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Scenario-Based Evaluation of Speed-Governor Control Strategies for Hydropower Turbine-Generator Systems under Load Disturbances and Hydromechanical Uncertainty

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ABSTRACT: *This paper presents a scenario-based comparative assessment of speed-governor control strategies for hydropower turbine-generator systems. A compact hydropower benchmark is adopted to capture the main dynamic features of governor operation, including the gate servo, water-starting effect, inverse mechanical-power response, equivalent swing dynamics, guide-vane saturation, and gate-rate limitation. Four representative controllers are evaluated under the same plant model and actuator constraints: PI, filtered PID, Fuzzy-PID, and linear quadratic integral (LQI) control. Their roles are examined through four operating scenarios, namely a single load step, repeated load changes, fluctuating load with renewable-like oscillations, and severe hydromechanical uncertainty. The results indicate that the PI controller offers structural simplicity and reliable steady-state restoration, but its transient recovery is relatively slow. The filtered PID controller improves damping with moderate implementation effort, whereas the Fuzzy-PID controller enhances the response during large error transients at the expense of increased gate activity. Among the tested methods, LQI achieves the most consistent overall speed-regulation performance. Across the considered scenarios, it provides the largest reduction in integral absolute error and root-mean-square speed deviation while maintaining acceptable guide-vane motion. The study is supported by a reproducible MATLAB simulation program and feasible numerical results, providing a transparent benchmark for selecting suitable hydropower speed-governor strategies.*

Keywords: *Hydropower plant; hydraulic turbine governor; speed control; PI/PID; Fuzzy-PID; LQI; load-frequency control; MATLAB simulation.*

NOMENCLATURE

Table 1. Main symbols and indices used in the paper.

Symbol/Index	Description	Unit
pu	Per-unit quantity	pu
Delta omega	Speed/frequency deviation	pu
Delta G	Guide-vane/gate opening deviation	pu
Delta P_m	Mechanical power deviation	pu
Delta P_L	Load disturbance	pu
T_g	Servo time constant	s
T_w	Water starting time	s
M	Equivalent inertia constant	pu.s
D	Load damping coefficient	pu
u	Governor output / gate command	pu
z	Internal waterway state	pu
xi	Integral state used by LQI	pu.s
IAE	Integral absolute error	pu.s
ITAE	Integral time absolute error	-
RMS	Root-mean-square speed deviation	pu

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I. INTRODUCTION

Hydropower plants are among the most flexible renewable generation assets. They are able to provide energy production, spinning reserve, and primary frequency regulation. The ability to stabilize speed after a power imbalance is strongly affected by the governor loop, the waterway dynamics, and the equivalent inertia of the connected power system. Standard hydropower modeling studies show that the water starting time and the turbine-governor interaction must be retained to obtain meaningful transient results [1]-[5].

The control task is difficult because the hydraulic waterway does not respond like a simple thermal actuator. After a gate movement, the water column accelerates gradually, and the initial mechanical-power response may move in the opposite direction. Classical PID tuning methods can improve this behavior but fixed gains may lose quality when the operating condition changes [6]. Advanced approaches, including Fuzzy-PID, surge-tank-aware control, stability-constrained design, synergetic control, sliding-mode control, disturbance-observer compensation, and model-based optimal control, have therefore been proposed [7]-[18].

This paper focuses on a fair and reproducible comparison. Four controllers are selected to represent increasing control capability: PI as the industrial baseline, PID as a damping-enhanced classical solution, Fuzzy-PID as an adaptive gain-scheduled controller, and LQI as a model-based state-feedback controller. The comparison is performed over four different scenarios rather than a single load step, allowing the practical role of each controller to be highlighted.

II. LITERATURE REVIEW

Hydropower plant modeling has been studied for decades. Kishor et al. reviewed hydropower plant models and control challenges, while the IEEE committee report and the de Mello model provided standard formulations for turbine-governor dynamics [1]-[3]. Babunski and Tuneski further discussed modeling and design issues for hydraulic turbine-governor systems, and Li et al. developed open-source hydro turbine and governor models useful for reproducible studies [4], [5].

