# 2 DOF Fuzzy Gain-Scheduling PI for Combustion Turbogenerator Speed Control

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**Abstract:** This paper presents two realizations a 2-DOF PI fuzzy gain-scheduling controller for wide-range speed control of combustion turbogenerators. The 2-DOF scheme allows independent tuning of the reference tracking and the disturbance rejection characteristics for the controlled system. Then, the fuzzy approach extends these characteristics all over the operating space of the combustion turbogenerator. Both realizations can be inserted into the speed control loop of existing control systems without degrading performance. Once in the loop, the controllers can be progressively tuned on-site, based on the inspection of speed responses. The proposed 2-DOF PI fuzzy gain-scheduling control schemes are suitable for application on actual combustion turbogenerators.

*Keywords:* Combustion turbogenerator, 2 DOF control schemes, Gain-scheduling, speed control, Fuzzy systems.

## 1. INTRODUCTION

Nowadays, power generation by means of combustion turbogenerators (CTG) plays a major role worldwide. Also, most power plants to be built in the next 20 years will be combined-cycles based on CTGs due to their advantages over other technologies. Advantages include low commissioning, low 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 based on toping combustion turbine cycles, Horlock (2001).

CTGs operate at relatively higher speeds, pressures and temperatures, than other plants, as well as, over wider operation ranges and faster changes of points of operation. Moreover, operation of CTGs is very highly automated, including the stages of startup, synchronization, loading in different modes, stopping and tripping. These characteristics set very tight requirements for the control system; the startup very probably being the most demanding stage for the control system Garduno and Sanchez (1995). 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.

Current CTG speed controls basically consist of a feedback loop, where a PI or PID algorithm provides the control signal from the speed deviation between the speed reference and measurements Woodward (2002). In general, such control algorithms cannot provide optimal response to more than one control objective. They can be tuned for reference signal tracking or disturbance rejection requirements, but both at the same time. Conversely, two-degrees of freedom (2-DOF) control strategies can be used to achieve both, good tracking of reference signals and rejection of external disturbances. Nevertheless, although several 2-DOF control schemes are available in the technical literature, there are few references on how to extend the benefits of 2-DOF control schemes over wide ranges of operation, as required by CTGs, Garduno and Lee (2000, 2003).

In this regard, this paper unveils two feasible realizations of 2-DOF PI fuzzy gain-scheduling schemes to control CTG speed at startup, from fuel ignition up to rated speed, just before synchronization of the power plant to the power grid. Section 2 presents the basics conventional and 2-DOF speed controls. Section 3 presents the realization of two 2-DOF PI fuzzy gain-scheduling (PI-FGS) controllers for CTG, Rodriguez and Garduno (2011), where a fuzzy system is used to spread the benefits of a 2-DOF PI structure all over the CTG startup operating space by implementing a gain-scheduling strategy. The fuzzy system nicely solves the problems of detection of operating conditions, controller switching and gain scheduling. Section 4 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. Section 5 summarizes this work and draws conclusions.

## 2. 2-DOF CONTROL SCHEMES

### *1.1 Conventional Speed Control Strategy*

Typical CTGs consist of five major components that operate continuously 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. Pressurized air is mixed with fuel and burned to produce the hot flue gas that is delivered to the turbine moving blades through expansion nozzles. 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.

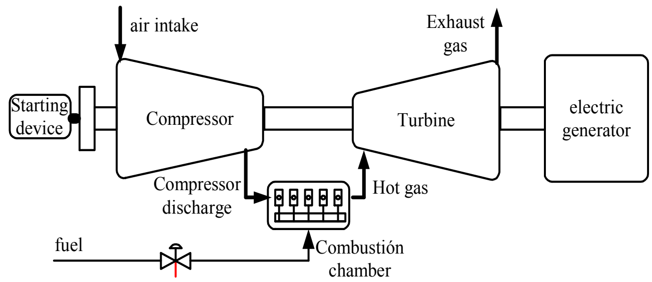


Fig. 1. Major components of a typical CTG.

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.

