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Research Article

Evaluating Fractional PID Control in a Nonlinear MIMO Model of a Hydroelectric Power Station

O. A. Rosas-Jaimes,[1] **G. A. Munoz-Hernandez**,[1] **G. Mino-Aguilar**,[1] **J. Castaneda-Camacho**,[1] **and C. A. Gracios-Marin**[2]

[1] *Benemerita Universidad Autonoma de Puebla, Av. San Claudio and 18 Sur. Puebla, C.P. 72570, Mexico*
[2] *Instituto Tecnologico de Puebla, Av. Tecnologico 420 Puebla, C.P. 72220, Mexico*

Correspondence should be addressed to O. A. Rosas-Jaimes; oscar.rosasj@correo.buap.mx

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In this paper a Fractional PID Control is presented. This control was designed for a hydropower plant with six generation units working in an alternation scheme. The parameters and other features of such a set of hydrogeneration units have been used to perform the respective tuning up. In order to assess the behavior of this controlled system, a model of such nonlinear plant is regulated through a classical PID by classical linearization of its set points, and then a pseudo-derivative part is substituted into a Fractional PID. Both groups of signals contain variations of voltage suggesting some abrupt changes in the supply of electricity fed to the network. Both sets of resulting signals are compared; the simulations show that the Fractional PID has a faster response with respect to those plots obtained from the classical PID used.

1. Introduction

Hydropower pumped storage stations are important because they have the capacity of releasing, on demand, large amounts of energy to an electrical net (Figure 1). Water is pumped to an upper reservoir from a lower one and released to generate electricity [1]. The model to be used in this work is based on Dinorwig, North Wales, UK [1–3]. It is composed of six reversible pump-turbines of 300 MW each [2, 3]. To modulate the flow, six valves that enclose the turbine inlet are used. Two closed loop control signals are used to determine the guide vane angle: an inner loop controls the generated power, and an outer loop controls the grid frequency. Different works have been published for Dinorwig [1–3]. In this study a nonlinear model will be considered. To improve the plant performance, different controllers have been employed [1] including a Fractional PID, whose performance is evaluated in this paper.

As can be seen in Figure 1, in the hydro station the behavior of a single unit depends on the flow in the common tunnel, because its penstocks share a common conduit [4, 5]. The number of units in operation among the operating points determines the total flow. It is a common practice that only one unit operates at *part-load*.

Notwithstanding the advances in automatic control, the use of classical controllers is still very common in hydropower systems. In the literature there are many examples where industrial loops are controlled by these classical controllers, getting results that accomplish the requirements of the power systems [1, 6]. However, as was stated, the hydropower plant (Dinorwig) is a complex system and some of its characteristics make it difficult to obtain an appropriate performance by "only" using classical controllers.

For many years, different variations of PID that include nonlinear characteristics have been reported. In recent years, applications of PID controllers with integral and derivative parts of fractional order have been described. Those studies show an improvement of the performance of the controlled systems [7]. For instance, a generalization of the PID controller was proposed by Podlubny [8, 9]; that approach includes an integrator of order λ and a differentiator of order δ ($PI^{\lambda}D^{\delta}$ controller). In that work, the better response of this type of controller as compared with the classical PID controller was demonstrated. Frequency domain approaches

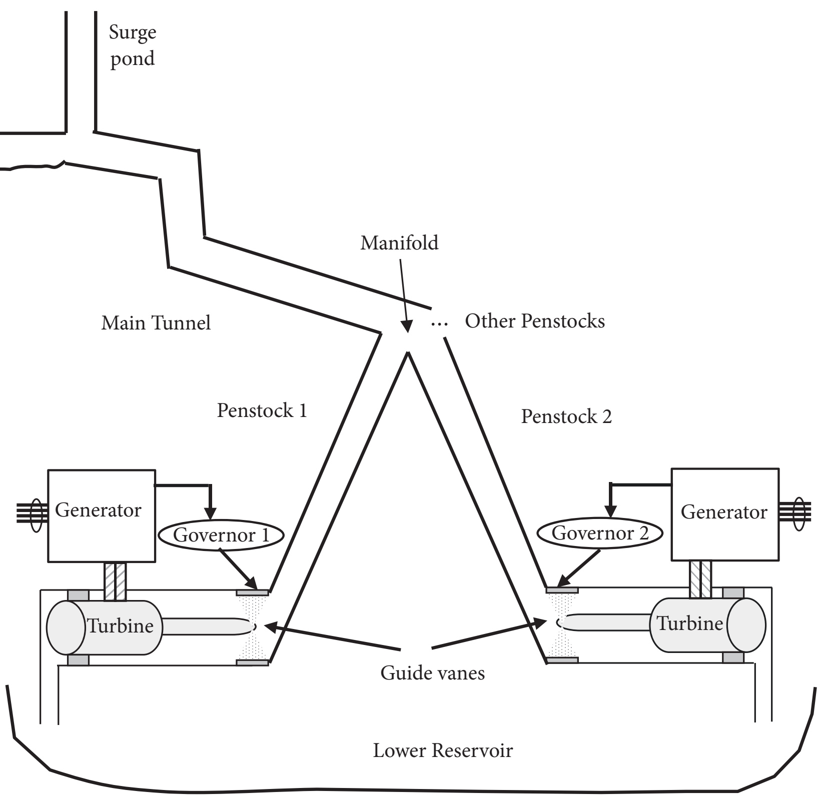

Figure 1: Dinorwig power station's representation showing only 2 of the 6 units.

for fractional order PID controllers have also been studied [10].

Several fractional order controller applications to hydropower plants have been published in recent years. Meng and Xue [11] have proposed, for example, a robust controller with fractional order for hydropower plants using automatic loop shaping to employ a Quantitative Feedback Theory (QFT) design. In that work, a flexible structure model is the main feature of this fractional order compensator. These authors have found that the fractional order controller is able to obtain a smaller high-frequency gain than the integer-order controller.

Chen et al. [12] have also described a fractional order PID controller (FOPID), whose parameters are calculated by means of a multiobjective optimization through a chaotic nondominated sorting genetic algorithm II (NSGAII). These authors used such a design to regulate a hydraulic turbine.

Xu et al. [13] have analyzed the dynamic stability of a mathematical model for a hydroturbine governing system using a fractional order regulator. The model includes a penstock system, a hydraulic servo-system, a generator, and a hydroturbine.

Wang et al. [14] have studied a finite time regulator when a hydroturbine is governed by using a fractional order nonlinear control. Their simulation results show that their proposed scheme is useful and robust.

Li et al. [15] have employed a fractional order regulator in a pumped storage unit. Their experimental results indicate that their proposal algorithm has shown excellent performance. Those results have also proved that the FOPID-CGGSA regulator presents superior benefits over other PID-type regulators with particular optimization proposals.

Xu et al. [16] have proposed a FOPID to control a reversible turbine. In their work, they use a combination of bacterial foraging (BFA) algorithm with a multiscenario functions set to select the controller's parameters.

Li, Yang, and Xia [17] have published a study that focused on the stability problems in a hydropower station, where a nonlinear hydropower generation system for the load rejection transient process was considered. They identified four critical variables of the system. Afterward, dynamic safety assessment based on the Fisher discriminant method was carried out. Their results demonstrate that the hydropower generation system in this study case can operate safely.

Fang, Yuan, and Liu [18] applied an approach based on active-disturbance-rejection-control fractional order PID to a hydroturbine speed governor system. Their proposed control has shown a strong ability of active disturbance rejection and more flexibility of nonlinear characteristics of hydroturbine speed governor system, which resolves the contradiction between fast response and small overshoot.

Nangrani and Bhat [19] have evaluated a Fractional Order Proportional Integrative Regulator for rotor angle control. Their results have shown that the proposed controller has improved the dynamic behavior of their power system.

