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Tuning of 2DOF Controllers for the Speed Control of a Gas Turbine

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Abstract:

This research paper aims at investigating the use of four types of 2DOF controllers to control the speed of a gas turbine for reference input tracking. MATLAB control and optimization toolboxes are used to tune the four controllers using functional constraints to adjust the performance of the closed loop control system. The performance of the control system of the gas turbine using the four 2DOF controllers is compared of that using a conventional PID controller where graphical and quantitative comparison is presented. The best 2DOF controller structure is assigned based on these comparisons.

Keywords — **Gas turbine speed control, 2DOF controllers, controller tuning, MATLAB optimization toolbox, Control system performance.**

I. INTRODUCTION

Gas turbines play an important role in engineering since they have wide range of applications. They are used in aircrafts, helicopters, ships, locomotives, tanks, buses, cars, electric power generation oil and gas industries, turbo-compressors, fans and pumps [1-6].

Abdin (2000) described the design model of a gas turbine and designed an optimal controller for the excitation system. He compared with conventional controllers [7]. Junji et.al. (2008) developed a gas turbine plant control system. The developed control system could control the entire plant incorporating boilers, steam turbines and auxiliary machines. They developed also compact control system for small and medium gas turbines [8]. Mahat, Chen and Jensen (2009) presented three different gas turbine governors for possible operation of distribution systems in an islanding mode of the Danish distribution systems. They showed the dynamic model of the gas turbine with fixed speed droop and with isochronous controller with feedback. They presented also the performance of the controller when islanded [9].

Biron, Sedigh and Biron (2011) provided a quantitative feedback theory for the robust control design of a gas turbine in the presence of uncertain parameters. They identified the dynamic model of the plant in the discrete and continuous form as a 3/4 transfer function model. They designed a QFT robust controller to control the identified gas turbine [10]. Khalipour, Valipour, Shayeghi and Razmjooy (2013) proposed a robust and evolutionary based PID controller to control the frequency response and evolutionary based PI controller to control temperature. They tuned the PID controller using the evolutionary algorithm [11]. Hafaila, Benyounes and Guemana (2015) proposed a PI control design for an industrial gas turbine based on fuzzy modelling. They concluded that their proposed fuzzy model was reliable and suitable for gas turbine control and diagnosis [12].

Mostafa and Hassan (2016) investigated the behavior of Micro Gas Turbine with PMSE under load variations using different controllers based on evolutionary computational techniques such as genetic algorithm, particle swarm optimization and adaptive accelerated coefficients particle swarm optimization [13].

Rangaswamy and Vijayaragavan (2018) proposed a control scheme for a gas turbine plant. They presented a design for for fuzzy controller to control an inlet guide vane controlling the air flow to the turbine and control the fuel flow against load/speed during demand conditions. They used conventional PID and fuzzy controllers with comparison of the dynamic system performance using the two control systems [14]. Imani and Mantazeri-Gh (2019) designed a mini-max switching controller for a high bypass two-spool turbofan engine. They extracted the conditions for absolute stability using the multivariable circle criterion. They compared the behaviour of the mini-max controller in tracking a desired fan speed with that of the min-max/SMS controller [15]. Mohamed and Khalil (2020) reviewed the modelling techniques and control strategies of gas turbine power generation plants. They classified the modelling approaches and reported the main features of each category or approach [16].

Park, Moon and Kim (2021) proposed a method to optimize the set point schedule of a PID controller to improve the ramp-rate while decreasing the negative impacts for a 170 MW class using a genetic algorithm. They used an advanced control to improve the ramp-rate of the gas turbine. They used optimized set-point schedules to minimize the fluctuation in the rotational speed and temperature using a genetic algorithm [17]. Talah and Bentarzi (2022) focussed their study on the effectiveness of the frequency control system in a combined cycle gas turbine plant. They developed a dynamic model for the plant and examined the response of the system following a frequency deviation [18].