### *1.2 Structure of 2-DOF Speed Controllers*

In general, 2-DOF controllers have a structure with 2 separately 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. Two realizations of 2-DOF PI controller structures are presented in what follows.

In the first 2-DOF PI controller structure, the feedback controller $C_{fb}(s)$ is based in a generalized PI controller:

$$U_{fb}(s) = K_{fb}\left(-\Delta Y(s)\right) + \frac{K_i}{s}\left(bR(s) - Y(s)\right) \tag{1}$$

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.

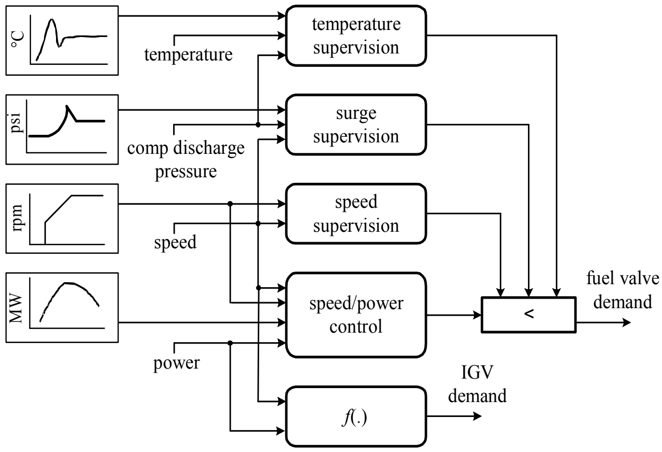


Fig. 2. Speed/power control scheme for a CTG.

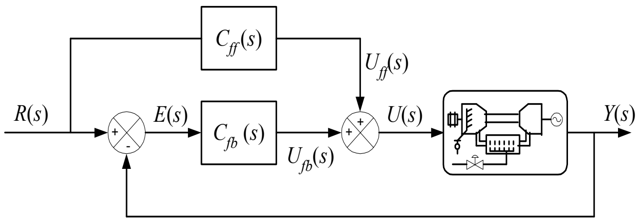


Fig. 3. 2-DOF controller structure.

The feedforward controller $C_{ff}(s)$ is based on a P controller:

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

where $K_{ff}$ is the proportional gain and $U_{ff}(s)$ is the feedforward control action. The change of the control action between two consecutive sampling instants, $k$ and $k$-1, is given by:

$$\begin{aligned}\Delta u(k) &= u_{ff}(k) + u_{fb}(k) \\ &= K_{ff}\Delta r(k) - K_{fb}\Delta y(k) + K_i Te(k).\end{aligned} \tag{3}$$

where $\Delta r(k)$ = $r(k)$ - $r(k\text{-}1)$ is the change in the reference signal, $\Delta y(k)$ = y($k$) - y($k$-$1$) is the change in the output signal, $e(k)$ = $r(k)$ – $y(k)$ is the error signal, $K_{ff}$ and $K_{fb}$ are proportional gains for the reference and output, respectively, and $K_i$ is the integral gain. Note that when $K_{ff}$ and $K_{fb}$ are equal, the generalized PI algorithm reduces to the conventional PI algorithm. The final control signal is obtained recursively as:

$$u(k) = \Delta u(k) + u(k-1) \tag{4}$$

A discrete-time recursive version of the generalized PI control law is shown in Fig. 4.

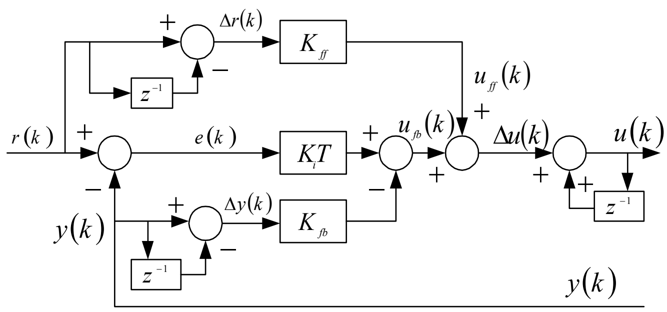


Fig. 4. First 2-DOF PI controller structure.