Classical PI/PID control remains important because of its simplicity and transparency. IMC-based PID tuning and engineering procedures have been applied to hydro governor systems with water hammer or waterway effects [6]. However, fixed gains can lose transient quality under changing hydraulic conditions. Intelligent and nonlinear controllers have therefore been investigated, including fuzzy-PID control [7], dynamic response control with surge tanks [8], stability and saturation analysis [9], [10], synergetic governing control [11], terminal sliding-mode control [12], and disturbance-observer-based integral sliding-mode control [13].

Recent work has also emphasized grid-aware and model-based control. Variable-speed hydropower and optimal control have been investigated for fast frequency reserve services and experimentally validated variable-speed generation [14], [15]. Reviews of long-headrace hydropower transients, smart-grid load-frequency control, and fuzzy logic methods further show that controller comparison must consider both regulation quality and actuator activity [16]-[18].

III. RESEARCH GAPS AND CONTRIBUTIONS

Three research gaps motivate this paper. First, many studies compare a proposed controller with only one baseline, which is not sufficient for practical selection. Second, controller performance is often reported for a single disturbance, whereas hydropower governors face load steps, repeated operating changes, fluctuations, and parameter uncertainty. Third, several simulation papers do not provide enough implementation detail to reproduce the figures and performance indices.

The contributions of this paper are as follows. First, four controllers are compared under the same hydropower model, actuator limits, and disturbance profiles. Second, four scenarios are introduced to evaluate different roles of the controllers: basic recovery, repeated changes, fluctuating demand, and hydromechanical uncertainty. Third, the results are supported by quantitative indices and implemented by MATLAB/Simulink software that is completely able to reproduce the responses and figures.

IV. HYDROPOWER MODEL AND CONTROL STRATEGIES

The benchmark model represents a single hydropower turbine-generator unit connected to an equivalent load. The model is deliberately compact but retains the dominant waterway and rotor dynamics. The gate servo, hydraulic turbine/waterway block, and swing equation are defined in (1)-(3).

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

$$\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1 - T_w s}{1 + 0.5 T_w s} \tag{2}$$

$$M \frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_L - D\Delta\omega \tag{3}$$

In simulation, the turbine transfer function is implemented through the internal waterway state z, as shown in (4). This realization reproduces the initial inverse mechanical-power response after a gate movement.

$$\dot{z} = \frac{\Delta G - z}{a} \tag{4a}$$

$$a = 0.5 T_w \tag{4b}$$

$$\Delta P_m = 3z - 2\Delta G \tag{4c}$$

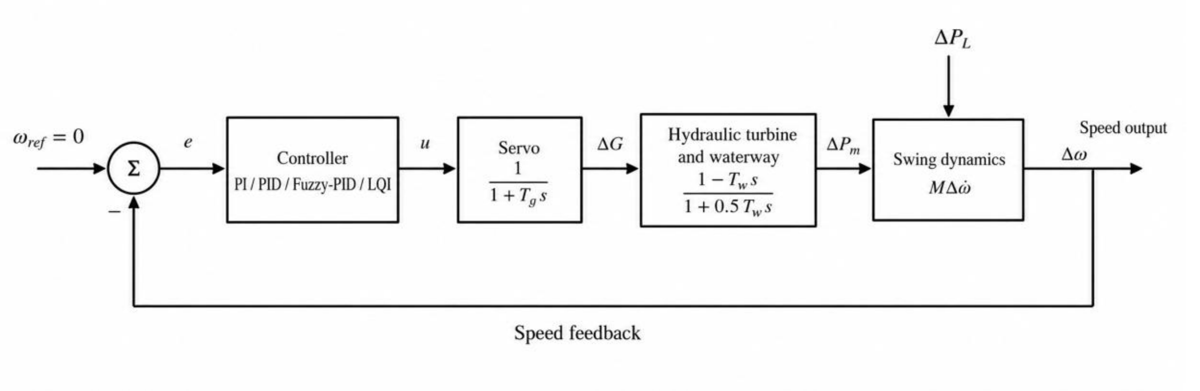

Fig. 1. Closed-loop hydropower speed-governor benchmark used in the comparative study