II. PROCESS

The controlled process is a heavy duty gas turbine plant having the following 0/4 transfer function model [19], $G_p(s)$:

$$G_p(s) = N(s)/N_r(s) = 2051/(s^4+42.54s^3+501.7s^2+1020s+2092) \quad (1)$$

The transfer function model in Eq.1 is for reference input speed tracking. It has a unit step time response for step input tracking generated by MATLAB commands '*step*' and '*plot*' [20] as shown in Fig.1. It has the following time based characteristics:

- Maximum percentage overshoot: 21.393 %
- Settling time: 3.85 s
- Steady state error: 0.0191

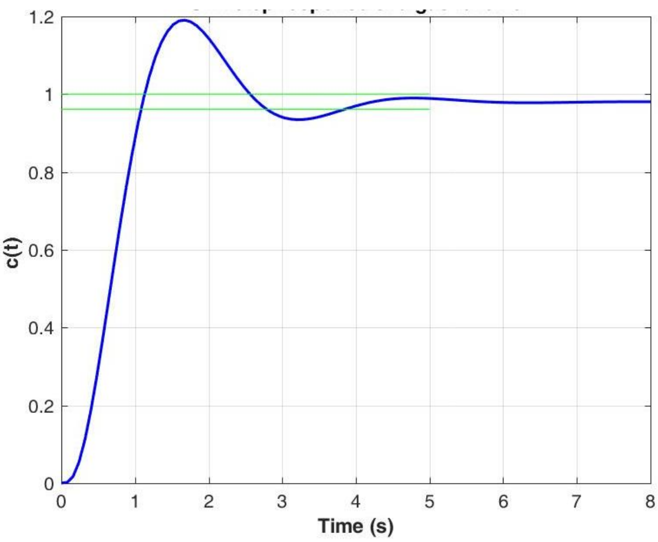

Fig.1 Unit step time response (open loop) of the gas turbine.

III. CONTROLLING THE GAS TURBINE USING A PID CNTROLLER

A conventional PID controller has a transfer function, $G_c(s)$ given by:

$$G_c(s) = K_{pc} + (K_i/s) + K_d s \quad (2)$$

Where: K_{pc} = controller proportional gain
K_i = controller integral gain
K_d = controller derivative gain

The closed loop transfer function of the control system incorporating a PID controller (defined by Eq.2) and the gas turbine (defined by Eq.1) is obtained from the block diagram with both controller and process in series in the forward path.

The MATLAB optimization command '*fmincon*' [13] is used to tune the PID controller using the integral of time multiplied by absolute error (ITAE) as an objective function subjected to functional constraints on the maximum percentage overshoot and the settling time to enhance the time-based characteristics of the closed loop control system. The tuning results are:

$K_{pc} = 0.3244$, $K_i = 0.7101$, $K_d = 0.1040$ (3)

The closed loop transfer function of the control system incorporating the PID controller with its tuned gains of Equation3 and the process with its transfer function given by Equation1 is given by:

$M(s) = (213.3\, s^2+665.4s+1456) / (s^5+47.54\, s^4+501.7\, s^3+1233\, s^2+2757s+1456)$ (4)

The unit step time response of the control system using the transfer function in equation 4, is shown in Figure 2.

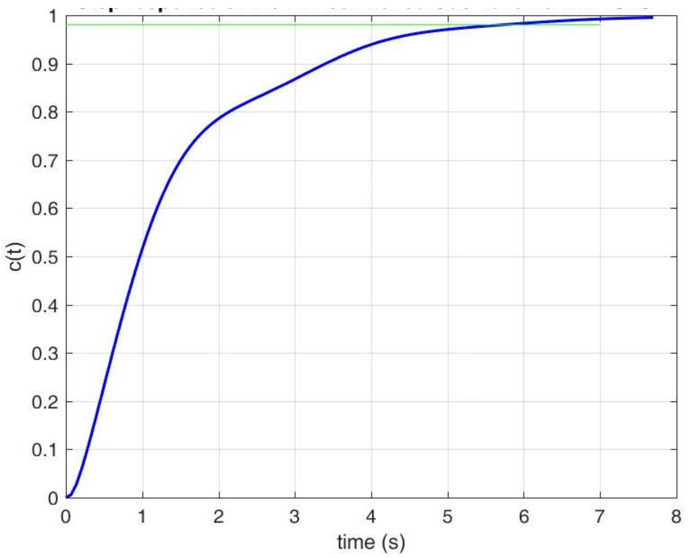

Fig. 2 Step time response of the PID controlled gas turbine.