Plant response optimization is significant for technical and economic reasons, and it is a priority for the company. Though many controllers have been applied to hydropower

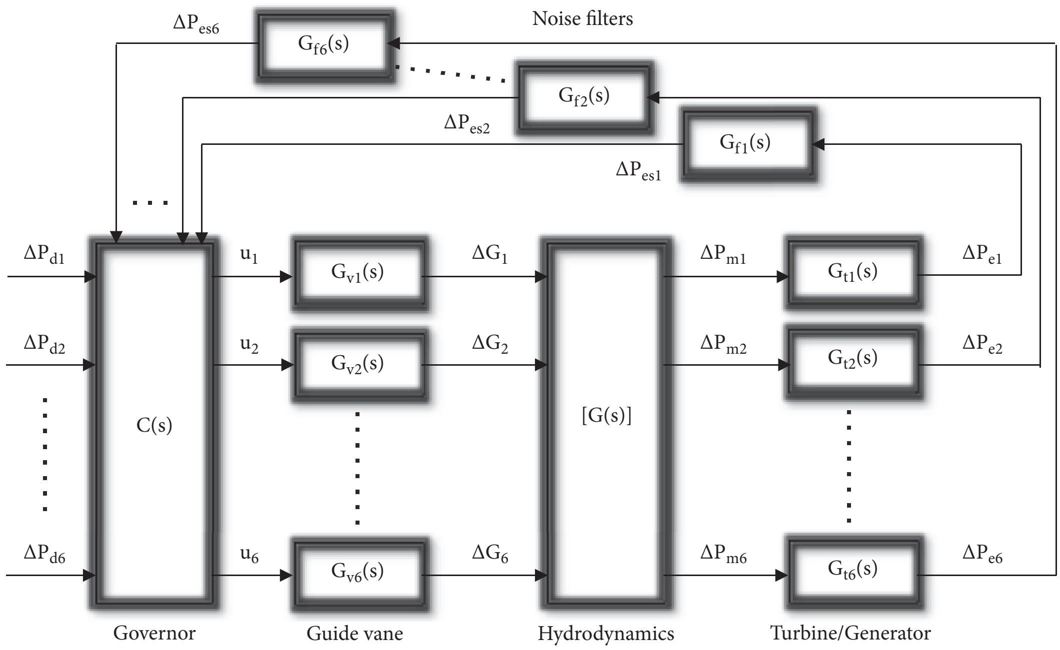

Figure 2: Subsystems of the power plant model.

systems, there are current opportunities. For example, Hote and Jain [20] recognized that the main challenge in Load Frequency Control is to develop a highly robust PID controller that maintains frequency deviation strictly in specified limits even in the presence of nonlinearities, physical constraints, and uncertain environment. For those reasons the main objective of the present paper is to increase power plants response in their precision and speed for short-term load perturbations and for frequency control using a nonlinear model to asset the performance of the proposed controller. To achieve this objective, a PID controller with fractional elements is deduced and evaluated as a proposed governor for a hydropower plant.

2. Hydropower Plant Model

In Dinorwig, the common tunnel produces an important cross-coupling effect; therefore the system is inherently multivariable [4]. This behavior has a contrary effect on the stability margin in closed loop. The units connected react modifying their control signals, via their governors, changing their operation points, while those units that are not connected have their valves closed in order to not "disturb" the flow. Consequently the number of active units determines the structure of the system. For this model all the variables are in per-unit (p.u.) form, standardized to 300MW and 50Hz; normally an electrical net with infinite busbars is assumed [21]; however, to simulate frequency control, a grid model is connected to the hydropower model. Figure 2 shows the 5 subsystems that compose the hydropower plant model. The governor is where the control signals are calculated; in this work a classical and a fractional order controller are evaluated; they are discussed in Sections 3 and 4. The guide vane model includes the valve dynamics and also the servo-mechanism for the six units; see (1). The hydrodynamics include the main tunnel and the six penstocks. Furthermore the turbine/generator is modeled, the outputs of this subsystem are filtrated before they are fed back; see (5).

For the guide vane subsystem, a hydraulic servo-system is employed to move the guide vanes in order to control the flow, represented by

$$\frac{\Delta G(s)}{u(s)} = \frac{1}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{1}$$

where u in (1) is the control signal [1, 2].

For the hydrodynamics subsystem, a nonlinear model that includes elastic characteristic is applied to simulate speed and power changes [4]. Figure 3 shows the interaction between the main tunnel and one penstock; the "surge tank and main tunnel" block will be connected to the other 5 penstocks in the complete hydraulic model.

In Figures 2 and 3, we have the following:

Surge impedance of the conduit, Z_0 (2)

Head loss coefficient in $m/(m^3/s)^2$, f_p

No load flow in m^3/s, q_{nl}

Turbine gain, A_t

Guide vane opening, ΔG

Mechanical power output of the turbine, ΔP_{mi}, i = 1, 2, . . ., 6

Electrical power alteration provided to the electrical net, ΔP_{ei}, i = 1, 2, . . ., 6

Length of penstocks in m, l

Water time constant in seconds, T_w [3, 22]

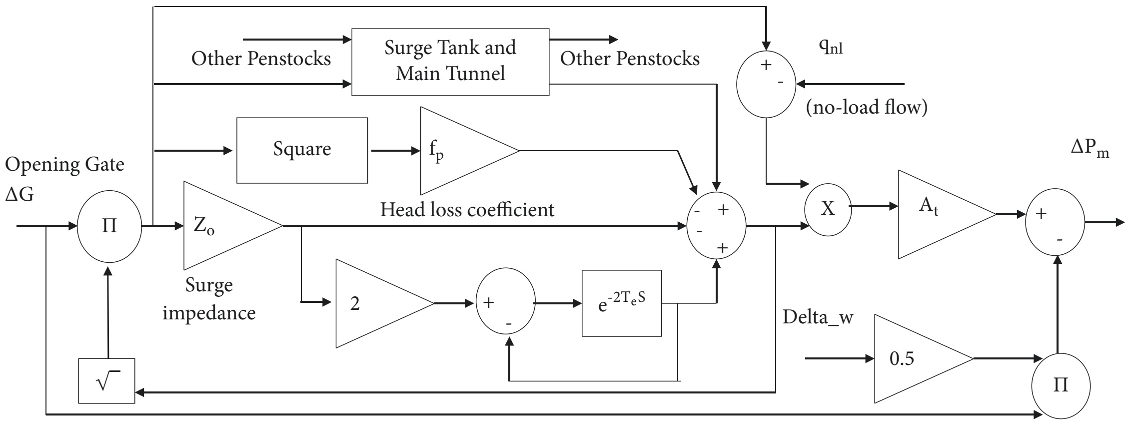

FIGURE 3: Hydraulic subsystem of the power plant.

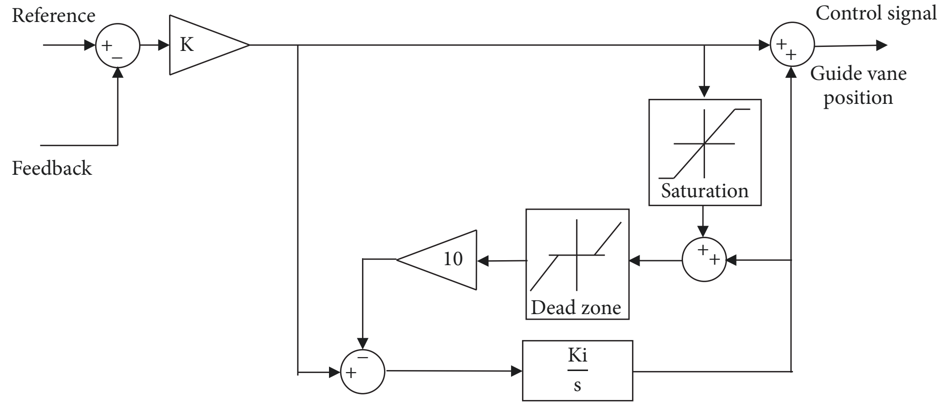

FIGURE 4: General scheme of PI antiwindup.

Wave travel time in seconds, T_e (3) [1, 3]

Velocity of sound in water in m/s, v

$$Z_o = \frac{T_w}{T_e} \quad (2)$$

$$T_e = \frac{l}{v} \quad (3)$$

It is considered, for practical purposes, that the factors A_t, f_p, and q_{nl} are identical to simulate this system. Because the power plant has large penstocks, the water columns were modeled assuming elastic behavior [4]. The coupling effect is also modeled by including the main tunnel, which is represented as a penstock.

In Figures 2 and 3, the mechanical power ΔP_m is the input to the turbine-generator which is modeled for the turbine/generator subsystem, assuming a steady state by the "swing" equations [22] and

$$\Delta P_m - \Delta P_e = 2Hs\Delta\omega \quad (4)$$

where

ΔP_e is the alteration in electrical power contributed to the grid

H is the inertia constant of the electrical subsystem

$\Delta\omega$ is the alteration of the rotor's angular velocity

Finally, a first-order filter is used for noise reduction, indicated as noise filters subsystem in Figure 2, which has the transfer function:

$$\frac{\Delta P_{es}(s)}{\Delta P_e(s)} = \frac{1}{s+1} \quad (5)$$

3. Classical and Fractional PID

To regulate hydropower stations, classical controllers have been used for many years. Linear transfer functions are normally the basis to tune up these controllers. Nonetheless, as was stated before, hydropower plants are highly nonlinear, time variant, and multivariable. Therefore, it is difficult to have a good performance with a classical linear controller. As these controllers are, normally, the actual governors for many hydropower stations, it is important to conduct studies for improving the classical governor performance.