The PI controller provides zero steady-state error through integral action. The PID controller adds filtered derivative damping. The Fuzzy-PID controller changes its gains according to the normalized error and normalized filtered derivative. The LQI controller uses state feedback with an additional integral state. Their control laws are defined in (5)-(8).

$$u_{PI}(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau, \quad e(t) = -\Delta\omega(t) \tag{5}$$

$$u_{PID}(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d d_f(t) \tag{6}$$

$$K_p = K_{p0}\left(1 + 0.70|e|_N + 0.20\left|d_f\right|_N\right) \tag{7a}$$

$$K_i = K_{i0}\left(1 + 0.80(1 - |e|_N)\right) \tag{7b}$$

$$K_d = K_{d0}\left(1 + 0.70\left|d_f\right|_N + 0.30|e|_N\right) \tag{7c}$$

$$u_{LQI}(t) = -K[\Delta\omega \ \Delta G \ z \ \xi]^T \tag{8a}$$

$$\dot{\xi}(t) = -\Delta\omega(t) \tag{8b}$$

For the Fuzzy-PID controller, the normalized terms are clipped to [0, 1], and the derivative signal is filtered with a 0.04 s first-order filter. For the LQI controller, the nominal augmented model uses Q = diag(700, 1, 1, 1200) and R = 12. The same saturation and gate-rate limits are applied to all controllers.

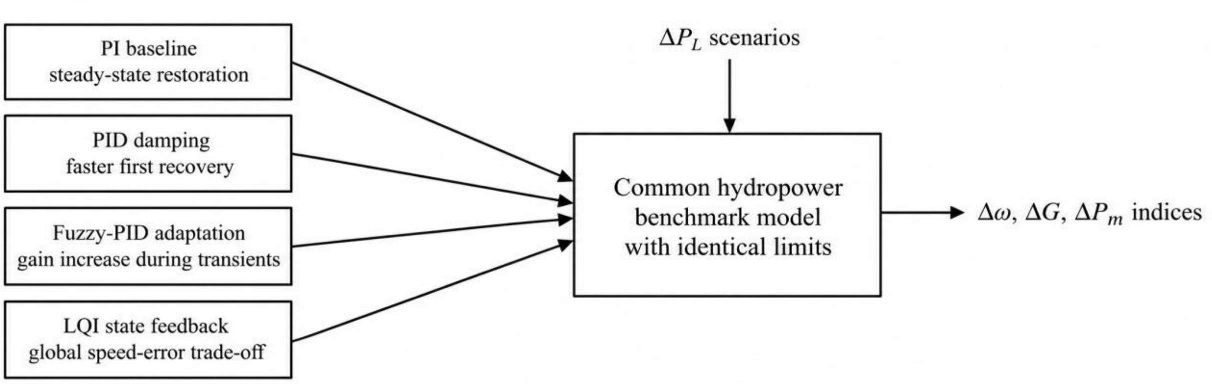

Fig. 2. Controller-role comparison framework used for scenario-based assessment

Table 2. Simulation parameters of the hydropower turbine-governor benchmark.