The step time response during reference input tracking using the PID controller has the following characteristics follows:

- Maximum percentage overshoot: 0
- Settling time (using a ±0.02 band around the steady state response): 5.7 s
- Steady state error: 0

IV. CONTROLLING THE GAS TURBINE USING A 2DOF-PID CONTROLLER (STRUCTURE 1)

There are a number of different structures for the 2DOF controller. The first structure is shown in Fig.3 [21].

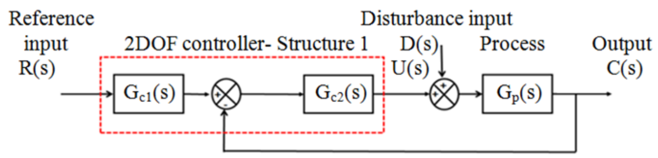

Fig.3 Process control using a 2DOF controller (structure 1 [21]).

Fig.3 shows the location of the reference and disturbance inputs of the control system and using terminology used by the author throughout his research.

The first sub-controller of transfer function G_{c1} may be a 1/1 filter, PI with filter, PID with filter [21], 2/2 PID controller [22] The other sub-controller having a transfer function $G_{c2}(s)$ may be a PI or PID controllers [21],[22] or a PID with filter [23]. The sub-controller type selected for Gc1 and Gc2 is a PID type giving a designation of 2DOF-PID (structure 1) having the transfer functions:

$$G_{c1}(s) = K_{pc1}+(K_i/s)+K_d s \quad (5)$$

and $$G_{c2}(s) = K_{pc2}+(K_i/s)+K_d s \quad (6)$$

Where: K_{pc1} = G_{c1} sub-controller proportional gain

K_i = G_{c1} and G_{c2} sub-controller integral

K_d = G_{c1} and G_{c2} sub-controller derivative gain

K_{pc2} = G_{c2} sub-controller proportional gain

This analysis means that this 2DOF-PID (structure 1) controller has four parameters to be tuned to adjust the dynamics of the control system for step input tracking.

The closed loop transfer function of the control system incorporating the 2DOF-PID (structure 1) controller and the gas turbine is obtained using the block diagram in Fig.3 and the unit step response of the control system is obtained using the command '*step*' of MATLAM [20].

The unit step time response for reference input tracking is used to assign an error function for use as an objective function to be minimized by the command '*fmincon*' of MATLAB subject to a number of functional constraints to control the performance of the closed loop control system and generate the tuned controller parameters [19]. The result of this tuning approach using an ITAE objective function is producing the following 2DOF-PID (structure 1) controller parameters:

$K_{pc1} = 1.8616$; $K_i = 2.4773$

$K_d = 1.0748$; $K_{pc2} = 1.4639$ (7)

The transfer function M(s) of the closed loop control system incorporating the gas turbine (Eq.1) and the tuned 2DOF-PID (structure 1) controller (Eqs.5, 6, 7) is:

$M(s) = (2204\, s^2 + 3818\, s + 5081) / (s^5+47.54s^4+501.7s^3+3224s^2+5095s+5081)$ (8)

Eq.8 reveals the fact that the control system with the 2DOF-PID (structure 1) controller has a 2/5 order. The graphical unit step reference input tracking time response of the control system is generated using Eq.8 and the 'step' command of MATLAB [20]. The result is the plot shown in Fig.4.

