

DEVELOPMENT OF CONTROL SCHEMES AND OPTIMAL TUNING OF SECONDARY CONTROLLERS FOR PARALLEL OPERATION OF GAS TURBINE PLANTS

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Abstract: *Parallel operation is the technique largely demanded by the systems delivering power when subjected to varying load conditions. Gas turbines generating mechanical power and acting as prime movers in many applications is required to be operated in parallel. Load sharing, reliability and stable operation of the system can be accomplished by operating gas turbines in parallel. This paper emphasises the two different schemes namely speed reference scheme and common error reference scheme to operate gas turbines in parallel. The gas turbine plants when operated in parallel is affected by loaded conditions and is unable to run at the set reference speed causing steady state error. This work explains a new common error reference scheme for parallel operation and compares with speed reference scheme. It also illustrates the effect of the secondary controller and its tuning methodologies to reduce the error and provide a fine tune during parallel operation. The secondary Proportional + Integral (PI) controllers used for fine control of the system is tuned using Zeighler Nichol's (ZN), Genetic Algorithm (GA) and Fuzzy Gain Scheduling (FGS) techniques and their results compared.*

Keywords: *Gas Turbines, parallel operation, PI controller, ZN, GA, FGS.*

1. Introduction

Load on systems delivering power varies externally and it is required to control the system to drive it to meet the load variations and also to regain its steady state conditions without much fluctuations. A gas turbine system delivers mechanical power and if disturbed by heavy load variations it becomes unstable. When operated in parallel and with suitable secondary controller it is possible to make gas turbines meet load fluctuations and a reliable operation. This paper deals with two schemes for

parallel operation of gas turbine plants and their control. The gas turbines have been mathematically modelled and used for simulation and analysis by many scientists and research people over the years [1-3]. Speed control loop is one of the appropriate primary control loop and Speedtronic governor is the predominantly used primary controller [4]. Due to the drooping nature of the speed governor used as a primary controller in gas turbine plants, suitable secondary controllers have been developed to fine tune the system output without error [5]. Many tuning methods using soft computing for secondary controllers were also been reported [6-9].

The parallel operation of gas turbine plants and its control requires suitable schemes and optimally tuned secondary controllers. The speed based control of parallel operation of gas turbines had already been carried out with variation of set point [10] and also with a fixed reference [11].

Common error reference scheme is the newly proposed methodology for connecting and operating gas turbine plants in parallel. It computes an error that is common for all the gas plants running in parallel thereby uniform control action is carried out considering disturbances in all the plants. A comparative analysis of Speed reference and common error reference schemes is explained in this paper. Also the PI secondary controllers were tried for tuning the gain constants using conventional ZN method and soft computing techniques like GA and FGS. The proposed results emphasise a suitable control scheme for parallel operation and an optimal tuning method for the secondary controller.

2. Gas Turbine Plant Model

The Rowen's mathematical model for a gas turbine plant [1] consists of a primary controller namely speedtronic governor, valve positioner, fuel system and the turbine system with rotor dynamics. This is a simplified model and provides better understanding on the system and its control. Nearly 23% of fuel goes uncontrolled to the system for its self-sustained operation and the remaining 77% can be controlled for the required output and to meet load demand variations. The primary speedtronic controller will sense the change in speed due to load variations and provide the necessary action. But its drooping properties result in a considerable error under steady state conditions. The complete mathematical model of a gas turbine plant used in this paper is shown in Fig. 1.

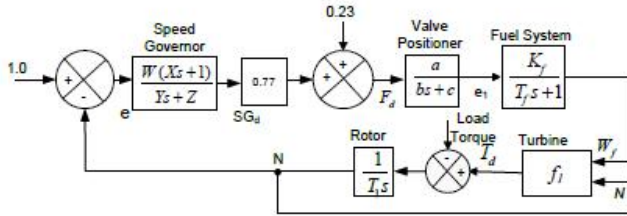


Fig. 1. Mathematical model of gas turbine plant

The basic equations involving the mathematical modelling of the gas turbine plant for the various subsystems are listed.