The performance of classical controllers depends strongly on their fixed value parameters. Generally, the main purpose of tuning is to have a suitable equilibrium among sensitivity, control effort, and fast response [23].

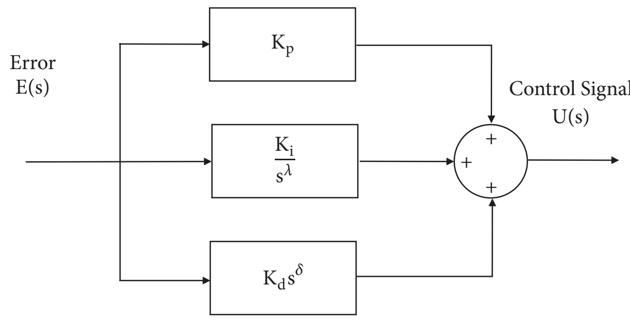

Figure 5: $PI^\lambda D^\delta$ controller (parallel general structure).

3.1. PI Antiwindup. A PI cautiously adjusted can offer suitable response although all processes are subjected to constraints. When constraints are activated, the performance of controllers can be significantly deteriorated. When the output of a system is saturated, making the error constant, an integral windup occurs. Because of a physical system, compared with an ideal one, it is physically impossible to reach the output in these conditions. This typically occurs when the output of the controller can no longer affect the controlled variable. To return the plant to stability, the control signal has to be of the contrary sign for a prolonged period, producing a longer settling time and a large overshoot [24–26].

A PI with antiwindup structure is showed in Figure 4. The PI controller contains an interior feedback track. To reduce the integrator input an internal saturation is employed. A value of 0.95 p.u. is usually employed for the saturation limit and the dead zone, both values selected manually. As was stated before, the hydropower model is in per-unit (p.u.) form, normalized to 300MW and 50Hz.

3.2. Fractional PID. The fractional order $PI^\lambda D^\delta$ (FOCPID controller) was first proposed by Podlubny [8, 9]. Figure 5 shows the internal structure of the fractional order controller [26]. In this controller, the λ-order integrator and the δ-order differentiator operators are real. The transfer function of such controller is represented by

$$C(s) = \frac{U(s)}{E(s)} = K_p + K_i s^{-\lambda} + K_d s^{\delta} \tag{6}$$

where (λ,$\delta > 0$)

K_p is the proportional constant

K_i is the integration constant

K_d is the differentiation constant

In discrete time the controller has the form:

$$C(z) = \frac{U(z)}{E(z)} = K_p + \frac{K_i}{\left(\omega\left(z^{-1}\right)\right)^{\lambda}} + K_d\left(\omega\left(z^{-1}\right)\right)^{\delta} \tag{7}$$

In both (6) and (7) taking λ =1 and δ =1, a classical PID controller is obtained. If λ =0 and K_i =0, a PD^δ controller is found [7, 27].

4. Gain-Scheduled Antiwindup PID with Integral and Derivative of Fractional Order

Gain scheduling is a common method to control nonlinear systems since it is simple and employs linear design methods [29, 30]. Conventionally, gain-scheduled controllers are designed by carrying out a first linearization of the system to be regulated at certain scheduling operational points. Next, for each of these operational points, linear controllers are designed; each one is valid "only" near to that operational point. Then the regulator parameters are calculated at every operational point selected [31].

Figure 6 shows the general structure of the antiwindup fractional order PID controller with gain scheduling. As can be seen, the parameters K_p, K_i, and K_d can be adjusted depending on an external algorithm. Various algorithms have been published to tune up FOPID [32–35]. For this work a compromise between fast response and short overshoot was pursued, according to an Integral of Time Absolut Error (ITAE) index which was used to adjust the control parameters. The hydraulic head (h) was the station parameter used to retune the controller; therefore a different set of parameters was selected depending on the value of h. To reduce the ITAE index was the principal condition taking into account selecting those parameters. The method is based on the one described by Awouda and Mamat [36].

In some applications, it has been shown that calculating the control signal with the derivative of the output rather than the derivative of the error could help to improve the performance of the system. This structure, called Pseudo-Derivative Feedback (PDF) controller, provides all the control aspects of a PID, excluding the system zeros that are naturally introduced by this controller [37]. Figure 7 shows a diagram with the general structure of a fractional order controller with gain scheduling.

5. Evaluation of the Antiwindup PID with Fractional Order

The function of a hydropower system in frequency control mode is to deliver opportune and correct supply of its contribution objective to the total power to the net. The concrete form of the demanded power is associated with net frequency deviation; nevertheless it can be indicated as

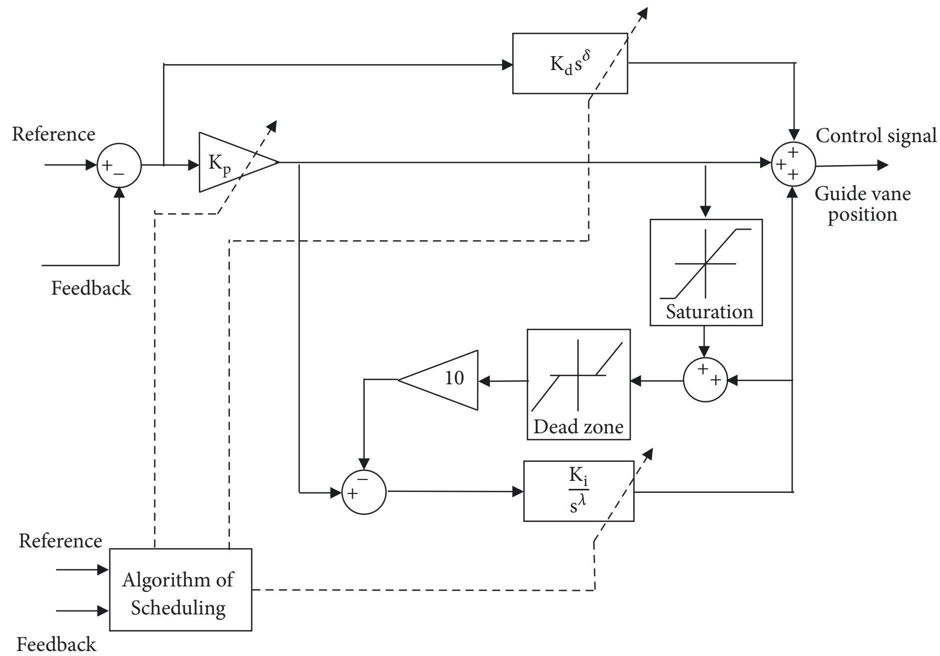

Figure 6: General structure of the antiwindup $PI^{\lambda}D^{\delta}$ gain scheduling controller.

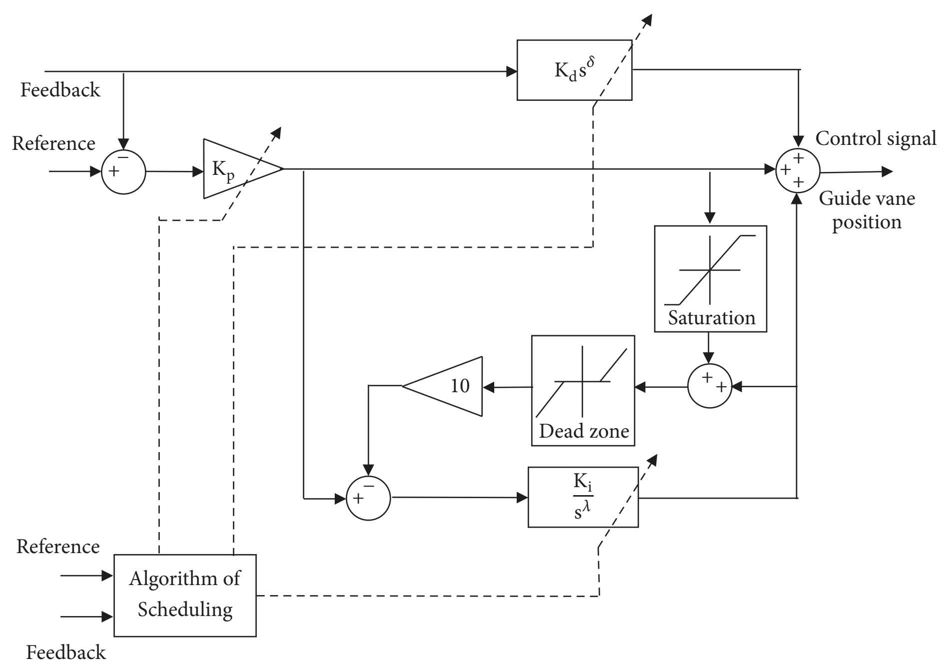

Figure 7: General structure of the antiwindup FO-PDF gain scheduling controller.

a relation of these input signals: step, ramp, and random [28, 38].