In the second 2-DOF PI controller structure, the feedback controller $C_{fb}(s)$ is the same as in the first case:

$$U_{fb}(s) = K_{fb}\left(-\Delta y(s)\right) + \frac{K_i}{s}\left(bR(s) - Y(s)\right) \tag{5}$$

Now the feedforward controller $C_{ff}(s)$ directly uses the reference value $r(k)$ at each sampling instant $k$, while in the first 2-DOF PI control structure the feedforward controller uses the change in the reference signal $\Delta r(k)$:

$$C_{ff}(s) = \frac{U_{ff}(s)}{R(s)} = K_{ff} \tag{6}$$

where $K_{ff}$ 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:

$$\begin{aligned} u(k) &= u_{ff}(k) + u_{fb}(k) \\ &= K_{ff} r(k) - K_{fb}\Delta y(k) + K_i Te(k) \end{aligned} \tag{7}$$

where $r(k)$ is the reference signal, $\Delta y(k) = y(k) - y(k-1)$ is the change in the output signal, $e(k) = r(k) - y(k)$ is the error signal, $K_{ff}$ and $K_{fb}$ are proportional gains for the reference and output, respectively, and $K_i$ is the integral gain. A discrete-time recursive version of this generalized PI control law is shown in Fig. 5.

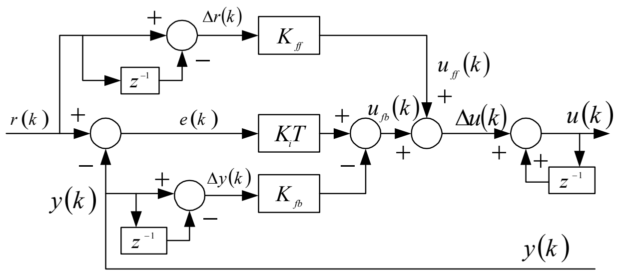

Fig. 5. Discrete-time version of second 2-DOF PI control structure.

## 3. 2-DOF PI FUZZY GAIN SCHEDULING CONTROL

Basically, the 2-DOF PI-FGS controller is created from a series of 2-DOF PI controllers working in parallel. Each of these controllers corresponds to one partition of the operating space (CTG startup speed range). Each controller is tuned to satisfy the tracking and rejection requirements of its partition, and put into service according to plant operating conditions. Hence, the 2-DOF PI controllers are 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. Then, the inference process implements the switching logic and the interpolation or gain scheduling function.

The PI-FGS controller is a Takagi-Sugeno-Kan (TSK) fuzzy system with four inputs and one output. The first input enters the scheduling variable, $\alpha$. The remaining inputs enter signals $\Delta r(k)$, $e(k)$ and $\Delta y(k)$, required by the digital 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. 6. The TSK fuzzy system has the following main characteristics. 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. Output is the weighted average combination of all rule outputs.

For type 1 2-DOF PI-FGS controller each rule of the fuzzy system implements a 2-DOF PI controller with the first structure. Therefore, rules have the form:

$$IF\ \alpha\ is\ A_i\ THEN\ \Delta u_i(k) = K_{ffi}\Delta r(k) - K_{fbi}\Delta y(k) + K_{ii}Te(k) \tag{8}$$

where $i$ = 1, 2, ..., $R$ is the rule number, $A_i$ is the fuzzy set defining the *i-th* partition of the operating space, $K_{ffi}$, $K_{fbi}$ 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.

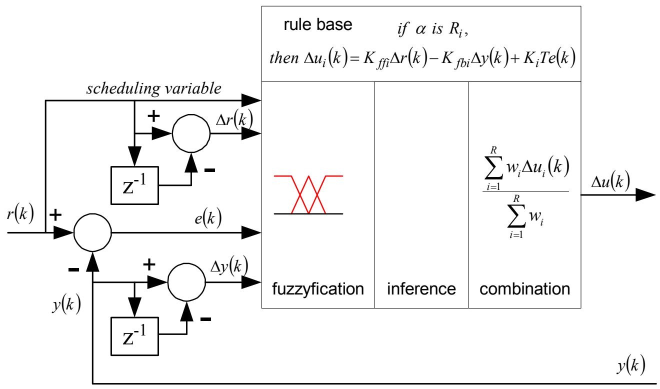


Fig. 6. Structure of 2 DOF PI-FGS controller.