Parameter	Symbol	Value	Unit
Equivalent inertia constant	M	8.0	pu.s
Load damping coefficient	D	1.0	pu
Servo time constant	T_g	0.25	s
Water starting time	T_w	1.20	s
Gate command saturation	u_{lim}	+/-0.25	pu
Gate rate limit	$\lvert dG/dt \rvert_{max}$	0.15	pu/s
Integration step	Delta t	0.005	s
Simulation method	solver	fixed-step Euler implementation	-

Table 3. Controller structures and intended roles

Controller	Tuning parameters	Role in the comparison
PI	$K_p = 1.80$, $K_i = 0.35$	Industrial baseline; reliable zero steady-state error but slowest transient damping.
PID	$K_p = 2.40$, $K_i = 0.50$, $K_d = 0.25$	Derivative damping accelerates recovery after load steps; derivative signal is filtered.
Fuzzy-PID	$K_{p0} = 2.20$, $K_{i0} = 0.48$, $K_{d0} = 0.22$	Adaptive gain scheduling strengthens the reaction during large errors; may increase gate activity.
LQI	K = [30.9711 0.5249 6.1362 -10.0000]	Model-based state feedback with integral action; best global trade-off in this benchmark.

Table 4. Simulation scenarios used to evaluate the controller roles

Scenario	Type	Disturbance profile	Parameter condition	Main purpose
S1	Single load step	+0.08 pu at 5 s	Nominal M and T_w	Basic nadir and settling performance
S2	Repeated operating changes	+0.08 pu at 5 s; -0.04 pu at 45 s; +0.03 pu at 75 s	Nominal M and T_w	Recovery after direction changes
S3	Fluctuating load	+0.05 pu at 5 s; sinusoidal fluctuation after 20 s; +0.025 pu at 70 s	Nominal M and T_w	Tracking under renewable-like power fluctuations
S4	Severe hydromechanical uncertainty	+0.08 pu at 5 s; +0.025 pu at 35 s; -0.045 pu at 65 s; +0.025 pu at 85 s	M = 10.0 pu.s and T_w = 1.44 s	Robustness with larger inertia and slower waterway dynamics

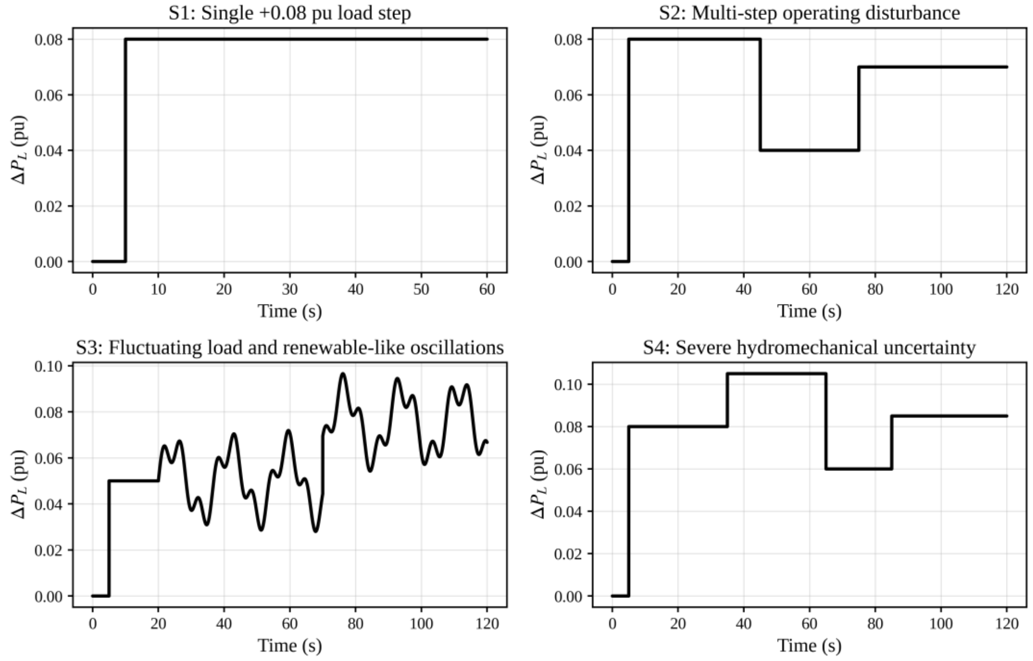

Fig. 3. Load disturbance profiles used in the four simulation scenarios

V. SIMULATION RESULTS AND DISCUSSION

The MATLAB simulations use a fixed integration step of 0.005 s. Each controller is evaluated using the same disturbance profile and actuator constraints. The main indices are peak absolute speed deviation, IAE, ITAE, RMS speed deviation, settling time, and gate travel. The following subsections discuss the controller role in each scenario.

