2-DOF Fuzzy Schemes for Combustion Turbogenerator Wide-Range Speed Control

R. Garduno-Ramirez, *Senior Member, IEEE*, A. Rodriguez-Martinez, and L. Castelo-Cuevas

Abstract-- **This paper presents two feasible realizations of 2-DOF wide-range speed control schemes for combustion turbogenerators. These schemes allow independent tuning of the reference tracking and disturbance rejection characteristics of the control system. The fuzzy approach extends these characteristics throughout the operating space of the combustion turbogenerator. Both realizations can be inserted into the speed control loop of existing control systems without degrading performance until the control system is fine tuned. The controllers can be progressively tuned on-site based on the inspection of current responses. The proposed 2-DOF fuzzy control schemes are suitable for application on actual power plants.**

Index Terms-- **Combustion turbogenerator, Wide-range operation, 2 DOF control schemes, Fuzzy systems.**

I. INTRODUCTION

NOWADAYS, power generation by means of gas turbine driven generators or combustion turbogenerators (CTG) is playing a major role worldwide. Also, most power plants to be built in the next 20 years will be combined cycles based on topping CTGs due to their advantages over other technologies, which include relatively low commissioning, maintenance and operation costs per unit of power, fast startup and response to load change, capability to use diverse fuel (diesel, oil and biomass), as well as versatility to integrate high performance combined cycles and cogeneration systems [1].

CTGs operate at relatively higher speeds, pressures and temperatures, with wider variation ranges and faster changes of points of operation, than other plants. Moreover, operation of CTGs has a very high level of automation, which includes the stages of startup, synchronization, loading in different modes and stop. All these characteristics set very tight requirements for the control system; the startup very probably being the most demanding stage for the control system [2]. At startup, the main duty of the control system is that of accelerating the CTG from turning gear-speed up to synchronization-speed according to a predefined acceleration pattern. With this aim, the speed control has to provide the correct control actions to follow with the highest fidelity the established acceleration pattern, avoiding the occurrence of stall, surge, high vibration, resonance, high temperature and combustion instabilities, and to compensate the effects of disturbances produced by normal operation events and other external forces, in the shortest time, saving fuel and preserving the CTG duty life.

Currently, speed control schemes for CTGs consist of a simple feedback loop where a PI or PID algorithm with fixed-gains calculates the control signal from the speed deviation between the speed reference, obtained from the acceleration pattern, and the speed measurements [3]. Such kind of control algorithms cannot provide optimal response to more than one control objective. They can be tuned to satisfy either reference signal tracking or disturbance rejection requirements, but both at the same time. To solve this problem, two-degrees of freedom (2-DOF) control strategies can be used to achieve good tracking of the reference signal and rejection of external disturbances. In addition, although several 2-DOF control schemes are available in the technical literature, there is very few references available on how to extend the benefits of 2-DOF control schemes throughout the whole range of operation of a power plant [4,5].

In this regard, this paper unveils two feasible realizations of 2-DOF fuzzy schemes to control CTG speed throughout startup, from fuel ignition up to rated speed, just before unit synchronization to the power grid. Section II presents the basics of CTG conventional speed control and 2-DOF speed control. Section III presents the realization of the PI NeuroFuzzy 2-DOF (PI-NF2DF) controller [6], which is a wide-range 2-DOF speed control scheme that replaces the P-feedforward and PI-feedback controller gains by fuzzy systems that implement non-linear mappings valid all the way through the CTG startup operating space. Section IV presents the realization of the PI fuzzy gain-scheduling (PI-FGS) controller [7], which is another wide-range 2-DOF speed control scheme that replicates a 2-DOF PI structure throughout the CTG startup operating space by means of a fuzzy gain-scheduling system, which implicitly solves the problems of detection of operating conditions, controller switching and gain scheduling. Section V shows some simulation experiments and results that provide valuable information regarding the performance of the proposed wide-range 2-DOF fuzzy speed control schemes, as compared to the conventional PI-based speed control schemes. Finally, Section VI summarizes this work and draws the conclusions.

R. Garduno-Ramirez is with the Division of Control Systems, Electrical Research Institute (IIE), Cuernavaca, Morelos 62490 Mexico (e-mail: rgarduno@iie.org.mx).