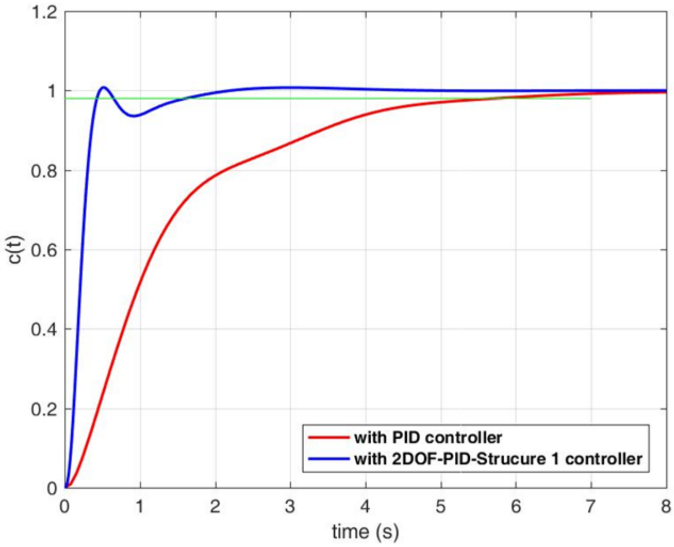

Fig. 4 Step time response of the 2DOF-PID (structure 1) controlled gas turbine.

The step time response during reference input tracking using the 2DOF-PID (structure 1) controller has the following characteristics:

- Maximum percentage overshoot: 0.7717 % compared with zero overshoot using a conventional PID controller.
- Settling time (using a ±0.02 band around the steady state response): 1.60 s compared with 5.7 s using a conventional PID controller.
- Steady state error: 0

V. CONTROLLING THE GAS TURBINE USING A 2DOF-PID CONTROLLER (STRUCTURE 2)

The 2DOF-PID controller (structure 2) has the configuration shown in Fig.5 [25]. One of the sub-controllers is receiving its input from the reference signal itself. The second sub-controller is set in the feedback path receiving its input from the process output. The forward sub-controller G_{c1} may be a conventional PID [24], a PID with filter [23] or conventional PI [25]. The feedback sub-controller G_{c2} may be a conventional PID with same integral gain different proportional and derivative gains that those in G_{c1} [24], a PID with filter multiplied by -1 [23] or conventional PI typical to that in G_{c1}[25].

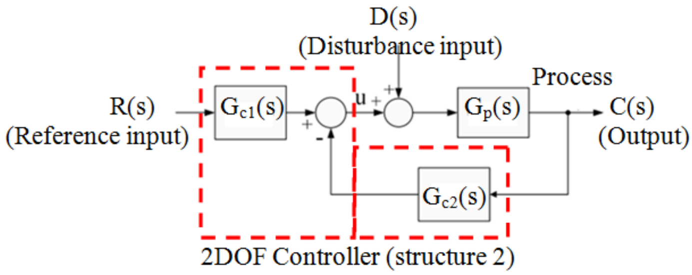

Fig.5 Process control using a 2DOF controller (structure 2 [25]).

After a number of investigations of the different options for G_{c1} and G_{c2} with the gas turbine mathematical model defined by Eq.1, the author used a PID sub-controller for both G_{c1} and G_{c2} with different proportional gain and typical integral and derivative gains. This 2DOF controller now becomes 2DOF-PID (structure 2). It has the same transfer functions given by Eqs.5 and 6. Thus having four gain parameters:K_{pc1}, K_i, K_d and K_{pc2} to be tuned to optimize the performance of the closed loop control system using the 2DOF-PID (structure 2) controller.

The closed loop transfer function of the control system incorporating the 2DOF-PID (structure 2) controller and the gas turbine is obtained using the block diagram in Fig.3 and the unit step response of the control system is obtained using the command '*step*' of MATLAM [20].

The unit step time response for reference input tracking is used to assign an error function for use as an objective function to be minimized by the command '*fmincon*' of MATLAB subject to a number of functional constraints to control the performance of the closed loop control system and generate the tuned controller parameters [19]. The result of this tuning approach using an integral of square error multiplied by square time (ISTSE) objective function is producing the following 2DOF-PID (structure 2) controller parameters:

$K_{pc1} = 1.4937$; $K_i = 2.7621$
$K_d = 0.6105$; $K_{pc2} = 1.5220$ (9)

The transfer function M(s) of the closed loop control system incorporating the gas turbine (Eq.1) and the tuned 2DOF-PID (structure 2) controller (Eqs.5, 6, 9) is:

$M(s) = (1252 s^2+3064s+5665) / (s^5+47.54s^4+501.7s^3+2272s^2+5214s+5665)$ (10)

Eq.10 reveals the fact that the control system with the 2DOF-PID (structure 2) controller has a 2/5 order. The graphical unit step reference input tracking time response of the control system is generated using Eq.10 and the '*step*' command of MATLAB [20]. The result is the plot shown in Fig.6.