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:

$$\Delta u(k) = \frac{\sum_{i=1}^{R} w_i \Delta u_i(k)}{\sum_{i=1}^{R} w_i} \tag{9}$$

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:

$$w_i = \mu_A(\alpha) \tag{10}$$

From (3), (9) and (10), the control signal change $\Delta u(k)$ is:

$$\Delta u(k) = \frac{\sum_{i=1}^{R} \mu_{A_i}(\alpha)\left(K_{ffi}\Delta r(k) - K_{fbi}\Delta y(k) + K_{ii}Te(k)\right)}{\sum_{i=1}^{R} \mu_{A_i}(\alpha)} \tag{11}$$

Finally, the control signal is obtained recursively:

$$u(k) = \Delta u(k) + u(k-1) \tag{12}$$

Similarly, for type 2 2-DOF PI-FGS controller each rule implements a 2 DOF PI controller with the second structure:

$$u_r(k) = \frac{\sum_{i=1}^{R} w_i\left(K_{ffi} r(k)\right)}{\sum_{i=1}^{R} w_i} \tag{13}$$

$$\Delta u_f(k)=\frac{\sum_{i=1}^{R} w_i\left(-K_{fbi}\Delta y(k)+K_{ii}Te(k)\right)}{\sum_{i=1}^{R} w_i} \tag{14}$$

With $u_f(k)$ obtained from:

$$\Delta u_f(k)=u_f(k)-u_f(k-1) \tag{15}$$

Finally, the control signal is obtained as:

$$u(k)=u_r(k)+u_f(k) \tag{16}$$

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. The speed control range spans from 1946 rpm through 5100 rpm.

The second design issue is that of partitioning the operating space, which must be made on the analysis of operating conditions and control requirements throughout startup. 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 mathematical model of the plant; partition can be done by inspection of the speed response using experience.

As a first approximation, consider the points marked in Fig. 7 and listed in Table 1. Partition of operating space is done with fuzzy sets. For simplicity trapezoidal or triangular fuzzy sets are chosen, with centre and base corners at the points of interest (Fig. 8). 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.

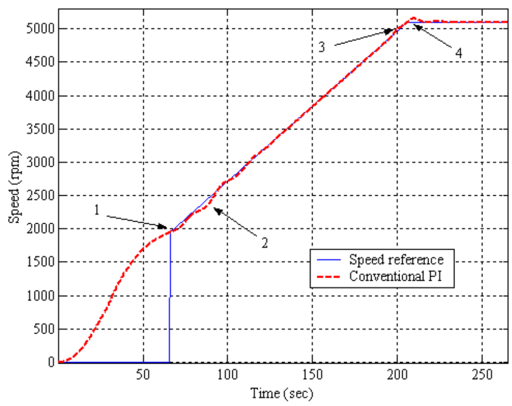


Fig. 7. CTG startup with PI control showing relevant points of operation.

**Table 1. 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 |

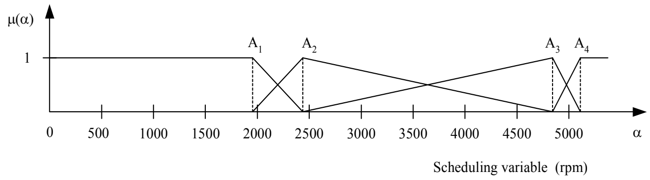


Fig. 8. Definition of fuzzy sets for operating space partition.