A. Scenario S1: single load-step disturbance

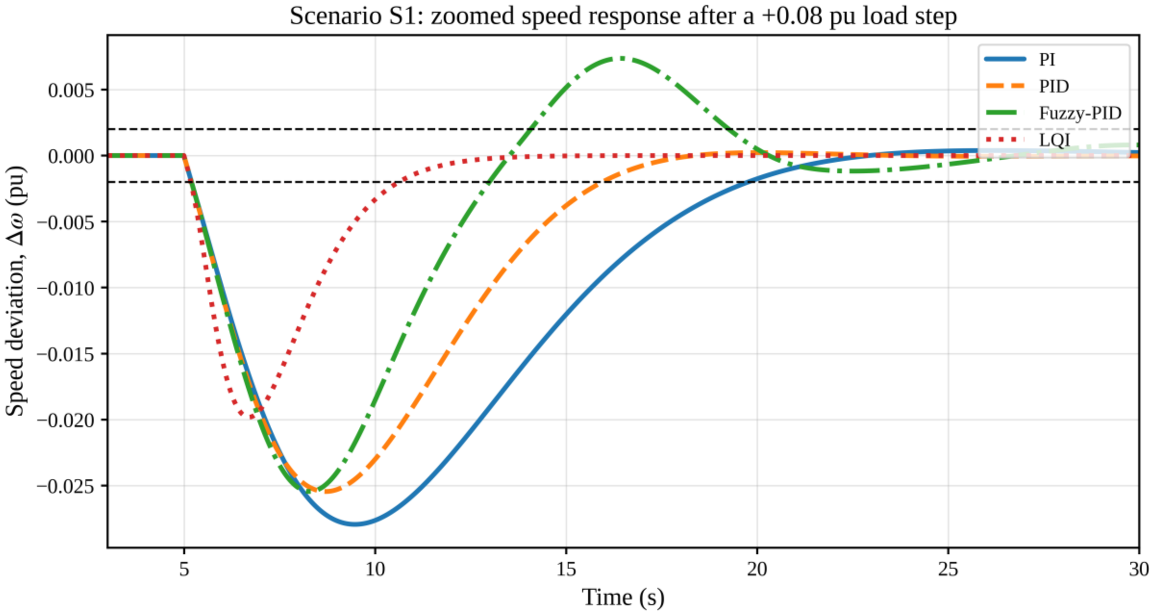

Fig. 4. Scenario S1: zoomed speed response after a +0.08 pu load step

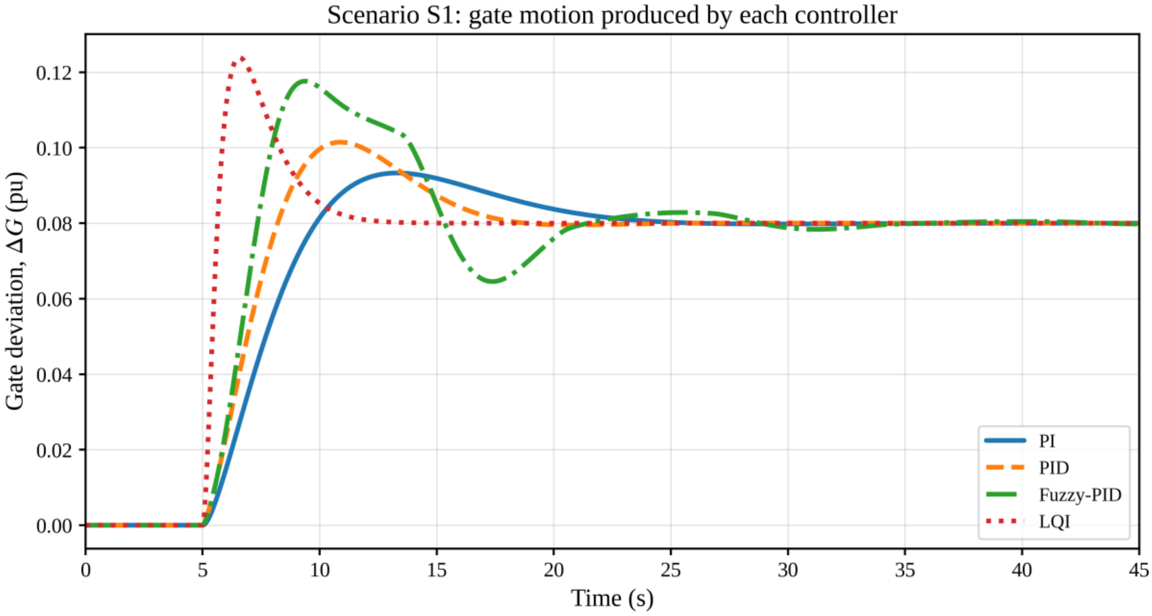

Fig. 5. Scenario S1: guide-vane/gate motion produced by each controller

Figures 4 and 5 show the basic stabilization behavior. PI restores the speed but gives the largest nadir and the slowest recovery. PID reduces the speed dip because the derivative term adds damping at the beginning of the transient. Fuzzy-PID has almost the same nadir as PID but produces larger gate oscillation because the gains increase during the transient. LQI gives the smallest nadir and the fastest recovery by coordinating the speed, gate, waterway state, and integral state.

Table 5. Scenario S1 quantitative results

Controller	Peak speed (pu)	IAE	ITAE	RMS	Settling time (s)	Gate travel
PI	0.02794	0.23413	2.65756	0.00885	14.770	0.10701
PID	0.02545	0.16143	1.58884	0.00707	10.950	0.12399
Fuzzy-PID	0.02544	0.15884	1.81641	0.00637	14.260	0.19665
LQI	0.01982	0.06129	0.46003	0.00374	5.625	0.16772