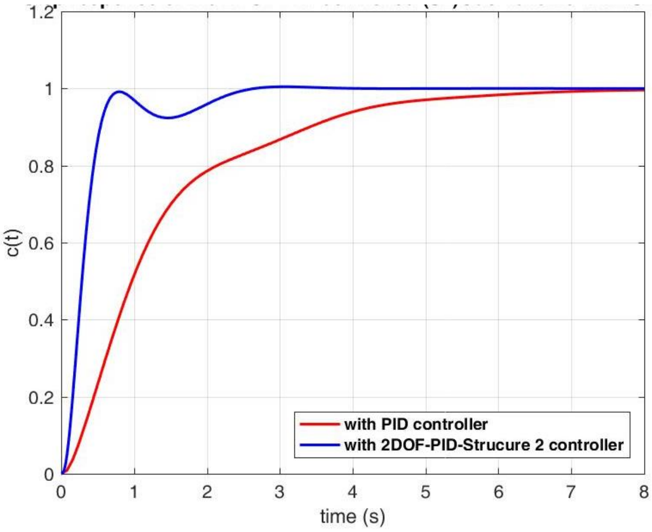

Fig. 6 Step time response of the 2DOF-PID (structure 2) controlled gas turbine.

The step time response during reference input tracking using the 2DOF-PID (structure 2) controller has the following characteristics:

- Maximum percentage overshoot: 0.4508 % compared with zero overshoot using a conventional PID controller.
- Settling time (using a ±0.02 band around the steady state response): 2.2 s compared with 5.7 s using a conventional PID controller.
- Steady state error: 0

VI. CONTROLLING THE GAS TURBINE USING A 2DOF-PID-PD CONTROLLER (STRUCTURE 3)

The 2DOF-PID-PD controller (structure 3) has the configuration shown in Fig.7 [26]. One of the sub-controllers (G_{c2}) is receiving its input from the reference signal itself and fed forward to a summing point with positive two inputs after the second sub-controller (G_{c1}) set after the main error detector of the closed loop control system. The forward sub-controller G_{c1} may be a PI with or without filter or a PID with or without filter [26]. The feedforward sub-controller G_{c2} may be a PD with or without filter [26].

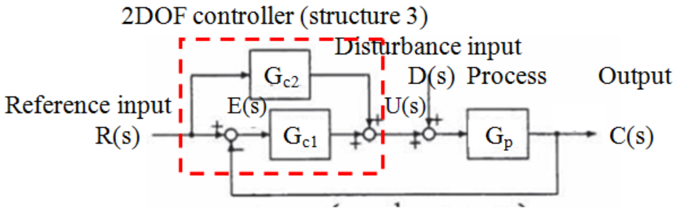

Fig.7 Process control using a 2DOF controller (structure 3 [26]).

After a number of investigations of the different options for G_{c1} and G_{c2} with the gas turbine mathematical model defined by Eq.1, the author used a PID sub-controller for G_{c1} and a PD sub-controller for G_{c2} with different proportional gain and same derivative gain. This 2DOF controller now becomes 2DOF-PID-PD (structure 3). It has the transfer functions:

$$G_{c1}(s) = K_{pc1} + (K_i/s) + K_d s \quad (11)$$

and $$G_{c2}(s) = K_{pc2} + K_d s \quad (12)$$

Thus having four gain parameters: K_{pc1}, K_i, K_d and K_{pc2} to be tuned to optimize the performance of the closed loop control system using the 2DOF-PID-PD (structure 3) controller.

The closed loop transfer function of the control system incorporating the 2DOF-PID-PD (structure 3) controller (Eqs.11 and 12) and the gas turbine (Eq.1) is obtained using the block diagram in Fig.7 and the unit step response of the control system is obtained using the command '*step*' of MATLAB [20].