A. Rodriguez-Martinez is with the Division of Control Systems, Electrical Research Institute (IIE), Cuernavaca, Morelos 62490 Mexico (e-mail: armtz@iie.org.mx).

L. Castelo-Cuevas is with the Division of Control Systems, Electrical Research Institute (IIE), Cuernavaca, Morelos 62490 Mexico (e-mail: lcastelo@iie.org.mx).

II. 2-DOF CONTROL SCHEMES

A. *Conventional Speed Control Strategy*

A typical CTG consists of five major components that operate continuously and simultaneously to produce electric power (Fig. 1). The starting device can be an electric motor to initially move the CTG. The compressor takes in atmospheric air, compresses it and sends it to the combustion chamber. In the chamber, pressurized air is mixed with fuel and burned to produce the hot flue gas that is delivered to the turbine moving blades through expansion nozzels. The exhausted flue gas is released to the atmosphere and the rotational mechanical energy is transmitted to the electric generator, which converts it into electric energy that is delivered to the power grid.

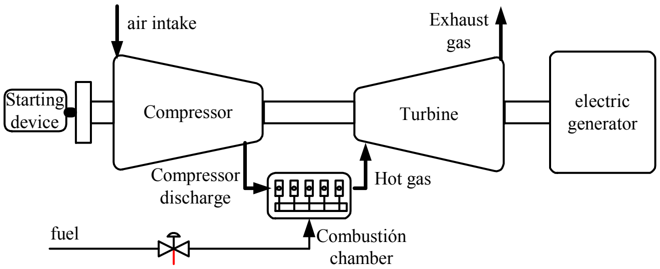

Fig. 1. Major components of a typical CTG.

Essentially, the control system structure of a typical CTG contains two control circuits: the inlet guide vanes (IGV) position control circuit to regulate air flow and a dual speed and power control circuit to regulate fuel flow. In the former circuit, flue gas temperature, compressor discharge pressure and turbine speed are permanently monitored to set safety limits to the fuel valve demand signal to ensure CTG physical integrity (Fig. 2). At startup, the control system activates the closed loop speed control at the time of fuel ignition up to rated speed. At the time of synchronization to the power grid, the closed loop power control is activated. These control loops are usually based on PI or PID control algorithms.

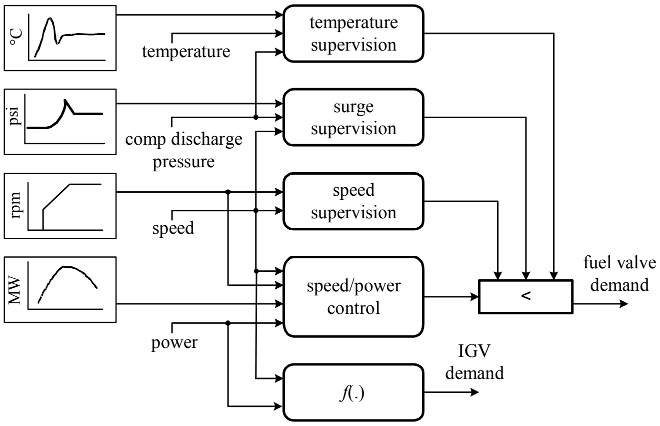

Fig. 2. Speed/power control scheme for a CTG.

B. *Structure of 2-DOF Speed Controllers*

In general, the 2-DOF controllers have a structure with 2 independently acting control trajectories or degrees-of-freedom (Fig. 3), where $R(s)$ is the speed reference, $Y(s)$ is the speed measurement, $E(s)$ is the speed error, $C_{fb}(s)$ is the feedback controller, $U_{fb}(s)$ is the feedback control signal, $C_{ff}(s)$ is the feedforward controller, $U_{ff}(s)$ is the feedforward control signal, and $U(s)$ is the total control signal. The feedforward controller $C_{ff}(s)$ solves the speed reference tracking problem and the feedback controller $C_{fb}(s)$ regulates speed and solves the disturbance rejection problem.

