral square error (ISE), Integral time square error (ITSE) and Integral absolute error (IAE).Then the parameters which achieved the best performance are selected to be the tuning parameters of the FOPID controller. The performance criteria of IAE is the best according to the lowest overshoot and shortest rise time, so the parameters of FOPID (K_P, K_I,K_D,λ, μ) controller, which evaluated by using that performance criterion, are expected to achieve the main aim to maintain turbine operation at optimum performance.

Table (2): the parameters of tuned FOPID with GWO

K_P	K_I	K_D	λ	μ
7.609383778	4.638500058	1.372830729	0.914517744	1.847641023

- **CASE (1) Sudden Additional Load**

To compare between the behavior of GWO-FOPID and existing temperature control system (PI controller) of HDGT a disturbance of increasing the exhaust temperature above the rated value is assumed, as the load of the turbine will increase suddenly by 20% above the rated MW value according to the power network load and frequency changes

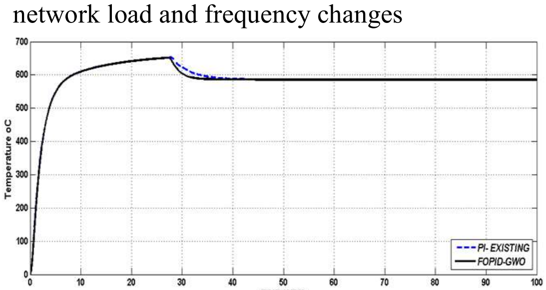

Fig.7. Exhaust temperature response for existing (PI-controller) and GWO-FOPID controller.

Referring to Figure (7), which represents the exhaust temperature response for GWO-PID and existing PI-controllers, the preference of the GWO-FOPID controller to deal with the assumed operation condition can be observed. Table (3) summarizes the more detailed results of the comparison.

Table (3) Comparison between GWO-FOPID and Existing PI- controllers

	GWO-FOPID controller	Existing PI-controller
Max value of temperature (max overshoot)	648°C (10.9%)	652°C (11%)
Time to start control action (rise time)	25 Sec.	28.3 Sec.
Time to track the temperature to steady-state.	31Sec.	44 Sec.

As can be observed from Figure (7) and Table 3, the rise time, settling time and absolute error of the GWO-FOPID control are shorter than the existing PI controller. However, it can also be observed that the overshoot of PI-control is more significant than that of the GWO-FOPID control. So, the GWO-FOPID controller can track the reference temperature well. Also; the high-temperature overshoot problem of the existing PI-control remains solved. Finally, it can be concluded that the using of the GWO-FOPID controller to control the temperature of the turbine increases the ability of HDGT to deal with running and operation conditions efficiently more than the existing PI-controller.

- **CASE (2) Variable Sequential Loading**

In this case, a variable realistic sequential loading for the turbine is assumed which has the following sequence as shown in Figure (8): (i) Increase from 100% of the rated MW to 120% at 10 Sec then remains constant for 20 Sec. (ii) Decay from 120% to 110% at 10 sec. (iii) Increase from 110% to 130% at 10 Sec. (iv) Decay from 130% to 110% at 30 Sec.

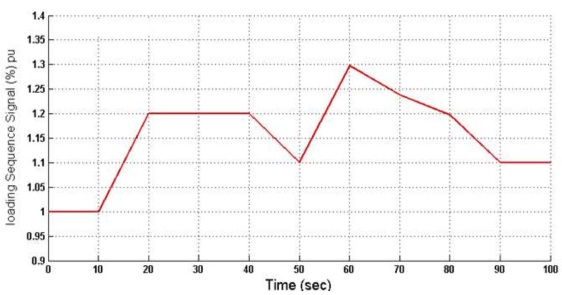

Figure.8.loading Sequence Signal

Figure (9) and Table (4) show the comparison between the behavior of GWO-FOPID and the existing temperature control system (PI-controller) for HDGT when the load of the turbine changes by the previous rate of MW values according to the power network load and frequency changes.

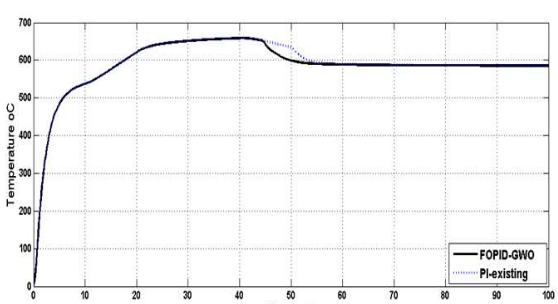

Fig.9. Exhaust temperature response for existing (PI-controller) and GWO-FOPID controller in case (2).

Table (4): Comparison between GWO-FOPID and Existing PI-controllers in case(2).

	GWO-FOPID controller	Existing PI-controller
Max value of temperature (max overshoot)	658°C (12.3%)	658°C (12.3%)
Time to start control action (rise time)	38Sec	40 Sec
Time to track the temperature to steady-state.	47 Sec	59Sec

7.Conclusion

The paper presents a new approach in optimizing the FOPID controller parameters to control the exhaust temperature of a 265 MW simple cycle HDGT single-shaft gas turbine. Results have shown that although the proposed GWO-FOPID controller incorporating ITSE, ISE, ITAE and IAE performance criteria can produce system responses with little rise time, settling time and absolute error as well as coping with ambient temperature variation. A suitable choice of FOPID-controller's parameters K_P, K_I, K_D, λ and μ can simultaneously maintain reasonably small values of all transient response characteristics including the rise time, settling time and absolute error, as well as maximum overshoot. The enhanced dynamic performance of HDGT provides the opportunity to increase the service life of the turbine, as it makes it possible to increase the loading on the same turbine in the future and raise the value of the energy generated.

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