The unit step time response for reference input tracking is used to assign an error function for use as an objective function to be minimized by the command '*fmincon*' of MATLAB subject to a number of functional constraints to control the performance of the closed loop control system and generate the tuned controller parameters [19]. The result of this tuning approach using an ISTSE objective function is producing the following 2DOF-PID-PD (structure 3) controller parameters:

K_{pc1} = 0.0668 ; K_i = 2.0871

K_d = 0.3174 ; K_{pc2} = 0.2496 ; (13)

The transfer function M(s) of the closed loop control system incorporating the gas turbine (Eq.1) and the tuned 2DOF-PID-PD (structure 3) controller (Eqs.11, 12) is:

$M(s) = (1302\ s^2 + 649.1\ s + 4281) / (s^5+47.54s^4+501.7s^3+1671s^2+2229s+4281)$ (14)

Eq.14 reveals the fact that the control system with the 2DOF-PID-PD (structure 3) controller has a 2/5 order. The graphical unit step reference input tracking time response of the control system is generated using Eq.14 and the '*step*' command of MATLAB [20]. The result is the plot shown in Fig.8.

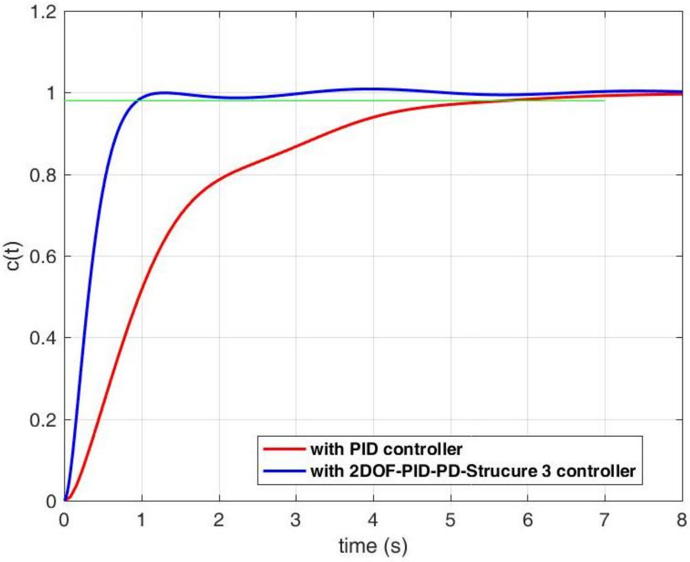

Fig. 8 Step time response of the 2DOF-PID-PD (structure 3) controlled gas turbine.

The step time response during reference input tracking using the 2DOF-PID-PD (structure 3) controller has the following characteristics:

- Maximum percentage overshoot: 0.76 % compared with zero overshoot using a conventional PID controller.
- Settling time (using a ±0.02 band around the steady state response): 0.95 s compared with 5.7 s using a conventional PID controller.
- Steady state error: 0

VII. CONTROLLING THE GAS TURBINE USING A 2DOF-PI-DF CONTROLLER (STRUCTURE 4)

The 2DOF-PI-DF controller (structure 4) has the configuration shown in Fig.9 [27]. One of the sub-controllers (G_{c1}) is set in the forward path of the control system and receives its input from the output of the main error detector [E(s)]. The second sub-controller (G_{c2}) is set in the feedback path of an internal loop starting from the output variable C(s) of the closed loop control system. The forward sub-controller G_{c1} may be a PI [27], [28]. The feedback sub-controller G_{c2} may be a derivative with filter (DF) or PID [27] or only PID [28].

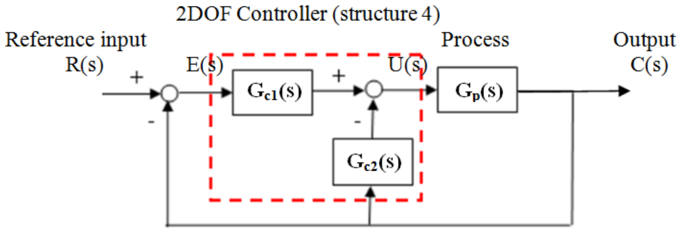

Fig.9 Process control using a 2DOF controller (structure 4 [27]).