$$SG_d = \frac{W(Xs+1)}{Ys+Z} e \quad (1)$$

$$F_d = 0.77SG_d + 0.23 \quad (2)$$

$$e_1 = \frac{a}{bs+c} F_d \quad (3)$$

$$W_f = \frac{K_f}{T_f s + 1} e_1 \quad (4)$$

$$f_1 = 1.3(W_f - 0.23) + 0.5(1 - N) \quad (5)$$

$$N = \frac{f_1 - T_d}{T_1 s} \quad (6)$$

3. Gas Turbines in Parallel

The reliable and economical operation of parallel operated systems is always an advantage over the individual unit systems. The load sharing capabilities and maintenance requirements thrust the need for parallel operation units supplying power. Gas turbine units can also be operated parallel and

controlled so that the expected output can be achieved. To maintain the synchronism under parallel operation, a proper uniform reference of 1 p.u. is used. The two techniques by which gas turbine plants can be operated parallel are the speed reference control and common error reference control.

4. Speed Reference Control

This method involves running and controlling the speed of a gas turbine based on the speed of the neighbouring machine. It is required to provide the reference of 1 p.u. for all the machines so that the speed is maintained in synchronism with the other machines. This is a cascaded operation and each of the machine's speed is dictated by the neighbouring machine [11]. This system also demands a secondary controller for fine tuning as the primary controller cannot provide an error free control. The schematic involved in connecting three gas turbine plants in speed reference is shown in Fig. 2.

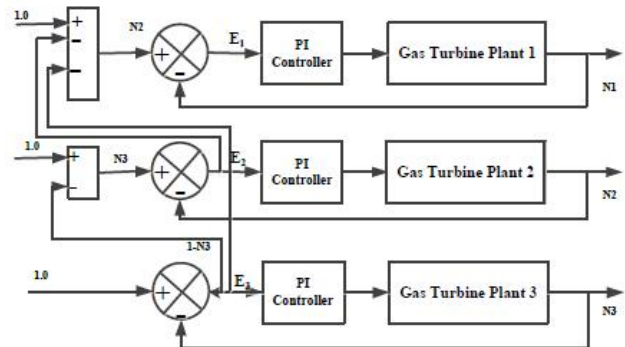


Fig. 2. Speed reference scheme of parallel Operation

The equations explaining the speed reference scheme of parallel operation from Fig. 2. are listed below.

$$E_1 = N_2 - N_1 \quad (7)$$

$$E_2 = N_3 - N_2 \quad (8)$$

$$E_3 = 1 - N_3 \quad (9)$$

5. Common Error Reference Control

Another fine and much more tedious control on parallel operation is explain by the common error reference control wherein the speed errors in all the gas turbines operating in parallel is summed up and it is subtracted with respect to the 1 p.u. reference. The difference obtained is then fed as reference common to all the gas turbines. This way a better synchronised operation can be achieved as all the plants and their controllers operate towards a

common error and to nullify it. The model for operating three gas turbines in common error reference scheme is shown in Fig. 3.

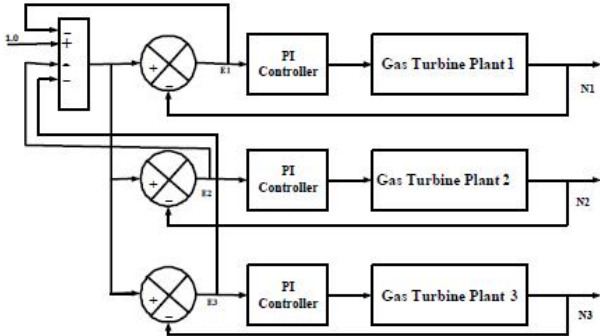


Fig. 3. Common error reference scheme of parallel Operation

From Fig. 3, the following equations can be derived based on common error reference (CER).

$$\text{CER} = 1 - [E_1 + E_2 + E_3] \quad (10)$$

$$E_1 = \text{CER} - N_1 \quad (11)$$

$$E_2 = \text{CER} - N_2 \quad (12)$$

$$E_3 = \text{CER} - N_3 \quad (13)$$

$$\text{CER} = [1 + N_1 + N_2 + N_3]/4 \quad (14)$$

In both the schemes of parallel operation, there is a requirement of a well-tuned secondary controller for error decrement and more synchronised operation and control of the system when subjected to load variations.

6. Secondary Controller for Parallel Operation

The deficient primary controller not able to provide a required errorless and fine control, demands the need for secondary controller. The secondary controller dealt in this paper is a PI controller with its proportional and integral gain constants to be tuned using a suitable tuning method. In this work the gain constants are tuned using three different techniques namely the conventional ZN method and soft computing based FGS and GA.