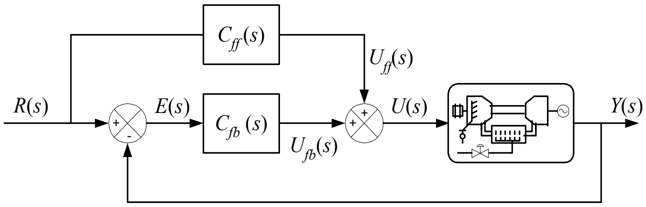

Fig. 3. 2DOF controller structure.

In the PI-NF2DF controller structure, the feedback controller $C_{fb}(s)$ is based in a PI controller:

$$C_{fb}(s) = \frac{U_{fb}(s)}{E(s)} = K_{fb} + \frac{K_i}{s} \tag{1}$$

where K_{fb} is the proportional gain, K_i is the integral gain, $E(s)$ is the error signal and $U_{fb}(s)$ is the corresponding feedback control action. In addition, the feedforward controller $C_{ff}(s)$ is based on a P controller:

$$C_{ff}(s) = \frac{U_{ff}(s)}{R(s)} = K_{ff} \tag{2}$$

where K_{ff} is the proportional gain and $U_{ff}(s)$ is the feedforward control action. The final control action generated by this control structure is given by:

$$U(s) = U_{ff}(s) + U_{fb}(s) \tag{3}$$

A discrete-time version of this 2-DOF control structure can be obtained for a sampling period T and discrete time index k as shown in Fig. 4, where z^{-1} is the sampling period time delay.

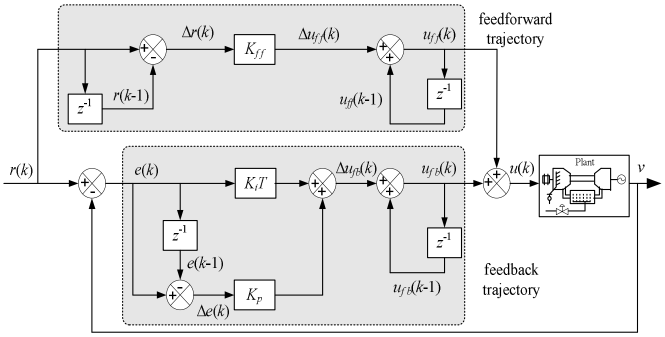

Fig. 4. Discrete-time version of 2-DOF structure for PI-NF2DF controller.

On the other hand, in the PI-FGS controller structure, the feedback controller $C_{fb}(s)$ is also based in a generalized PI controller:

$$U_{fb}(s) = K_{fb}\left(aR(s) - Y(s)\right) + \frac{K_i}{s}\left(bR(s) - Y(s)\right) \tag{4}$$

where K_{fb} is the proportional gain, K_i is the integral gain, the weighting coefficients a=0 and b=1 and $U_{fb}(s)$ is the corresponding feedback control action. Also, the feedforward controller $C_{ff}(s)$ is based on a P controller:

$$C_{ff}(s)=\frac{U_{ff}(s)}{R(s)}=K_{pr} \tag{5}$$

where K_{pr} is the proportional gain and $U_{ff}(s)$ is the feedforward control action. Thus, the final control action generated by this control structure is given by:

$$u(t)=u(t)_{ff}+u_{fb}(t)=K_{pr}r(t)-K_{pf}y(t)+K_i\int e(t)dt \tag{6}$$

where $r(t)$ is the reference signal, $y(t)$ is the output signal, $e(t)$ = $r(t)$ – $y(t)$ is the error signal, K_{pr} and K_{pf} are proportional gains for the reference and output, respectively, and K_i is the integral gain. Note that when K_{pr} and K_{pf} are equal, the generalized PI algorithm reduces to the conventional PI algorithm. A discrete-time recursive version of the generalized PI control law is shown in Fig. 5.

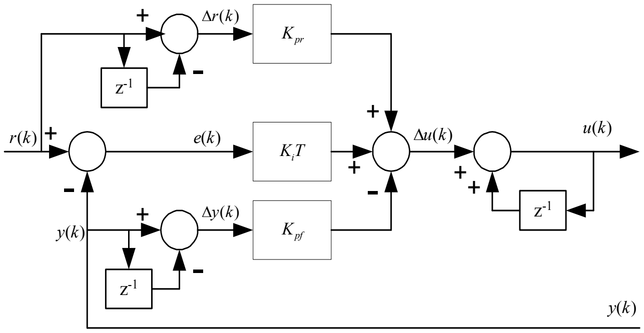

Fig. 5. Discrete-time version of 2-DOF structure for PI-FGS controller.