After a number of investigations of the different options for G_{c1} and G_{c2} with the gas turbine mathematical model defined by Eq.1, the author used a PI sub-controller for G_{c1} and a DF sub-controller for G_{c2}. This 2DOF controller now becomes 2DOF-PI-DF (structure 4). It has the transfer functions:

$G_{c1}(s) = K_{pc} + (K_i/s)$ (15)

and $G_{c2}(s) = K_d s/(Ts+1)$ (16)

where: K_{pc} = proportional gain of G_{c1}

K_i = integral gain of G_{c1}

K_d = derivative gain of G_{c2}

T = time constant of G_{c2} filter

Thus having four gain parameters: K_{pc}, K_i, K_d and T to be tuned to optimize the performance of the closed loop control system using the 2DOF-PI-DF (structure 4) controller.

The closed loop transfer function of the control system incorporating the 2DOF-PI-DF (structure 4) controller (Eqs.15 and 16) and the gas turbine (Eq.1) is obtained using the block diagram in Fig.9 and the unit step response of the control system is obtained using the command '*step*' of MATLAB [20].

The unit step time response for reference input tracking is used to assign an error function for use as an objective function to be minimized by the command '*fmincon*' of MATLAB subject to a number of functional constraints to control the performance of the closed loop control system and generate the tuned controller parameters [19]. The result of this tuning approach using an ISTSE objective function is producing the following 2DOF-PI-DF (structure 4) controller parameters:

$K_{pc} = 5.4783$; $K_i = 1.9823$

$K_d = 2.7580$; $T = 0.0110$ s (17)

The transfer function M(s) of the closed loop control system incorporating the gas turbine (Eq.1) and the tuned 2DOF-PI-DF (structure 4) controller (Eqs.15, 16) is:

$M(s) = (123.1s^2+11280\,s+4066) / (0.01095s^6+1.521s^5+53.04s^4+512.9s^3+6823s^2+13370s+4066)$ (18)

Eq.18 reveals the fact that the control system with the 2DOF-PI-DF (structure 4) controller has a 2/6 order. The graphical unit step reference input tracking time response of the control system is generated using Eq.18 and the '*step*' command of MATLAB [20]. The result is the plot shown in Fig.10.

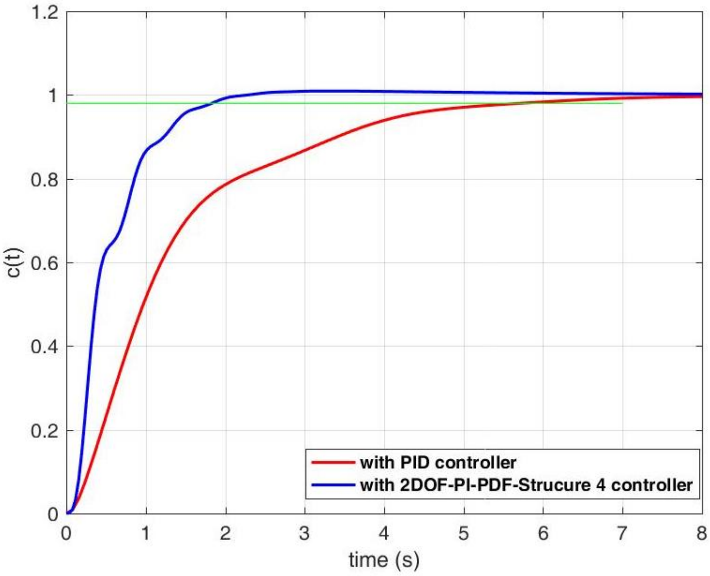

Fig. 10 Step time response of the 2DOF-PI-DF (structure 4) controlled gas turbine.

The step time response during reference input tracking using the 2DOF-PI-DF (structure 4) controller has the following characteristics:

- Maximum percentage overshoot: 0.9126 % compared with zero overshoot using a conventional PID controller.
- Settling time (using a ±0.02 band around the steady state response): 1.834 s compared with 5.7 s using a conventional PID controller.
- Steady state error: 0

VIII. COMPARISON BETWEEN THE FOUR 2DOF CONTROLLERS CONTROLLING THE GAS TURBINE

The 2DOF controllers, structure 1, structure 2, structure 3 and structure 4 are compared with the conventional PID controller when used to control the gas turbine for reference input tracking. The comparison is shown in Fig.11.