7. Tuning of Secondary Controller by Zeighler Nichol's Method

The system under study is a gas turbine plant model and it is subjected to increment in

proportional gain till the system possesses self-sustained oscillations of constant magnitude and frequency. This condition is explained as marginally stable condition of the system. The gain corresponding to this condition is called ultimate gain K_u and the time period of oscillation is T_u . Using K_u and T_u , the proportional and integral gain constants can be obtained by using the formulae proposed by ZN [12] as shown in the following Table 1.

Table 1. ZN rule for PI controller

K_p	K_i
$0.45K_u$	$\frac{1.2K_p}{T_u}$

The K_u and T_u for the gas turbine system operating in parallel are obtained as 6.822 and 1.84s respectively and using the ultimate gain and the time period of oscillation, the PI controller gains K_p and K_i is obtained as 3.0699 and 2.002 respectively using the ZN formula.

8. Tuning of Secondary Controller by Genetic Algorithm

GA is a search algorithm based on evolutionary concepts of natural selection and genetics. It helps in determining an optimal value for a variable that provides minimisation or maximisation of the function involving the variable. The function is called the fitness function and in the gas turbine system, the fitness function is taken as Integral Square Error (ISE). And the GA with its genetic operations like parental selection, reproduction, crossover and mutation tries to minimise ISE and provide the optimal gain constants for the PI controller [13-15].

For the parallel operation of three gas turbine plants involving three secondary PI controllers, the number of variables involved is 6. The initial population taken is 20. The cross over probability and mutation probability is 0.8 and 0.05 respectively. The GA provides the PI gain constants when the best value and the mean value of the fitness function are equal. The tuned values of the secondary PI controller for parallel operation by the two different schemes were provided in Table 2.

Table 2. PI gain constants by GA tuning

	Gas Plant 1		Gas Plant 2		Gas Plant 3	
	K_p	K_i	K_p	K_i	K_p	K_i
Speed Reference	4.9402	0.0612	2.2888	0.0506	0.6667	0.0427
Common Error Reference	5.4683	0.2006	5.5649	0.1431	5.4567	0.2000

9. Tuning of Secondary Controller by Fuzzy Gain Scheduling Method

The ZN method of tuning the gains of the PI secondary controller is found to have a fixed value of K_p and K_i values irrespective of the system variations or load variations. The FGS tuning is a soft computational technique by which the gain constants of the PI controller can be varied with respect to system dynamics and variation in load. This provides a better control over the process variable and improves both steady state and transient behaviour of the system. FGS as shown in Fig. 4, utilises the error in speed and its derivative to tune the PI secondary controller gains [16-19] for the gas turbines operated in parallel.

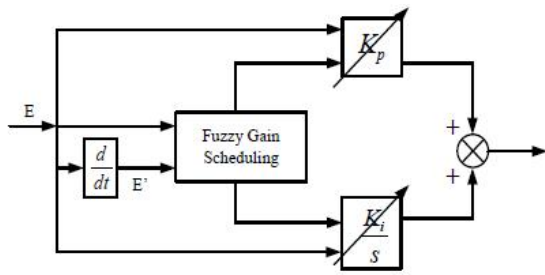


Fig. 4. Fuzzy gain scheduling

Triangular and trapezoidal membership functions are used for representing inputs and output of the system as shown in Fig. 5. Medium Negative (MN), Small Negative (SN), Zero (Z), Small Positive (SP), Medium Positive (MP) are the triangular functions used. Large Negative (LN) and Large Positive (LP) were the trapezoidal functions for the values beyond normal operating range. The range for the input E is taken as -0.0171 to 0.0171 and for its derivative E' the range is -0.0283 to 0.0283. The output range is -0.005 to 0.005. The scaling factor used for the proportional gain K_p is 27 and for the integral gain K_i it is 3.

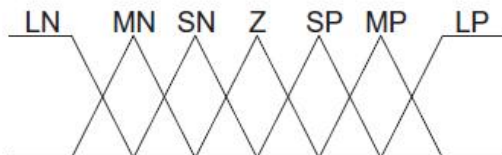


Fig. 5. Triangular and trapezoidal membership functions

A rule base is developed for the gas turbine system based on the knowledge available about

the system for different inputs and their outputs. Table 3 shows the rules for developing the FGS for the controller gains to control the parallel operation of the gas turbine system.