III. 2-DOF NEURO-FUZZY PI CONTROL

In the case of the PI-NF2DF controller, to spread the benefits of the 2-DOF structure to all the operating points at startup, the controller gains were exchanged by wide-range mappings based on neurofuzzy systems (Figs. 6, 7). Then, the PI-NF2DF controller consists of a neurofuzzy P feedforward control circuit and a neurofuzzy PI feedback control circuit, which may be independently tuned to improve both, the speed reference tracking response and the disturbance rejection response throughout the startup operating range. The PI-NF2DF is first designed as a linear controller equivalent to the existing PI controller so that substitution can be carried out without altering the current CTG startup response. Once in the loop, the PI-NF2DF neurofuzzy input-output mappings may be arbitrarily modified to improve the controller performance.

In this work, the input-output mappings are realized by means of one-input-one-output neurofuzzy systems to be able to design any arbitrary relationships between inputs and outputs, as required at different points of operation during startup of CTG.

Neurofuzzy systems allow design of fuzzy systems using the automatic learning methods of neural networks. Therefore, the neurofuzzy systems are initially trained to reproduce the input-output relationship defined by linear mappings with slopes equal to the K_{ff}, K_i and K_p gains. This approach allows placement of the PI-NF2DF controller in the speed control loop without disturbing the quality of current CTG startup response. Figs. 8, 9 and 10 define the input triangular and output singleton membership functions of the neurofuzzy systems for the case with seven partitions of the operating space. Likewise, Table I lists the IF-THEN rules of the three neurofuzzy systems. Once in the loop, a few parameters of the neurofuzzy systems may be changed to improve CTG response.

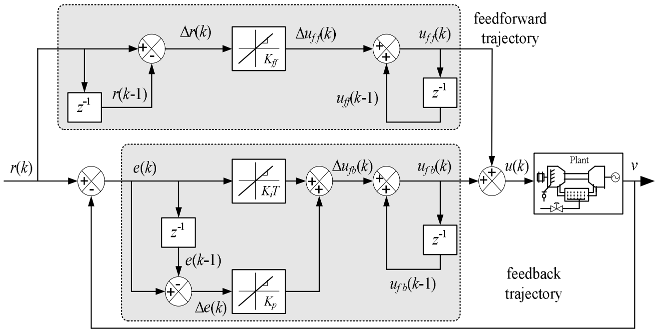

Fig. 6. Discrete-time 2-DOF controller with wide-range mappings.

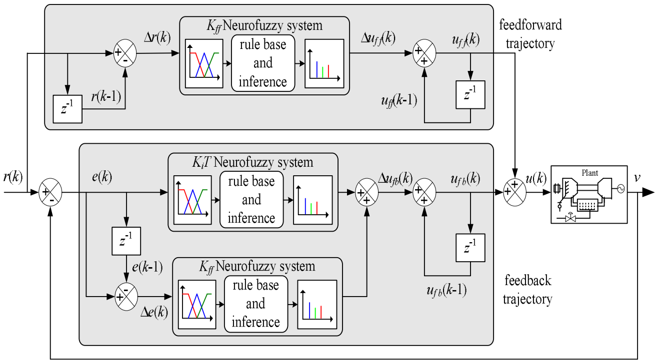

Fig. 7. Neurofuzzy systems in the PI-NF2DF controller.

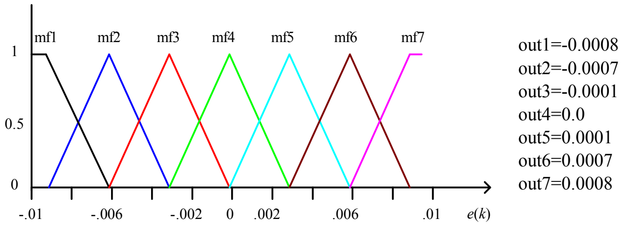

Fig. 8. Membership functions for linear K_i neurofuzzy system.