In this work some specifications are used to evaluate the hydroelectric station performance, which were proposed by Jones et al. [28]; those specifications represent an equilibrium between an important enhancement in speed and accuracy of response but are not so stressful that they result in impractical control activity and tunnel pressures.

The step response specification for one unit in operation is showed in Figure 8 [28]. Test P_1, *primary response* is usually the most significant criterion, which measures the time to accomplish a minimum 90% of the required step power change. Other important parameters are the overshoot (P_2) and the initial negative excursion (undershoot, P_6).

The Gain Scheduling Pseudo-Derivative Feedback Fractional Order with Antiwindup method (GS-PDF-AWU-FO)

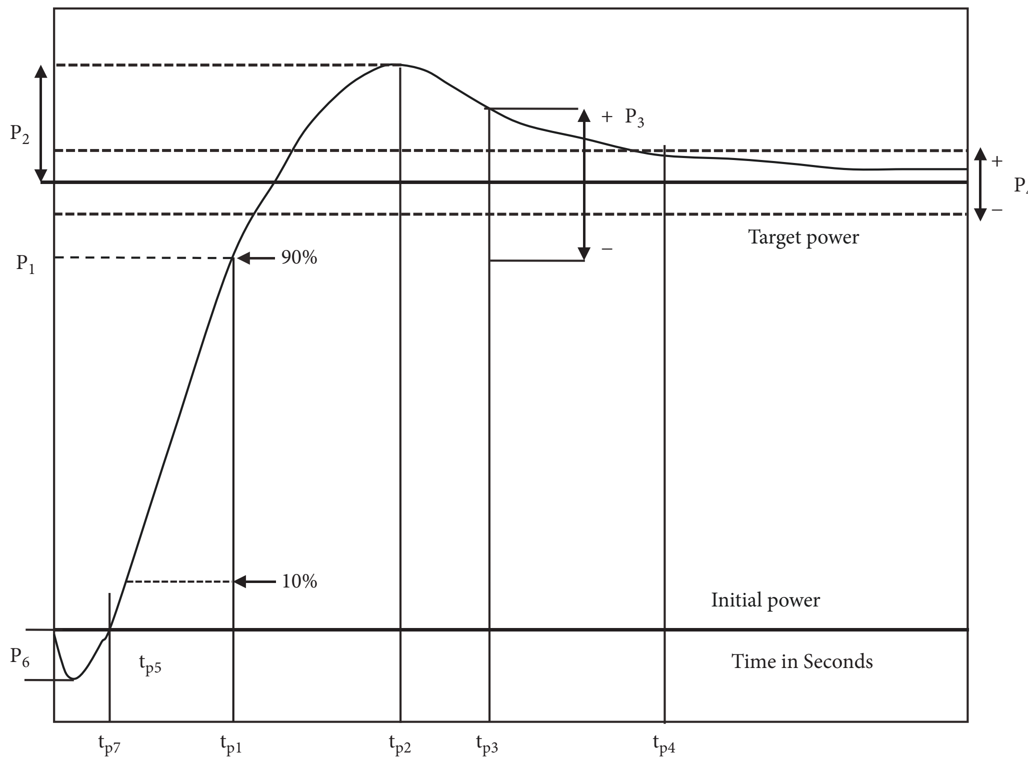

Figure 8: Specifications for a response to a step change in demanded power [1, 28].

was compared with an antiwindup PID controller (PID-AWU) with fix parameters (compromise to six operational units). Several simulations were run to assist the response of the two controllers. To evaluate the controllers an integral of time-weighted absolute error (ITAE) index was used. Both controllers were tuned for six operational units. However, the GS-PDF-AWU-FO has a different set of parameters depending on the value of the hydraulic head.

Adjusting a PID controller involves selecting the correct parameters that admit the controller to accomplish a required output specification. Mansoor [2] has presented a study with different sets of control parameters for Dinorwig's turbines in addition to the classical controller. The PI control with this set of parameters has a function that is a balance between one and six operational units. Hence, to optimize the functioning of the power system diverse groups of control constants were selected for different operational conditions, the extreme cases.

The PID-AWU parameter values were chosen as K = 0.16, K_i = 0.667, and K_d = 0 (working really as a PI controller), with a Rate Limit of 0.2 p.u. (Figure 3), in search of the best response when all units are in operation. The GS-PDF-AWU-FO was tuned for h=1 with λ= 0.95, δ= 0.6, K_p = 0.14, T_i = 0.85, and T_d = 0.025. For h=0.9 only two parameters were retuned: K_p = 0.16 and Ti=0.75 (Figure 7).

Figure 9 shows the reference values of the simulation; those values were selected because they represent "normal" changes when the frequency control mode is active. These references are also consistent with the ones reported by Munoz-Hernandez et al. [1], Mansoor [2], and Munoz-Hernandez [3]. The simulation begins with steps of 0.8 p.u. tested for the six units at time t = 0 for unit 1 and 0.5 for units 2-6. Formerly a 0.05 p.u. step is tested for unit 1 at t=100 s. Unit 2 was lifted to 0.8 p.u. and after that a step at 0.05 p.u. was tested only for unit 2 at t=500 s. At 600 s all units were fixed to 0.8 p.u. After that a 0.05 p.u. step was tested for all units at t=700 s. At t = 800 the value of the h is changed from 1 to 0.9 p.u. With this new value for h a 0.05 p.u. step was introduced to unit 1 at t = 900 s. Then unit 1 is getting back to 0.8 p.u. and then a step of 0.05 is applied at t= 1100 s to all units. Finally, at t=1200 s the unit 1 is connected in frequency control model using a model of the British Grid [1, 39].

Following the changes at the references specified before (Figure 9), the response produced by the Gain Scheduling Pseudo-Derivative Feedback Fractional Order with Anti-windup method (GS-PDF-AWU-FO) is compared with an antiwindup PID controller (PID-AWU). The results for one unit and six operational units, with h=1, are shown in Figures 10 and 11, respectively. In both cases the output under the GS-PDF-AWU-FO is faster than the one obtained under PID-AWU, although for six operational units the GS-PDF-AWU-FO produces an overshoot of less than 0.5%. As can be seen from Figure 10, one operational unit and h=1, the primary response of the system under the PID is higher (15.79 seconds) than the one obtained under the GS-PDF-FO (13.57 seconds). The result is similar to the system with six operational units and h=1 (Figure 11); in this case the primary response under the PID is 12.37 seconds and under the GS-PDF-AWU-FO is 10 seconds.

The cross-coupling responses for GS-PDF-AWU-FO and the modified PID-AWU are shown in Figure 12, where it is seen that although the GS-PDF-AWU-FO produces

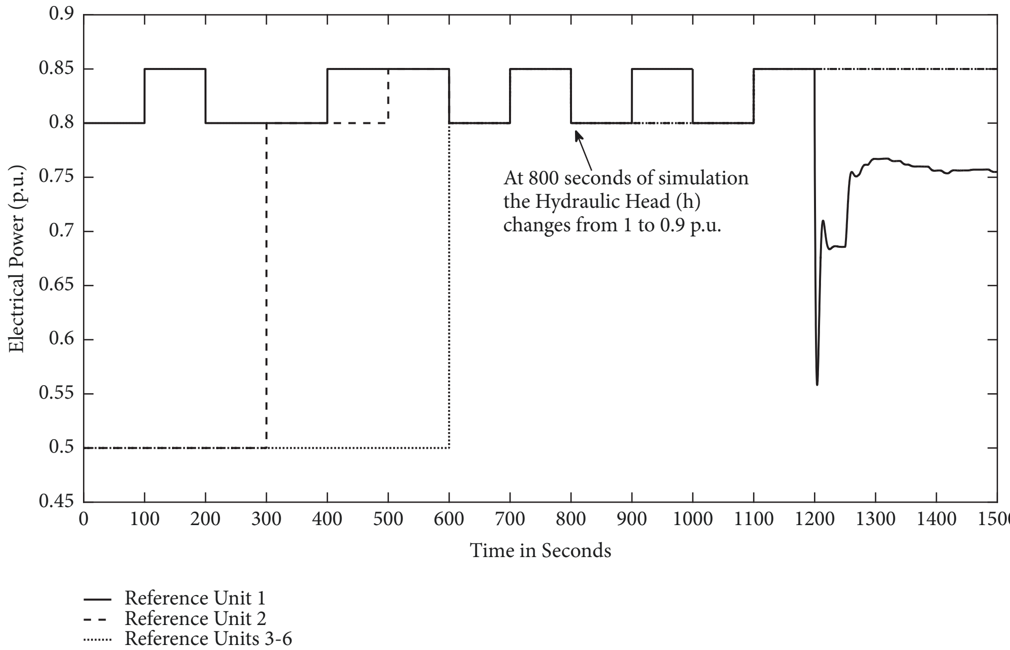

Figure 9: References used to simulate the hydropower plant.