Table 3 Rule base for FGS to tune K_p and K_i

E/E'	LN	MN	SN	Z	SP	MP	LP
LN	LP	LP	LP	MP	MP	SP	Z
MN	LP	MP	MP	SP	SP	Z	SN
SN	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SP	SP	SP	Z	SN	SN	MN	LN
MP	SP	Z	SN	SN	MN	MN	LN
LP	Z	SN	MN	MN	MN	LN	LN

10. Simulation and Results

The two parallel operating schemes namely speed reference and common error reference using the mathematical modelling of gas turbine plant is developed in Matlab Simulink [21]. The system is tested with load variations at three different instances of time. At 150s and 350s a step load of magnitude 0.4 p.u. and 0.2 p.u., is removed from gas plant 1 and gas plant 3 respectively. Load of magnitude 0.6 p.u. is added at 250s to gas plant 2. The load variations used to test the system is represented in Fig. 6. The response of the system for this load variations are noted with and without secondary controllers. Also the results on the impact of the ZN, GA and FGS tuned secondary controller on the system is studied and compared.

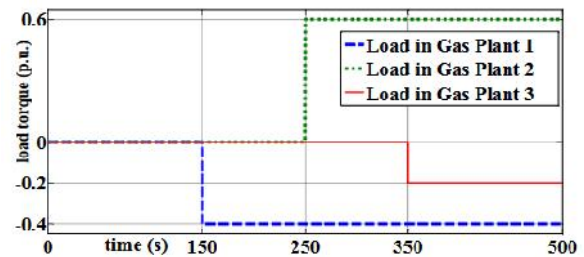


Fig. 6. Step Changes in Load Torque

11. Without Secondary Controller

The speed response of gas turbine plants operating in parallel with the above mentioned loads are simulated without the secondary controller. The response of the two parallel operating schemes are shown in Fig. 7 and Fig. 8.

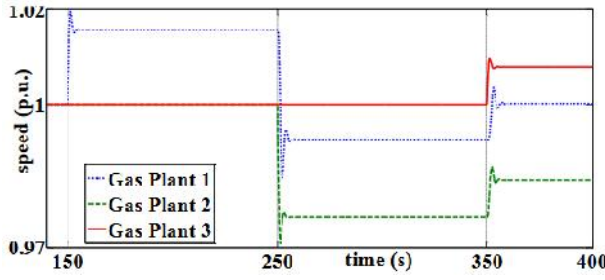


Fig. 7. Response of speed reference scheme without Secondary Controller.

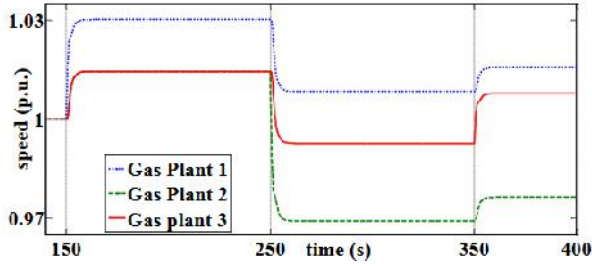


Fig. 8. Response of common error reference scheme without secondary controller.

The simulation results provide the conclusion that without secondary controller both the schemes have considerable error caused due to load variations in each gas plants and the system had not settled down at the reference speed of 1 p.u.

12. With ZN Tuned Secondary Controller

The tuned values of K_p and K_i by ZN method were used as PI gain constants for the secondary controllers in each of the gas turbine plants and the response of the two parallel operating schemes under different loaded conditions are shown in Fig. 9 and Fig. 10.

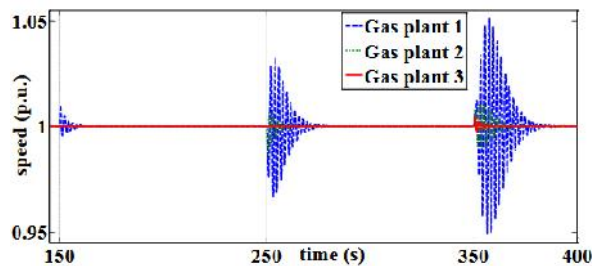


Fig. 9. Response of ZN tuned controller for speed reference scheme

From the responses it is found that the ZN tuned controller had made the system to settle at the reference speed of 1 p.u.