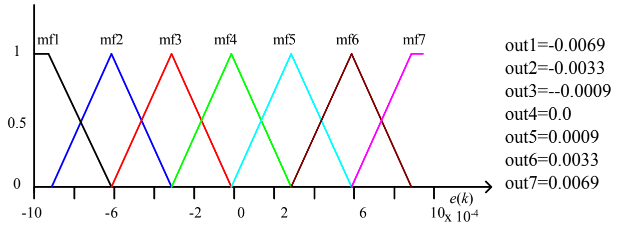

Fig. 9. Membership functions for linear K_p neurofuzzy system.

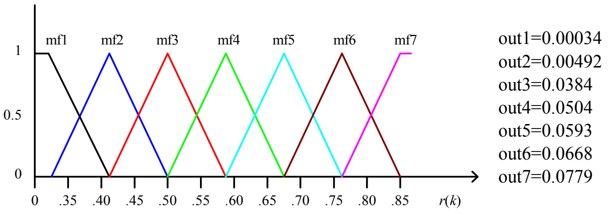

Fig. 10. Membership functions for linear K_{ff} neurofuzzy system.

TABLE I
RULE BASE OF NEUROFUZZY SYSTEM

Num	Rule
1	IF input is mf1, THEN output is out1
2	IF input is mf2, THEN output is out2
3	IF input is mf3, THEN output is out3
4	IF input is mf4, THEN output is out4
5	IF input is mf5, THEN output is out5
6	IF input is mf6, THEN output is out6
7	IF input is mf7, THEN output is out7

IV. 2-DOF FUZZY GAIN-SCHEDULING PI CONTROL

Basically, the PI-FGS controller is composed of a series of generalized PI controllers working in parallel. Each one of these controllers corresponds to one partition of the operating space (startup speed range), it is tuned to satisfy the tracking and rejection requirements of its partition, and it is put into service according to the plant operating conditions. The PI-FGS controller is assembled by means of a fuzzy system. Fuzzification implements the mechanism to detect the plant current operating conditions. Inference rules implement the generalized PI local controllers, one per rule. The inference process implements the switching logic and the interpolation or gain scheduling function.

The PI-FGS controller is based on a Takagi-Sugeno-Kan (TSK) fuzzy system with four inputs and one output. The first input enters the scheduling variable, α. The remaining inputs enter the signals $\Delta r(k)$, $e(k)$ and $\Delta y(k)$, required by the digital version of the generalized PI to calculate the control signal. The output of the TSK fuzzy system is the change in the control signal $\Delta u(k)$. Structure of the PI-FGS controller and the TSK fuzzy system are depicted in Fig.11. The TSK fuzzy system has the following main characteristics. The scheduling variable membership functions are trapezoidal and triangular. Singleton fuzzification is used to simplify calculations by the inference mechanism. Inference mechanism is based on individual rules. The total output is the weighted average combination of all rule outputs.

Each rule of the fuzzy system is associated to a single partition of the operating space and implements a generalized PI controller. Therefore, rules have the form:

$$IF\ \alpha\ is\ A_i\ THEN\ \Delta u_i(k) = K_{pri}\Delta r(k) - K_{pfi}\Delta y(k) + K_{ii}Te(k) \qquad (7)$$

where i = 1, 2, ..., R is the rule number, A_i is the fuzzy set defining the *i-th* partition of the operating space, K_{pri}, K_{pfi} and K_{ii} are the generalized PI parameters or gains of the *i-th* rule or controller, and $\Delta u_i(k)$ is the control signal generated by the *i-th* rule or controller.

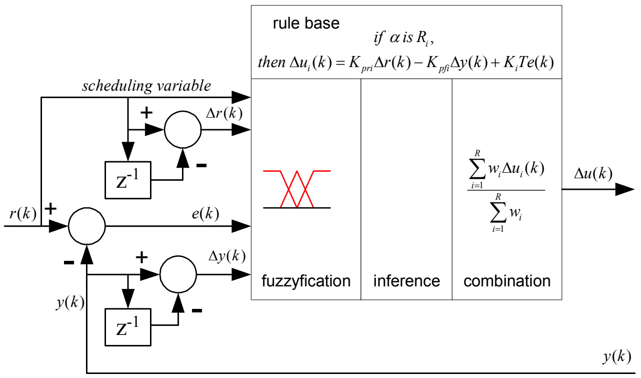

Fig. 11. Structure of PI-FGS controller.