Subsequently, a 2 DOF PI controller is assigned to each partition through the inference rules of the fuzzy system. From (8) and the definition of fuzzy sets, $A_i$, in Fig. 8, the following inference rules are obtained:

$$\begin{aligned}
&IF\ \alpha\ is\ A_1\ THEN\ \Delta u_1(k)=K_{ff1}\Delta r(k)-K_{fb1}\Delta y(k)+K_{i1}Te(k)\\
&IF\ \alpha\ is\ A_2\ THEN\ \Delta u_2(k)=K_{ff2}\Delta r(k)-K_{fb2}\Delta y(k)+K_{i2}Te(k)\\
&IF\ \alpha\ is\ A_3\ THEN\ \Delta u_3(k)=K_{ff3}\Delta r(k)-K_{fb3}\Delta y(k)+K_{i3}Te(k)\\
&IF\ \alpha\ is\ A_4\ THEN\ \Delta u_4(k)=K_{ff4}\Delta r(k)-K_{fb4}\Delta y(k)+K_{i4}Te(k)
\end{aligned} \tag{17}$$

Inference rules for the second structure of PI-FGS controller are as follows:

$$\begin{aligned}
&IF\ \alpha\ is\ A_1\ THEN\ \Delta u_1(k)=K_{ff1}r(k)-K_{fb1}\Delta y(k)+K_{i1}Te(k)\\
&IF\ \alpha\ is\ A_2\ THEN\ \Delta u_2(k)=K_{ff2}r(k)-K_{fb2}\Delta y(k)+K_{i2}Te(k)\\
&IF\ \alpha\ is\ A_3\ THEN\ \Delta u_3(k)=K_{ff3}r(k)-K_{fb3}\Delta y(k)+K_{i3}Te(k)\\
&IF\ \alpha\ is\ A_4\ THEN\ \Delta u_4(k)=K_{ff4}r(k)-K_{fb4}\Delta y(k)+K_{i4}Te(k)
\end{aligned} \tag{18}$$

## 4. SIMULATION EXPERIMENTS

Feasibility demonstration of both 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 and both 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.

First, responses with the type 1 2-DOF PI-FGS controller are compared to the responses with a conventional PI controller. Fig. 9 shows startup speed responses obtained with both the conventional PI and the type 1 2-DOF PI-FGS (trial and error, and automatic tuning). Complementarily, Fig. 10 shows the control signals issued by the three controllers. The 2-DOF PI-FGS controller tuned by trial and error has smaller amplitude oscillations at the major interest regions. This provides softer control actions and less thermal stress.

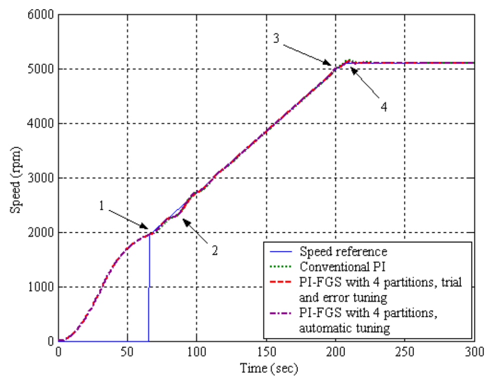


Fig. 9. Speed response of PI and PI-FGS with 4 partitions.

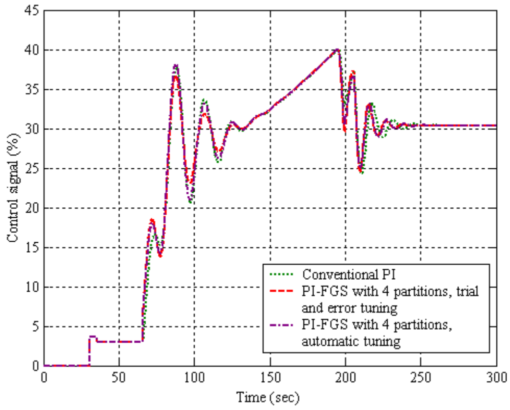


Fig. 10. Control signals of PI and PI-FGS controllers.

Table II reports IAE and CE indexes to have a better appreciation of controller performance. The 2-DOF PI-FGS controller has better IAE performance than the conventional PI control for both manual and automatic tuning. Also, trial and error tuning provided better response than automatic tuning. This result is relevant in the sense that on-site manual tuning can provide results as good as those given by the optimization routines.