The time based characteristics of the step time response using the five controllers are compared quantitatively in Table 1.

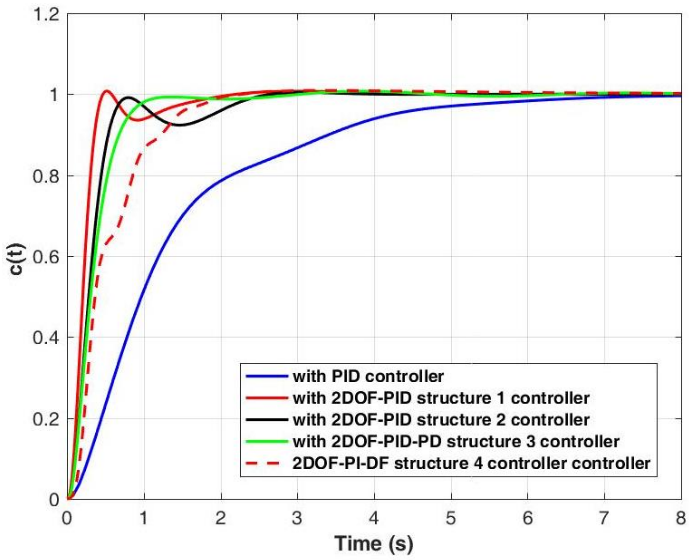

Fig. 11 Step time response of the 2DOF controlled gas turbine.

TABLE 1
COMPARISON OF CONTROL SYSTEM CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF THE GAS TURBINE

Controller	OS_{max} (%)	T_s (s)	e_{ss}
PID	0	5.700	0
2DOF-PID (structure 1)	0.7717	1.600	0
2DOF-PID (structure 2)	0.4508	2.200	0
2DOF-PID-PD (structure 3)	0.7600	0.950	0
2DOF-PI-DF	0.9126	1.834	0

(structure 4)			

IX. CONCLUSION

- The dynamic problem of controlling a gas turbine for a speed control was investigated using four 2DOF-based controllers.
- The gas turbine under control had a 0/4 dynamic model (transfer function) .
- The step time response of the gas turbine in an open loop mode for reference input tracking had a 21.393 % maximum percentage overshoot, 3.85 s settling time and 0.0191 steady state error.
- The gas turbine was first controlled by a conventional PID controller as a comparison base for the other 2DOF controllers. When properly tuned it could generate a time response for step input tracking without any overshoot or steady state error and a 5.7 s settling time.
- The first 2DOF controller investigated was a 2DOF-PID (structure 1) controller having four gain parameters. When tuned it could generate a time response for step input tracking with 0.7717 % maximum percentage overshoot, 1.6 s settling time and zero steady state error.
- The second 2DOF controller investigated was a 2DOF-PID (structure 2) controller having four gain parameters. When tuned it could generate a time response for step input tracking with 0.4508 % maximum percentage overshoot, 2.2 s settling time and zero steady state error.
- The third 2DOF controller investigated was a 2DOF-PID-PD (structure 3) controller having four gain parameters. When tuned it could generate a time response for step input tracking with 0.76 % maximum percentage overshoot, 0.95 s settling time and zero steady state error.
- The fourth 2DOF controller investigated was a 2DOF-PI-DF (structure 4) controller having four gain parameters. When tuned it could generate a time response for step input tracking with 0.9126 % maximum percentage overshoot, 1.834 s settling time and zero steady state error.
- All the controllers investigated in the present work were tuned using the MATLAB optimization toolbox with functional constraints on the maximum percentage overshoot and the settling time.
- The comparison of the performance of the closed loop control system incorporating the gas turbine and the controllers under study revealed that all the investigated controllers provided a maximum percentage overshoot $\leq$ 0.9126 % a settling time $\leq$ 2.2 s and a zero steady state error.
- The 2DOF-PID-PD (structure 3) controller was considered as the best controller to control the gas turbine under study providing a settling time < one second when used for step input tracking.

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