The total control signal change, generated by the TSK fuzzy system is the weighted average of the control signals generated by each rule or controller:

$$\Delta u(k) = \frac{\sum_{i=1}^{R} w_i \Delta u_i(k)}{\sum_{i=1}^{R} w_i} \qquad (8)$$

where the weights w_i are calculated as the product of the membership values of the inputs being fuzzified. Since only the first input is being fuzzified:

$$w_i = \mu_{A_i}(\alpha) \qquad (9)$$

From (6), (7) and (8), the control signal change $\Delta u(k)$ is:

$$\Delta u(k) = \frac{\sum_{i=1}^{R} \mu_{A_i}(\alpha)\left(K_{pri}\Delta r(k) - K_{pfi}\Delta y(k) + K_{ii}Te(k)\right)}{\sum_{i=1}^{R} \mu_{A_i}(\alpha)} \qquad (10)$$

Finally, the control signal is obtained recursively:

$$u(k) = \Delta u(k) + u(k-1) \qquad (11)$$

The first relevant issue to design the PI-FGS controller is to select the scheduling variable, which must be strongly related to the change of the CTG operating conditions. In this case, the speed reference signal is chosen since its evolution is highly correlated to plant operation. The speed control range of operation spans from 1946 rpm through 5100 rpm.

The second relevant design issue is that of partitioning the operating space, which must be based on the analysis of operating conditions and control requirements throughout startup. One possibility is to define partitions in terms of plant dynamics as determined by variation of its dominant poles. Although precise, this approach requires a mathematical model of the plant that could be very difficult to obtain in practice. In this work, it is proposed to define partitions using a set of points of operation that are selected by their impact on the CTG speed response. Advantages of this approach include no need of a plant mathematical model; can be done by inspection of the speed response and makes use of operation staff experience.

As a first approximation, consider the points marked in Fig. 12 and listed in Table I. Partition of operating space is done through fuzzy sets. For simplicity fuzzy sets are chosen trapezoidal or triangular, with center and base corners at the points of interest (Fig. 13). Thus detection of the operating conditions is given by the degree of membership of the scheduling variable to each one of the fuzzy sets or partitions defined this way.

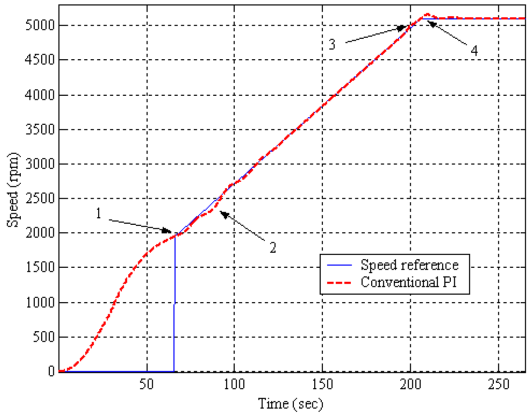

Fig. 12. CTG startup with conventional PI control.Relevant points of operation during GTPP startup.

TABLE II
POINTS OF OPERATION SELECTED TO DEFINE PARTITIONS

Point	Event	Speed (rpm)
1	Activation of acceleration pattern	1946
2	Starting engine out of service	2436
3	IGVs opening and bleeding valves closing	4830
4	Change of slop for synchronization speed	5100

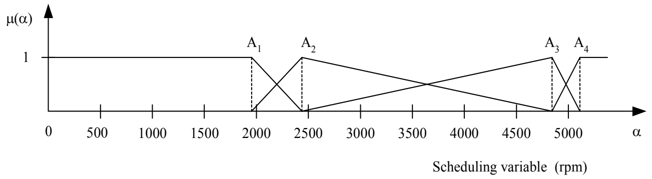

Fig. 13. Definition of fuzzy sets for operating space partition.