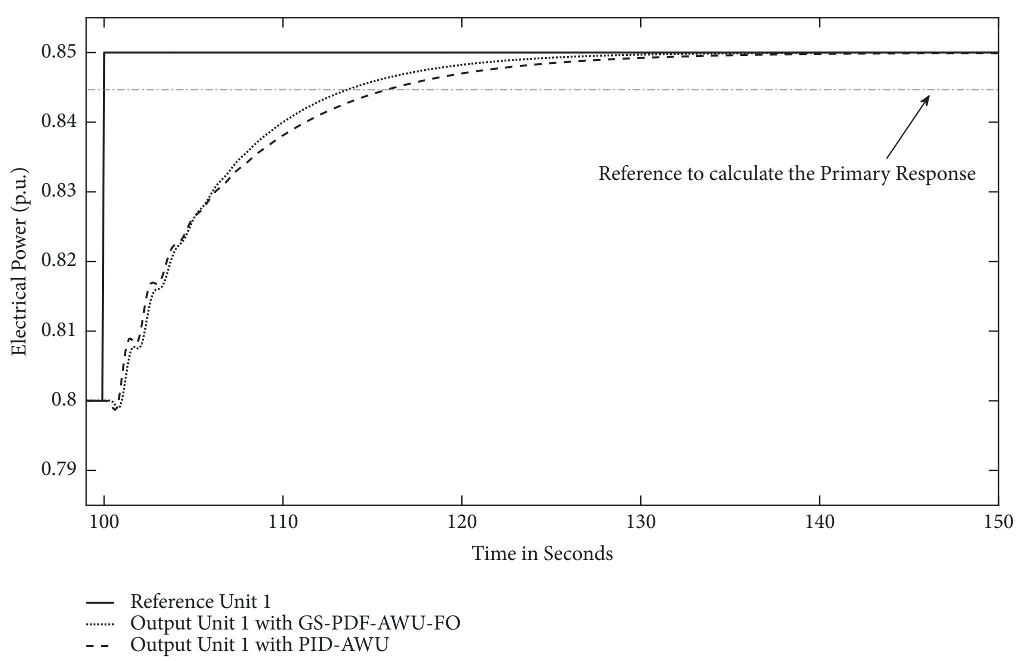

Figure 10: Step responses of PID and GS-PDF-FO, both with antiwindup, one operational unit, and h=1.

a bigger overshoot, it improves the nonminimum phase undershoot.

Following the sequence of the references indicated before (Figure 9), the outputs obtained by the GS-PDF-AWU-FO are compared with the ones from a PID -AWU. The results for one unit and six operational units, with h=0.9, are shown in Figures 13 and 14, respectively. As with h=1, in both cases the output under the GS-PDF-AWU-FO is faster than the one obtained under PID-AWU. Also for six operational units the GS-PDF-AWU-FO produces an overshoot, again less than 0.4%. As can be seen from Figure 13, one operational unit and h=1, the primary response of the system under the PID is higher (19.03 seconds) than the one obtained under the GS-PDF-FO (16.46 seconds). The result is similar to the system with six operational units and h=1 (Figure 13); in this case the primary response under the PID is 14.74 seconds and under the GS-PDF-AWU-FO is 12.37 seconds.

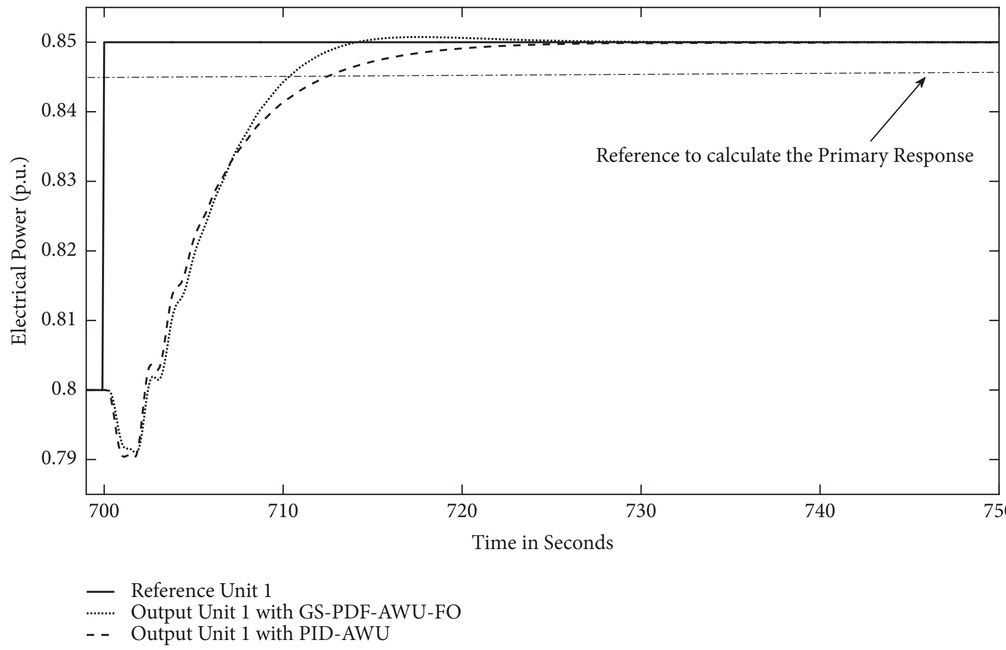

Figure 11: Step responses of PID and GS-PDF-FO, both with antiwindup, six operational units, and h=1.

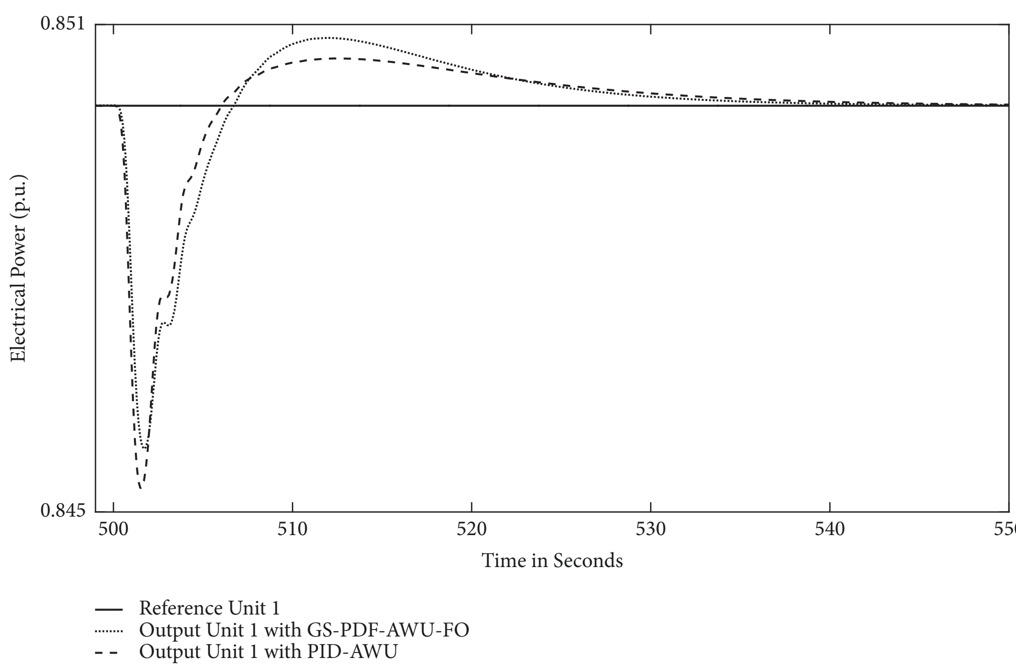

Figure 12: Cross-coupling reaction of unit 1 when unit 2 is under a step of 0.05 with 0.85 of operational point while h=1.

For both groups of simulation, one and six operational units, with different values of the hydraulic head (h=1 and h=0.9), ITAE indexes were calculated. For all cases, this index is lower when the system is controlled by the GS-PDF-AWU-FO rather than PID-AWU (Figure 15).

It is common that hydropower governors include a derivative term in the feedforward track from the reference for frequency control [22]. This produces a rapid change in power in response to rapidly changing frequency. A critical component of power systems is the model for the power network, because it is fundamental to assist or even to predict how the frequency will respond to power modifications. Evidently, the dynamic characteristics of a power network depend on its precise configuration at any instant. Nevertheless, studies have shown that a severe injection of power onto a network will often cause the frequency to increase, reaching a peak after some tens of seconds, after which it will fall back slightly.