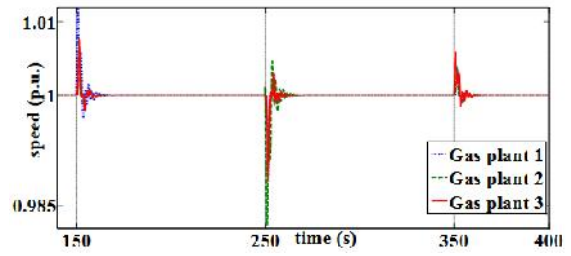


Fig. 10. Response of ZN tuned controller for common error reference scheme

Moreover the speed reference scheme proves to have more transients than the common error reference scheme and take time to settle to the final steady state value. The peak value of the response in common error reference scheme is considerably less when compared to its counterpart. Also in speed reference scheme, as the cascaded system increases with more number of plants, the load variations at the extreme plant induces more transients in the system which is not experienced in common error reference scheme.

13. With GA Tuned Secondary Controller

Each of the three secondary controllers are tuned for their best PI gain constants using the GA tuning methodology. The gain constants arrived are used up in each of the corresponding controller in both the parallel operating schemes. The graphical response provided by each of the schemes is shown in Fig. 11 and Fig. 12.

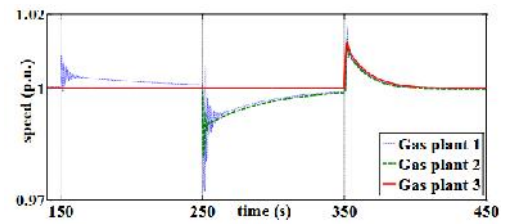


Fig. 11. Response of GA tuned controller for speed reference scheme

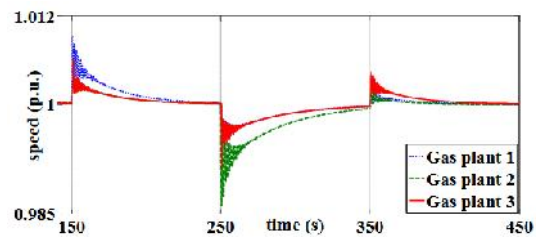


Fig. 12. Response of GA tuned controller for common error reference scheme

14. With FGS Tuned Secondary Controller

With the fuzzy gain scheduled tuning of the secondary PI controller the response of the system is obtained as in Fig. 13 and Fig. 14 for the two schemes of parallel operation.

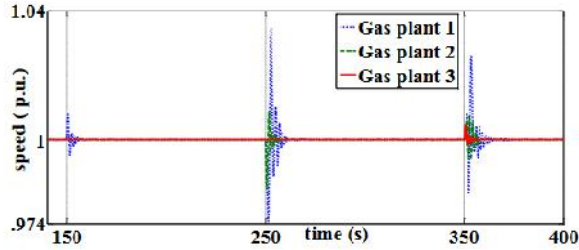


Fig. 13. Response of FGS tuned controller for speed reference scheme

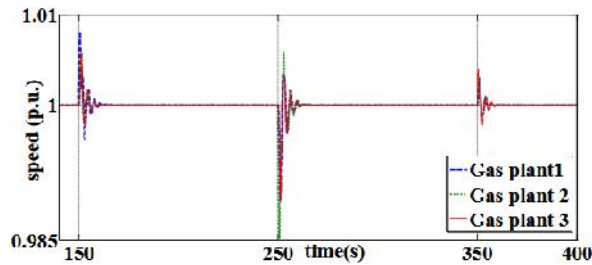


Fig.14. Response of FGS tuned controller for common error reference scheme

The responses indicate the FGS tuning had provided a very fine tuning for both the parallel operating systems. The transient as well as the steady state response of the system had comparable improvement. The peak response had been minimised and the both the parallel operating schemes have been controlled to tackle the load variations in a better way.

Apart from the comparison of graphical responses of the two parallel operating schemes with differently tuned secondary controllers, another comparison is made using the performance indices [22] for each of the tuning methods. The three performance indices considered were the ISE, Integral Time Absolute Error (ITAE) and the Integral Time Square Error (ITSE). The evaluation of the above mentioned criterions is done based on the error from each of the gas plants operating in parallel under both schemes.

$$ISE = \int (E_1)^2 + (E_2)^2 + (E_3)^2 dt \quad (15)$$

$$ITAE = \int |(E_1) + (E_2) + (E_3)|t dt \quad (16)$$

$$ITSE = \int ((E_1)^2 + (E_2)^2 + (E_3)^2)t dt \quad (17)$$

Table 4 showcases the values of the performance indices taken for the time interval between 140s and 500s during which the load variations are effected. Each of the two parallel operating schemes under the influence of ZN, GA and FGS tuned secondary controllers were analysed.