Subsequently, a generalized PI controller is assigned to each partition through the inference rules of the fuzzy system. From (7) and the definition of fuzzy sets, A_i, in Fig. 13, the following inference rules are obtained:

$$\begin{aligned} &IF\ \alpha\ is\ A_1\ THEN\ \Delta u_1(k) = K_{pr1}\Delta r(k) - K_{pf1}\Delta y(k) + K_{i1}Te(k) \\ &IF\ \alpha\ is\ A_2\ THEN\ \Delta u_2(k) = K_{pr2}\Delta r(k) - K_{pf2}\Delta y(k) + K_{i2}Te(k) \\ &IF\ \alpha\ is\ A_3\ THEN\ \Delta u_3(k) = K_{pr3}\Delta r(k) - K_{pf3}\Delta y(k) + K_{i3}Te(k) \\ &IF\ \alpha\ is\ A_4\ THEN\ \Delta u_4(k) = K_{pr4}\Delta r(k) - K_{pf4}\Delta y(k) + K_{i4}Te(k) \end{aligned} \quad (12)$$

V. SIMULATION EXPERIMENTS

Feasibility demonstration of both PI-NF2DF and PI-FGS controllers is carried out by means of simulation experiments with the mathematical model of a 24 MW CTG in a graphical simulation environment in a personal computer. Experiments consist in performing CTG startup simulations with each of the conventional PI, the PI-NF2DF and the PI-FGS controllers, all of them in discrete-time versions. Speed tracking performance is evaluated with the IAE (integral of absolute error) and CE (control effort) performance indexes.

Fig. 14 shows the CTG startup with both the PI and nonlinear PI-NF2DF controllers. After tuning, performance with the PI control reported IAE=2968.8 and with the PI-NF2DF IAE=2136. These results essentially demonstrate that performance may be significantly enhanced using the knowledge-based manual tuning procedure. Results also show that manual tuning yields a performance close to that obtained with the numerical optimization tuning. Fig. 15 shows the control signals provided by the same controllers. The CE indexes are very close one to another, which means that the improved performance with the PI-NF2DF controller does not necessarily implies larger control effort.

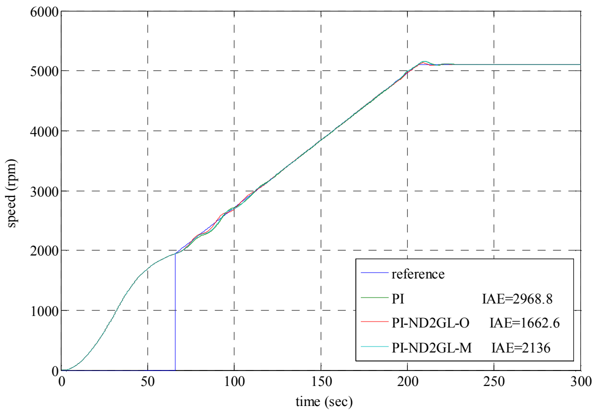

Fig 14. CTG startup with PI and PI-NF2DF controllers.

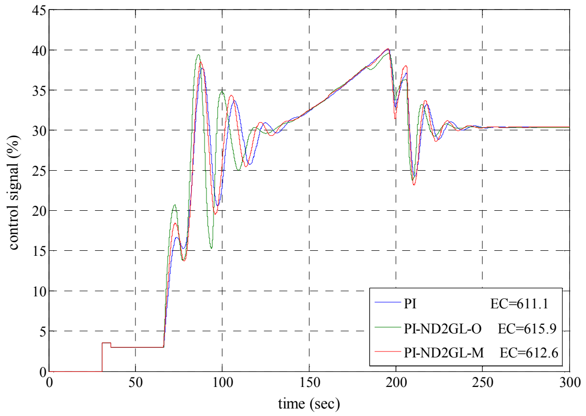

Fig 15. CE for CTG startup with PI and PI-NF2DF controllers.

In the same way, responses with the PI-FGS controller are compared to the responses with a conventional PI controller. Fig. 16 shows startup speed responses obtained with both the conventional PI and the PI-FGS (trial and error, and automatic tuning) controllers. Complementarily, Fig. 17 shows the control signals issued by the three controllers. The PI-FGS tuned by trial and error has smaller amplitude oscillations at the major interest regions. This provides softer control actions and less thermal stress.