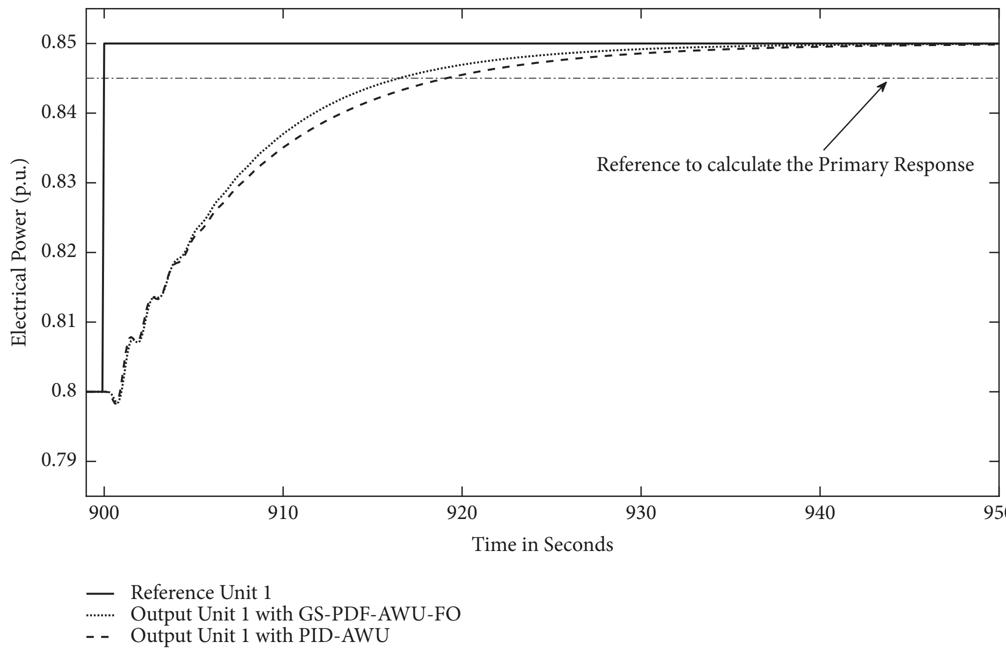

Figure 13: PID and GS-PDF-FO step responses, both with antiwindup, one operational unit, and h=0.9.

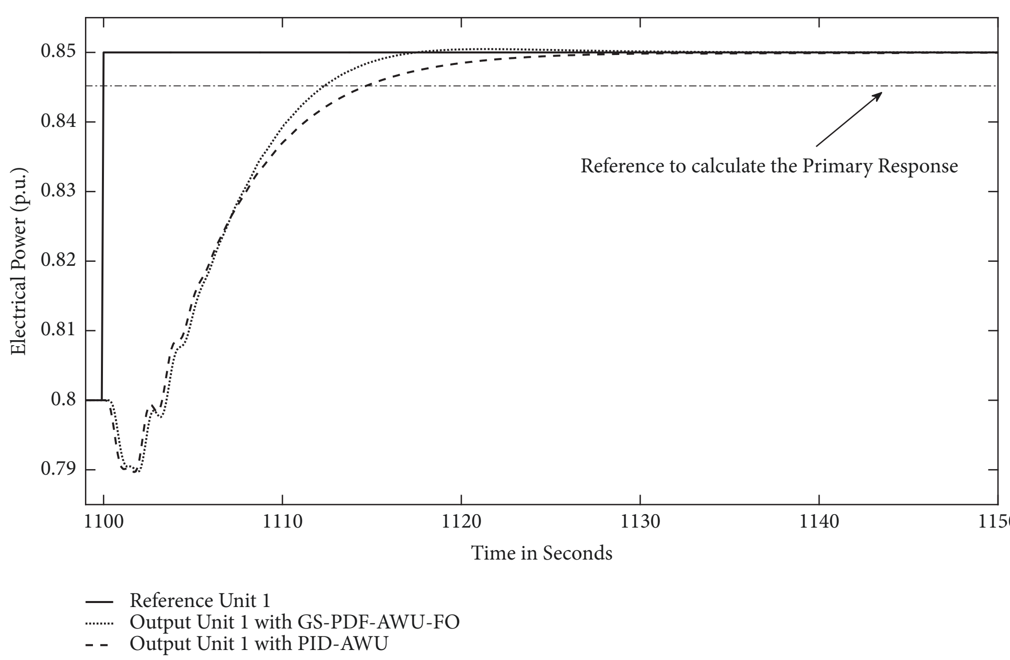

Figure 14: PID and GS-PDF-FO step responses, both with antiwindup, six operational units, and h=0.9.

In order to assist the system under frequency control it is essential to simulate the connection to the grid. For this purpose, a second-order transfer function is used in this work (8). This equation expresses fluctuations in grid frequency to load imbalance. The first time constant related to the addition of all the inertias of the rotating machines and the second time constant related to all governing mechanisms connected to the electrical net.

$$\Delta\omega_G = K\omega_n^2 T_R \left(\frac{s + 1/T_R}{s^2 + 2\zeta\omega_n s + \omega_n^2}\right)\left(\Delta P_e - \Delta P_L\right) \quad (8)$$

In this equation [1, 40]:

K is the grid "stiffness"

T_R is the time constant of the regulatory mechanisms

ω_n is the grid natural frequency

ζ is the grid damping factor

The grid works as a collector whose accumulated energy is proportional to the synchronous frequency of all the rotational equipment connected [22]. The total "amount"

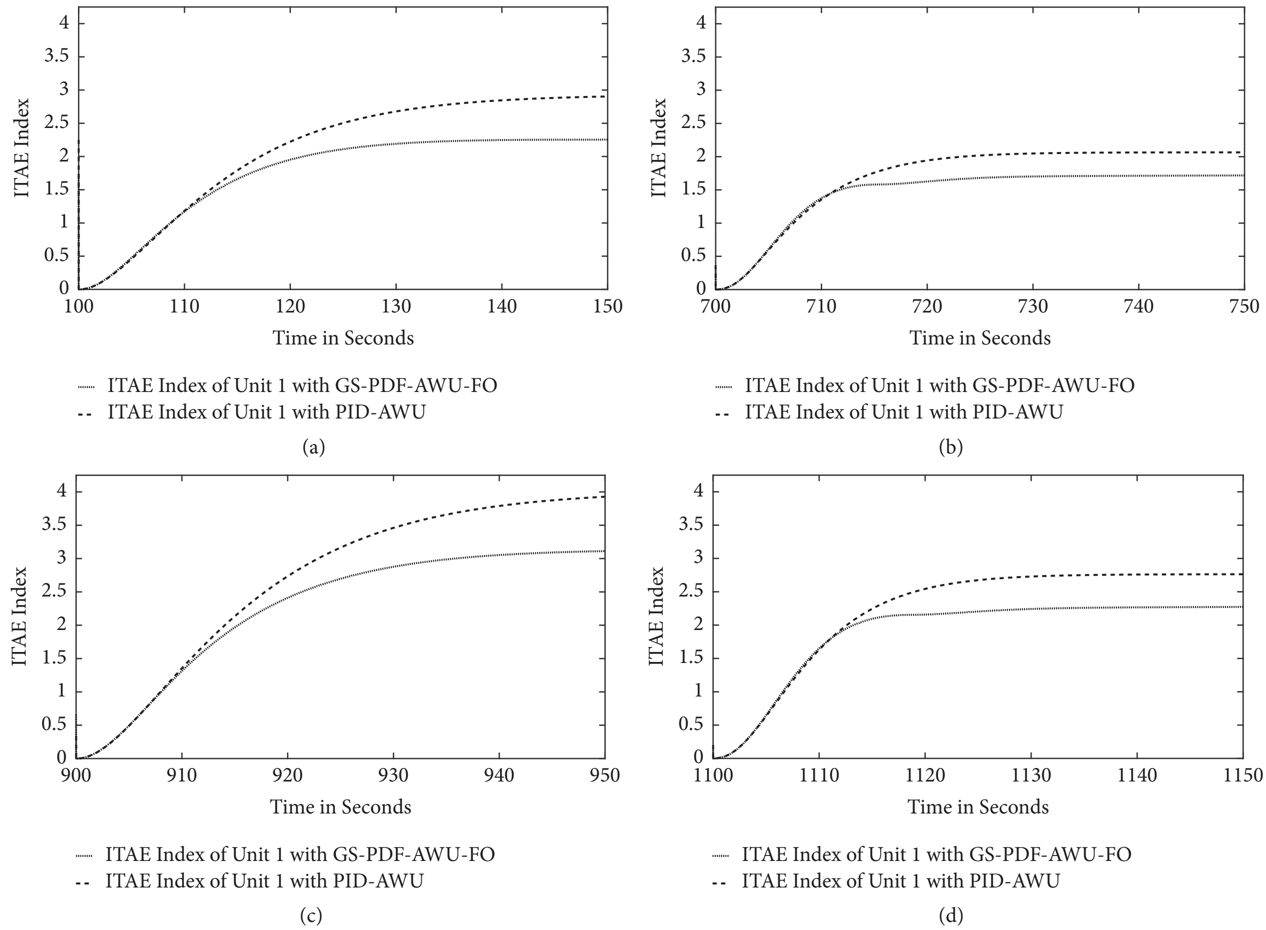

FIGURE 15: ITAE indexes. (a) One operational unit, h=1. (b) Six operational units, h=1. (c) One operational unit, h=0.9. (d) Six operational units, h=0.9.