A bar chart graph using the values of Table 4 is illustrated in Fig. 15 to differentiate between the two parallel operating schemes with respect to each of the performance indices. It can be observed that the FGS tuned controller had better performance indices values for ISE, ITAE and ITSE compared to ZN and GA tuned controllers.

Table 4 Performance indices of the two schemes with different secondary controllers

	ZN Tuned		GA Tuned		FGS Tuned	
	Speed ref	Common error ref	Speed ref	Common error ref	Speed ref	Common error ref
ISE	0.018	0.0002	0.0045	0.00062	0.0026	0.00012
ITAE	265.59	21.922	280.47	85.8359	63.275	15.5209
ITSE	6.0268	0.0611	1.2821	0.1549	0.7931	0.0283

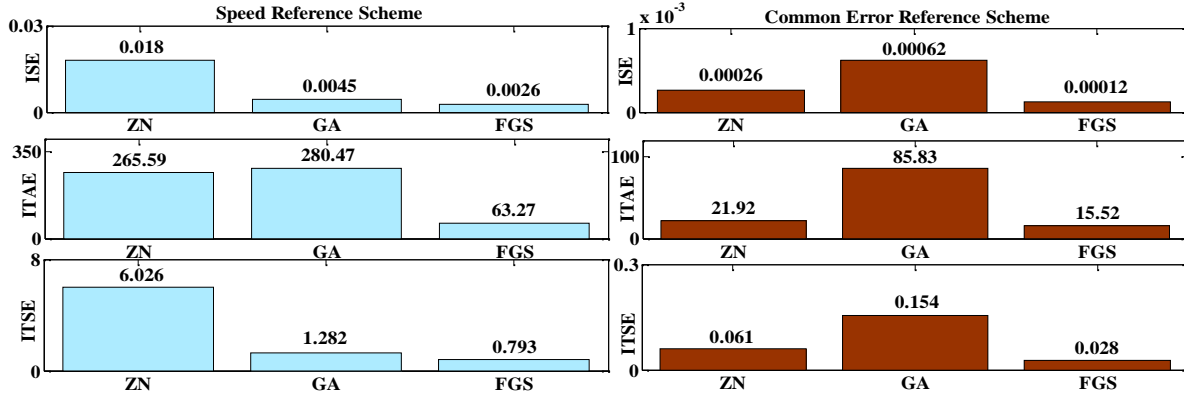


Fig. 15. Bar chart comparison of the performance indices.

15. Conclusion

Three gas turbine plants are connected as per the two parallel operating schemes and they are subjected to load variations at different time instances. Common error reference scheme had provided better synchronised operation than speed reference scheme with or without controller as all the three plants had their speed varying identically. Both the schemes with their primary controllers were found unable to meet the set reference speed of 1 p.u. The secondary controllers using ZN, FGS and GA tuning methodologies are tried on both the parallel operating schemes and the results analysed. It is found that FGS tuning provides optimal gain constants for the PI controller. Graphical illustrations and performance indices justify the above statement with better control on transient and steady state performances enforced by FGS tuned secondary controllers.

Appendix

e = Error in speed (p.u.)

SG_d = Output of the speed governor

W, X, Y, Z = Governor transfer function coefficients:

$W=K_D$; $X=0$; $Y=0.05$; $Z=1$

a, b, c = Fuel system transfer function coefficients :

$a=1$; $b=0.05$; $c=1$

f_t = Turbine torque

W_f = Per unit fuel flow

K_f = Fuel System gain constant = 1

T_f = Fuel system time constant = 0.4

N = per unit turbine rotor speed

s = Laplace operator

e_1 = Valve position

F_d = Per unit fuel demand signal

K_D = Droop gain = 2 to 10%

T_l = Rotor time constant = 12.2

Td = Load Torque

K_p, K_i = PI gain constants

t = time

E_1, E_2, E_3 = Error for each controller in gas plants 1, 2 & 3

N_1, N_2, N_3 = Speed of gas turbine plant 1, 2 & 3

E = Error input to the FGS controller

E' = Derivative of error E

CER = Common Error Reference

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