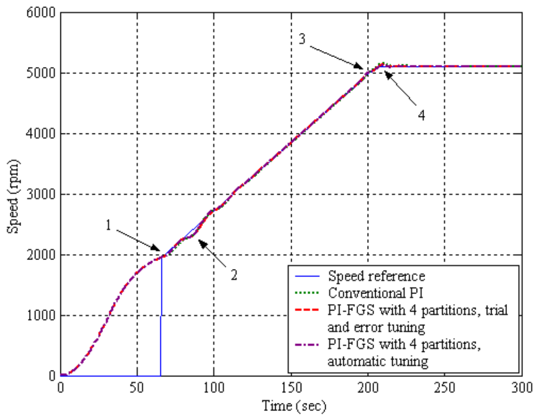

Fig. 16. Speed response of conventional PI and PI-FGS with 4 partitions.

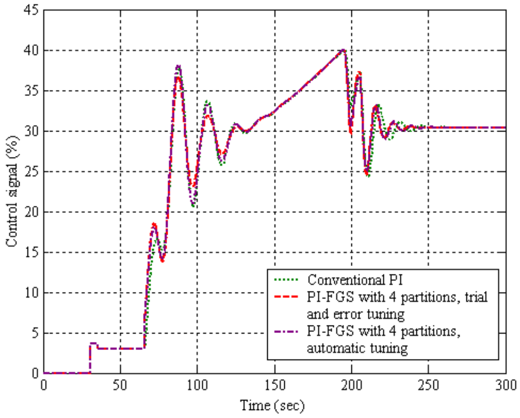

Fig. 17. Control signals of conventional PI and PI-FGS controllers.

Table III reports IAE and CE indexes to have a better appreciation of PI-FGS performance. It shows that the PI-FGS controller has better IAE performance than the conventional PI control for both manual and automatic tuning. Furthermore, trial and error tuning provided better response than automatic tuning. This result is relevant in the sense that manual tuning can provide results as good as those given by the optimization routines, since the former is the one that can be used on-site.

TABLE III
SPEED RESPONSE PERFORMANCE

Controller	IAE	EC
PI conventional	2968.8	611.10
PI-FGS with 4 partitions, trial and error tuning	1962.0	611.10
PI-FGS with 4 partitions, automatic tuning	2154.0	612.6

VI. CONCLUSIONS

This paper unveiled the PI-NF2DF and PI-FGS controllers to govern the speed response of a CTG during startup.

The nonlinear PI-NF2DF controller can outperform the conventional PI control where required. Tuning this controller can be carried out on-site in actual CTG, using response data from previous design response as starting point. A few iterations are required.

Results of simulation experiments demonstrate that the PI-FGS algorithm can improve performance of speed control well beyond that obtained with the conventional PI algorithm. Also, application of PI-FGS to actual CTG can be easily carried out on-site starting with the current controller settings.

In general, realization of the PI-NF2DF controller is easier than realization of the PI-FGS controller. Nevertheless the extra effort invested in building and tuning the PI-FGS controller can yield even better performance. Both 2-DOF controllers are suitable for application in actual CTGs.

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VIII. BIOGRAPHIES

Raul Garduno-Ramirez received his B.S. and M.S. degree in Electrical Engineering from the National Polytechnic Institute, Mexico, in 1985 and 1987, and his Ph.D. degree in Electrical Engineering from the Pennsylvania State University in 2000 as a Fulbright Fellow. In 1986, he was with the National Mechanical Laboratory in Tsukuba, Japan. Since 1987 he has been with the Electrical Research Institute- Mexico, where he is involved with the development of control systems for power plants. His current research interests include digital and intelligent control, process optimization and computational intelligence. Dr. Garduno is a member of the National Research System in Mexico and a Senior Member of IEEE.

Arnulfo Rodriguez-Martinez is a Communications and Electronics Engineer by ESIME-IPN (1987) and Master of Science in Control Engineering by the National Research and Technology Development Centre (2004). Since 1987 works at the Electrical Research Institute with the Control and Instrumentation Department. Has taken part and lead several projects to design and develop instrumentation and control systems for process industry. His current areas of interest include intelligent and digital control. He is a member of ISA.

Luis Castelo-Cuevas. Mechanical Engineer by the Morelos State Autonomous University (1992) and Master of Science in Control Engineering by the National Research and Technology Development Centre (2004). Since 1993 has been with the Department of Control and Instrumentation of the Electrical Research Institute working in modernization of control systems for power plants. His current areas of interest include development of neurofuzzy control strategies in PLCs and integration of digital control systems. Has published several papers in national and international journals and conferences.