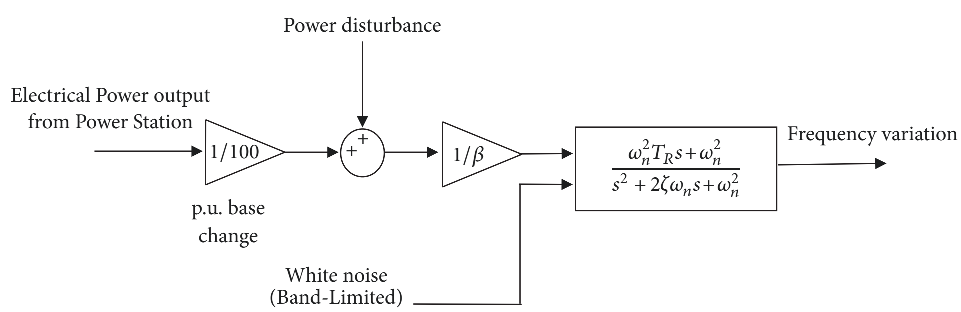

FIGURE 16: Grid model.

of the grid load (which ranges from 30 to 55GW in Great Britain) produces variations in the parameters K, T_R, ω_n, and ζ. Whereas ΔP_e is known, ΔP_L is the sum of a vast numbers of time-varying contributions, so ΔP_L is included in the model as an additive, random disturbance [1, 40].

In Figure 16 the net model, employed in this work, is showed [1]. This grid model simulates frequency variation. To introduce weak rapid variations a 0.003 p.u. white noise with limited band is included, as a disturbance element, in the net model. On the other hand, to introduce strong variations a high disturbance is included, using a step (in this case, 0.014 p.u. at t = 1250 s of simulation). The values of the parameters for the second-order model were $K = 0.089$, $T_R = 8$, $\omega_n = 0.37$, and $\zeta = 0.54$ [40]. The values of the second-order model and the disturbance elements are comparable with the ones reported by Munoz-Hernandez et al. [1, 30], Mansoor [2], and Jones [39].

A comparison of the responses produced by the hydropower station under PID-AWU and GS-PDF-AWU-FO controllers, with unit 1 in frequency variation and units 2-6 with a fix operational point at 0.85 p.u., was performed

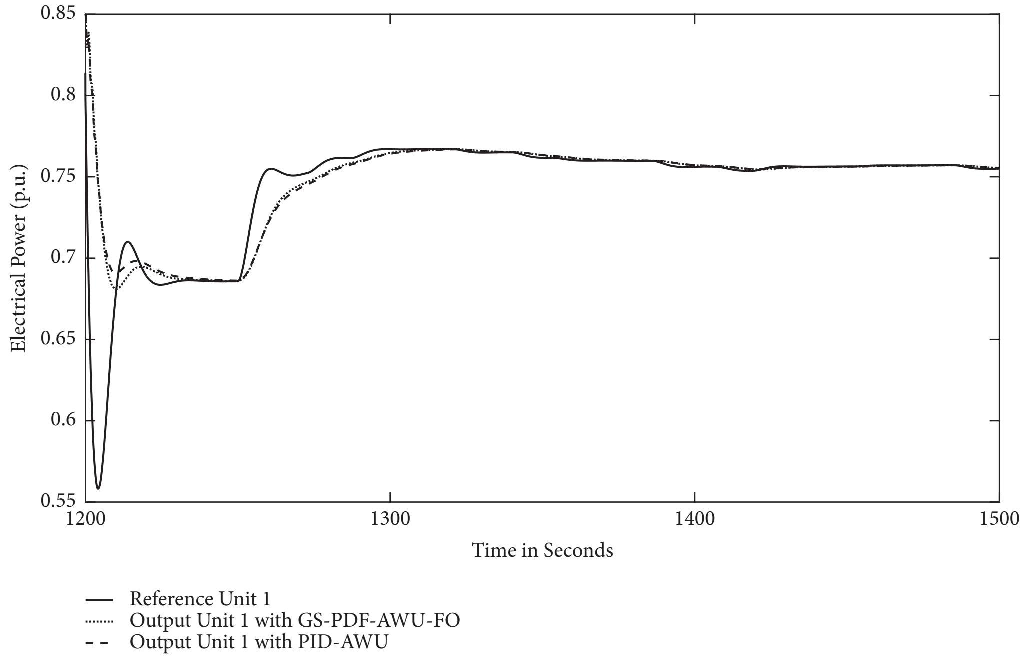

Figure 17: Evaluation of the responses produced by PID and GS-PDF-FO (both with antiwindup) with unit 1 in frequency variation (connected to the grid) and units 2-6 with 0.85 p.u. of fix operational point, h=0.9 p.u.

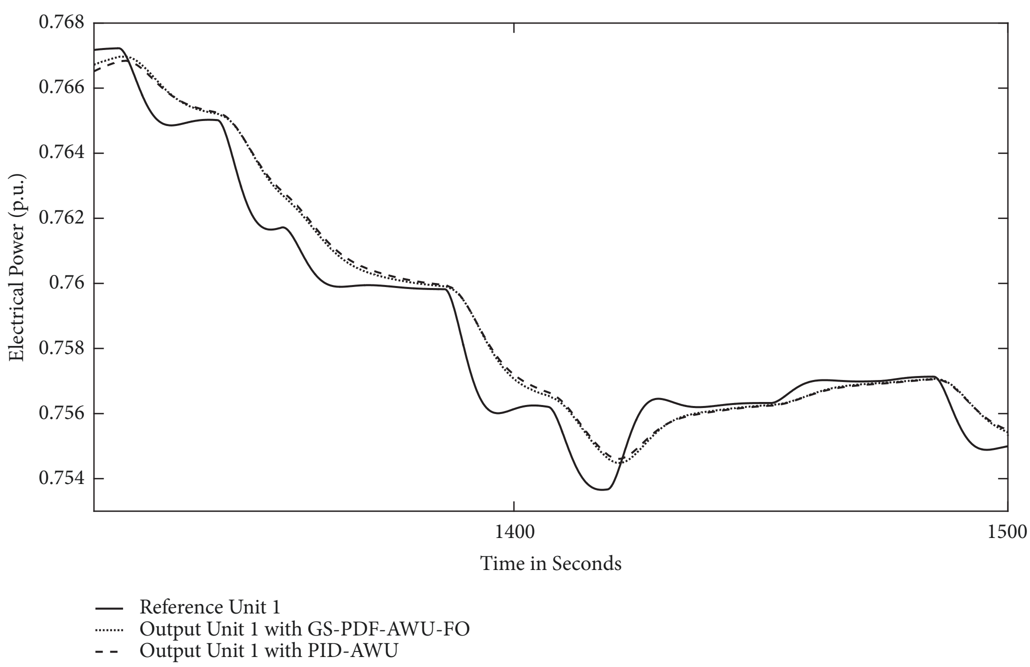

Figure 18: Evaluation of the responses produced by PID and GS-PDF-FO (both with antiwindup) with unit 1 in frequency variation (connected to the grid) and units 2-6 with 0.85 p.u. of fix operational point, h=0.9 p.u. (zoom).

using a hydraulic head equal to 0.9 p.u. (in Figure 9 with references shown). The reference value to units 2-6 was chosen close to the maximum power that is 0.95 [3]. As can be seen from Figures 17 and 18 both controllers produce responses that follow the input closely. However, the ITAE indexes, showed at Figure 19, indicate a better performance of the GS-PDF-AWU-FO.