**Table 2. 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 | 612.60 |

Even better performance may be obtained with the 2-DOF PI-FGS controller considering more partitions, which can be defined by inspection of the CTG speed response. Cases with 6 partitions are considered for both 2-DOF PI-FGS structure controllers. From Fig. 9 extra points of operation are selected between Points 1 and 2, and 3 and 4, as listed in Table III. This table also lists the parameter values of the generalized PI controller for each partition.

**Table 3. Selected operating points and controller parameters of type 1 2-DOF PI-FGS with 6 partitions**

| Point | Speed (rpm) | $K_{ff}$ | $K_{fb}$ | $K_i$ |
|---|---|---|---|---|
| 1 | 1946 | 3.4835 | 3.454 | 1.018 |
| 2 | 2250 | 3.5197 | 2.2709 | 0.0763 |
| 3 | 2436 | 3.49 | 3.4695 | 0.0867 |
| 4 | 4830 | 3.5040 | 3.3587 | 1.796 |
| 5 | 4920 | 3.496 | 3.42 | 0.171 |
| 6 | 5100 | 3.479 | 4.3299 | 0.108 |

Responses of both 2-DOF PI-FGS controllers with 6 partitions are closed-up in Figs. 11 and 12. Fig. 11 shows responses at the beginning of the startup ramp. Figs. 11 and 12, show that both controllers have similar responses. Fig. 13 shows the control signals issued by both controllers, where it is seen that both signals are very similar too.

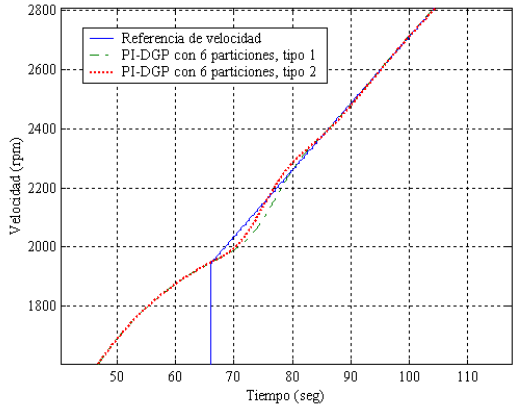


Fig. 11. Speed response of PI-FGS type 1 and type 2 with 6 partitions.

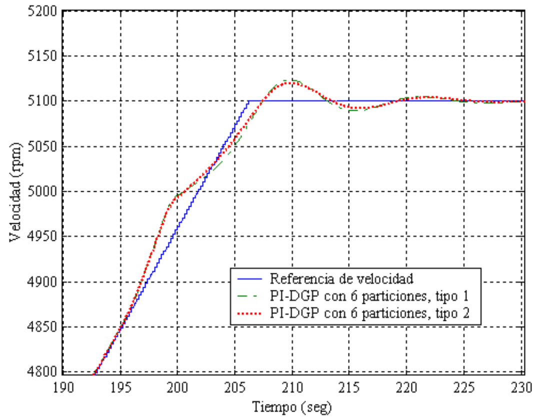


Fig. 12. Speed response of PI-FGS type 1 and type 2 with 6 partitions.

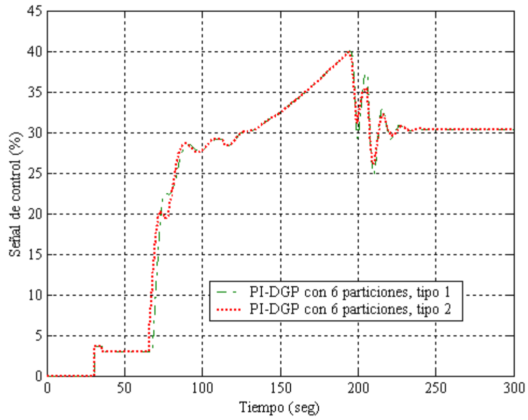


Fig. 13. Control signals of both PI-FGS type 1 and type 2 controllers.

To better appreciate the performance of the controllers, Table IV reports the IAE and CE indexes. Clearly, response of 2-DOF PI-FGS type 2 controller, outperforms that of the 2-DOF PI-FGS type 1 controller.