The last analysis was developed to evaluate the performance of the GS-AWU-PDF-FO controller (with antiwindup) using the ITAE index as the way to select the tuning parameters. However, to compare the performance of GS-AWU-PDF-FO controller looking to fulfill the restrictions proposed by Jones et al. [28] this controller was retuned. Figures 20 and 21 show the specifications for single

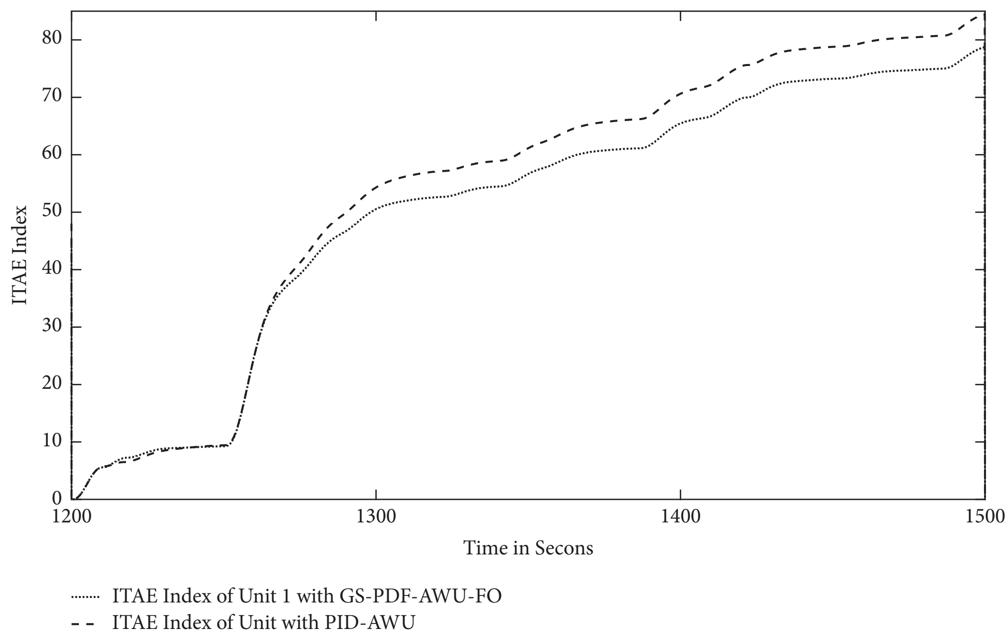

Figure 19: ITAE indexes of the comparison of the responses produced by PID and GS-PDF-FO (both with antiwindup) with unit 1 in frequency variation (connected to the grid) and units 2-6 with 0.85 p.u. of fix operational point, h=0.9 p.u.

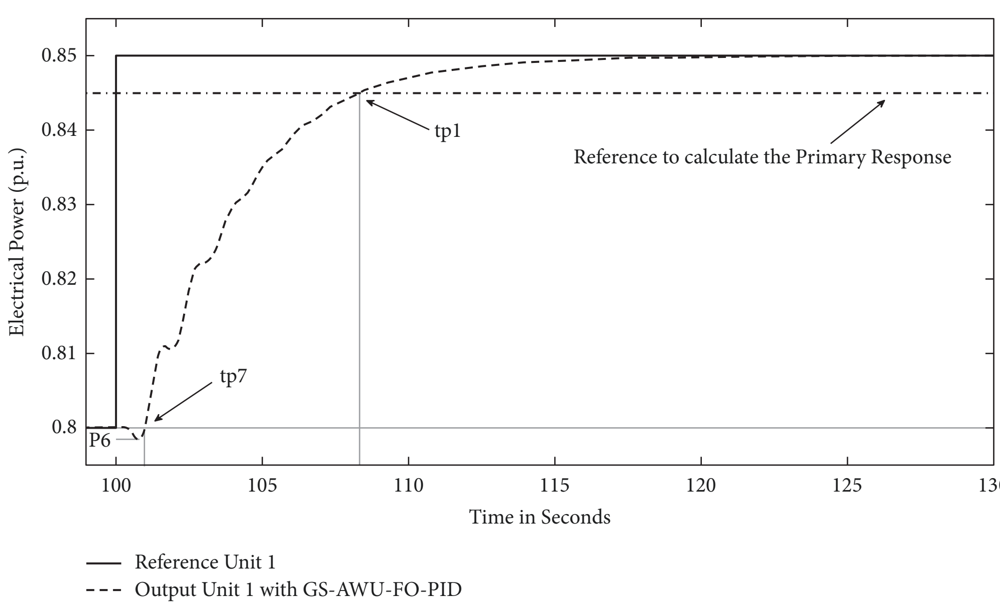

Figure 20: Step response of GS-PDF-FO with antiwindup, one operational unit, and h=1.

operational unit and also compares the parameters reported by [3] and the ones obtained using GS-AWU-PDF-FO as a controller. As can be seen in Table 1, all parameters are lower (or equal) than the ones from the standard when GS-AWU-PDF-FO is controlling the hydropower system.

6. Conclusions

The results from this study have shown that antiwindup GS-PDF-AWU with fractional order could be employed for a hydropower system to enhance its performance. When the nonlinear characteristic of the system is considered, as with GS-PDF-AWU, it is possible to improve the direct transient responses. The inclusion of adaptive characteristics, hydraulic head value, produces a rapid, well-damped response when the hydraulic head is at the maximum limit, without affecting the stability when this parameter has a lower value. Also the response of the hydropower plant under the GS-PDF-AWU-FO has a better performance when grid changes were evaluated. Finally, these results have showed that the anti-windup PDF controller with fractional order could produce

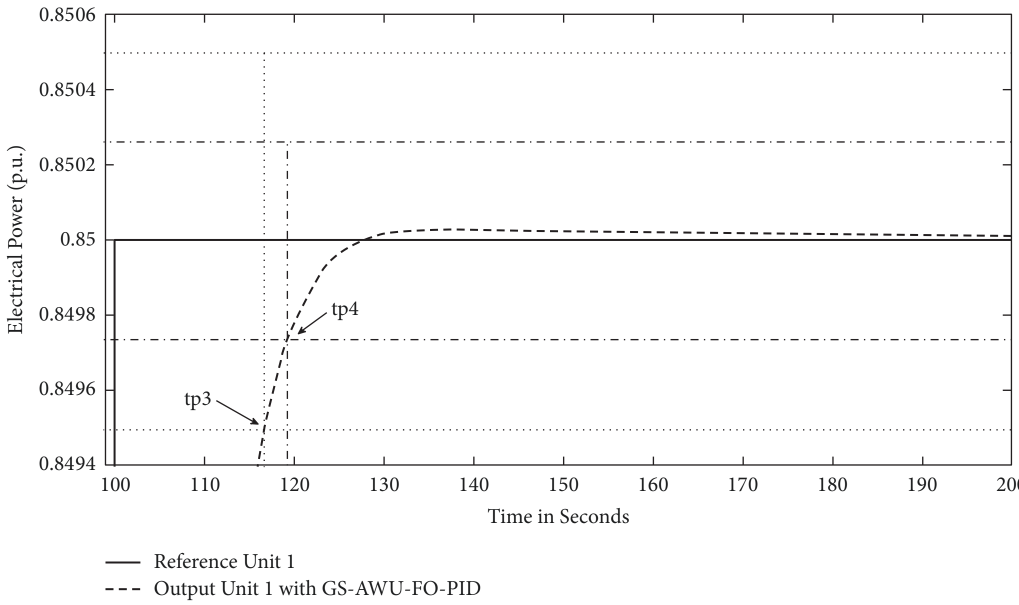

Figure 21: Step response of GS-PDF-FO with antiwindup, one operational unit, and h=1 (zoom).

Table 1: Specification of step response for advanced control design at Dinorwig [1, 3].

Test	Specification for single unit operation.	Single unit response with the governor reported in [3].	Single unit response with GS-AWU-PDF-FO.
P1	$P_1 \geq 90\%$ at $t_{p1} = 10s$	81% at 10s, 90% at 13.7 s	94.6 % at 10 s, 90% at 8.3 s
P2	$P_2 \leq 5\%$ and $t_{p2} \leq 20s$	No overshoot	No overshoot
P3	$t_{p3} = 25s$ for $P_3 \leq 1\%$	25.9 s	16.9 s
P4	$t_{p4} = 60s$ for $P_4 \leq 0.5\%$	29.2 s	19.3 s
P5	$t_{p5} = 8s$	12.1 s	7.64 s
P6	$P_6 = 2\%$	1.75%	2%
P7	$t_{p7} = 1.5s$	0.88 s	0.975 s

concrete advantages for hydroelectric systems operating in fast response.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

Highlights. (i) Nonlinear modeling of a hydropower station. (ii) Evaluation of the application of Fractional PID Controller to a hydroelectric station to increase the performance.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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