**Table 4. Speed response performance**

| 2-DOF PI-FGS Controller | IAE | EC |
|---|---|---|
| Type 1, 6 partitions, trial and error tuning | 1036.8 | 605.7 |
| Type 2, 6 partitions, trial and error tuning | 892.8 | 606.3 |

Finally, simulation experiments with the 2-DOF PI-FGS type 2 controller with 7 partitions were made. From Fig. 12 and table III an extra point of operation is selected between current Points 5 and 6, as listed in Table V. This table also lists the parameter values of the controller for each partition.

Figs. 14 and 15 show startup speed responses obtained with both the conventional PI and the 2-DOF PI-FGS type 2 with 7 partitions. It is clear how the 2-DOF PI-FGS type 2 controller with 7 partitions outperforms the conventional PI controller. Fig. 16 shows the control signals issued by the two controllers. The 2-DOF PI-FGS shows much smaller amplitude oscillations at the beginning of the startup ramp and a little less at the end, compared to the control signal with a conventional PI controller.

**Table 5. Selected operating points and controller parameters of type 2 2-DOF PI-FGS with 7 partitions**

| Point | Speed (rpm) | $K_{ff}$ | $K_{fb}$ | $K_i$ |
|---|---|---|---|---|
| 1 | 1946 | 3.4886 | 3.458 | 0.988 |
| 2 | 2250 | 3.52 | 2.2759 | 0.0759 |
| 3 | 2436 | 3.4954 | 3.4745 | 0.0868 |
| 4 | 4830 | 3.5030 | 3.3401 | 1.1132 |
| 5 | 4920 | 3.4503 | 2.81 | 0.1905 |
| 6 | 4980 | 3.4971 | 4.3027 | 0.1102 |
| 7 | 5100 | 3.479 | 4.3325 | 0.1083 |

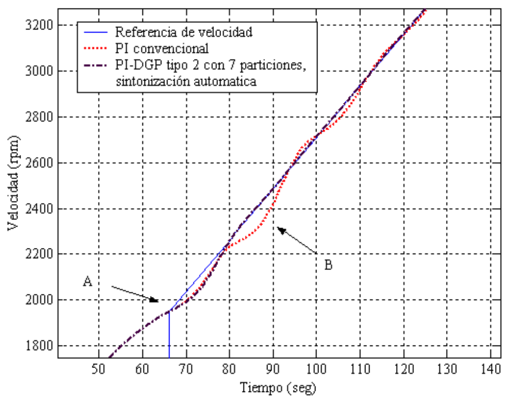


Fig. 14. Speed response of PI and PI-FGS type 2 with 7 partitions.

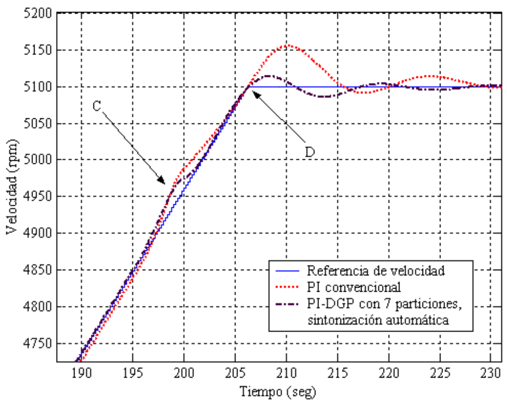


Fig. 15. Speed response of PI and PI-FGS type 2 with 7 partitions.

Table 6 reports the IAE and CE indexes. Clearly, response of 2-DOF PI-FGS type 2 controller, outperforms that of the PI conventional controller.

**Table 6. Speed response performance**

| Controller | IAE | EC |
|---|---|---|
| PI conventional | 2968.8 | 611.10 |
| PI-FGS with 7 partitions, automatic tuning | 874.8 | 605.25 |

## 5. CONCLUSIONS

This paper unveiled two PI-FGS structure controllers to govern the speed response of a CTG during startup. Results of simulation experiments demonstrate that both PI-FGS algorithms 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. Both 2-DOF controllers are suitable for application in actual CTGs.

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