B. Scenario S2: repeated operating load changes

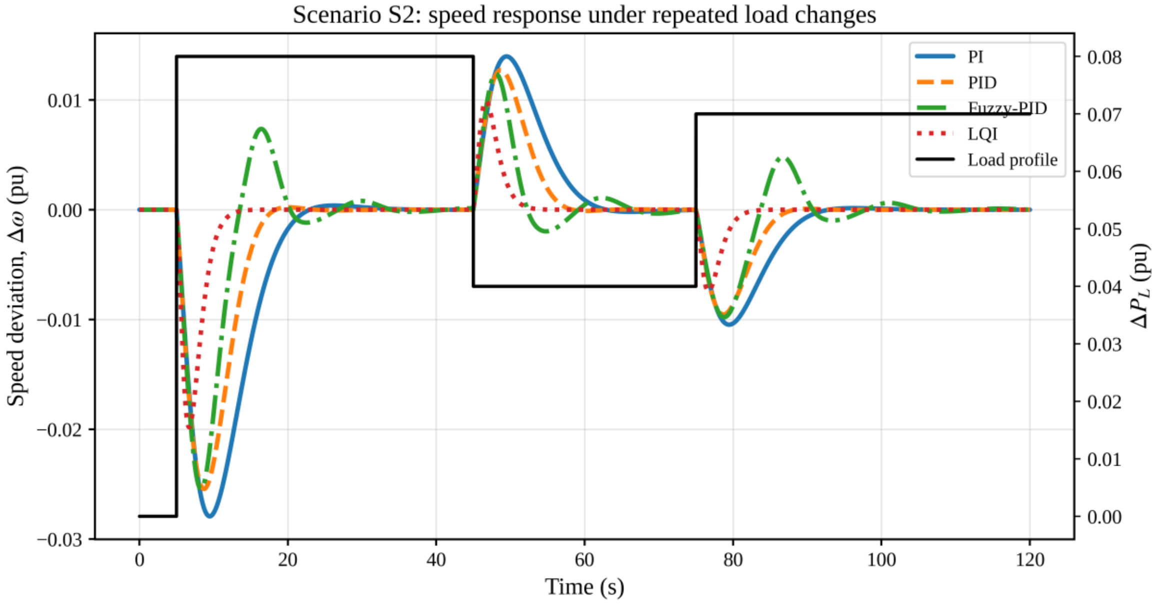

Fig. 6. Scenario S2: speed response under repeated load changes

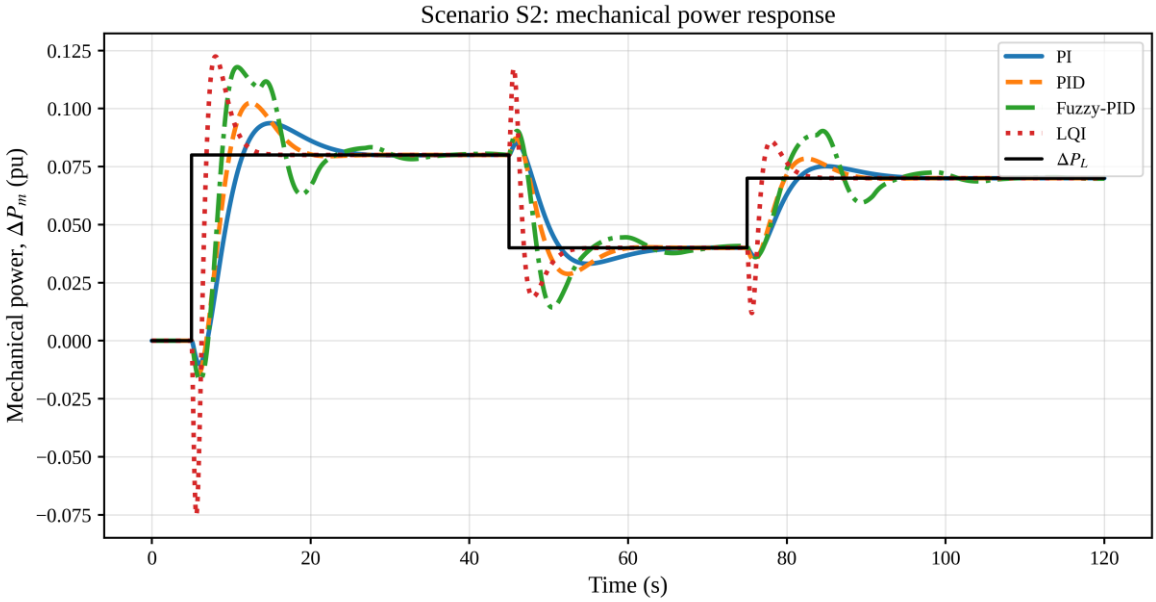

Fig. 7. Scenario S2: mechanical power response and load demand

Scenario S2 tests the ability to recover repeatedly after the operating point changes. Figure 6 shows that all controllers maintain stability and return the speed close to zero after each event. However, the amount of accumulated error differs strongly. PI has a large total error because each transient decays slowly. PID improves the response by reducing the duration of each speed excursion. Fuzzy-PID reacts sharply but may generate secondary oscillations. LQI remains the most balanced controller because the speed error is corrected quickly without excessive long-lasting gate movement.

Table 6. Scenario S2 quantitative results

Controller	Peak speed (pu)	IAE	ITAE	RMS	Final settling time (s)	Gate travel
PI	0.02794	0.43892	15.80636	0.00738	82.560	0.20056
PID	0.02545	0.30269	10.44525	0.00589	79.395	0.23248
Fuzzy-PID	0.02544	0.30510	11.84296	0.00532	84.250	0.39012
LQI	0.01982	0.11492	3.69722	0.00312	74.390	0.31432

C. Scenario S3: fluctuating load and renewable-like oscillations

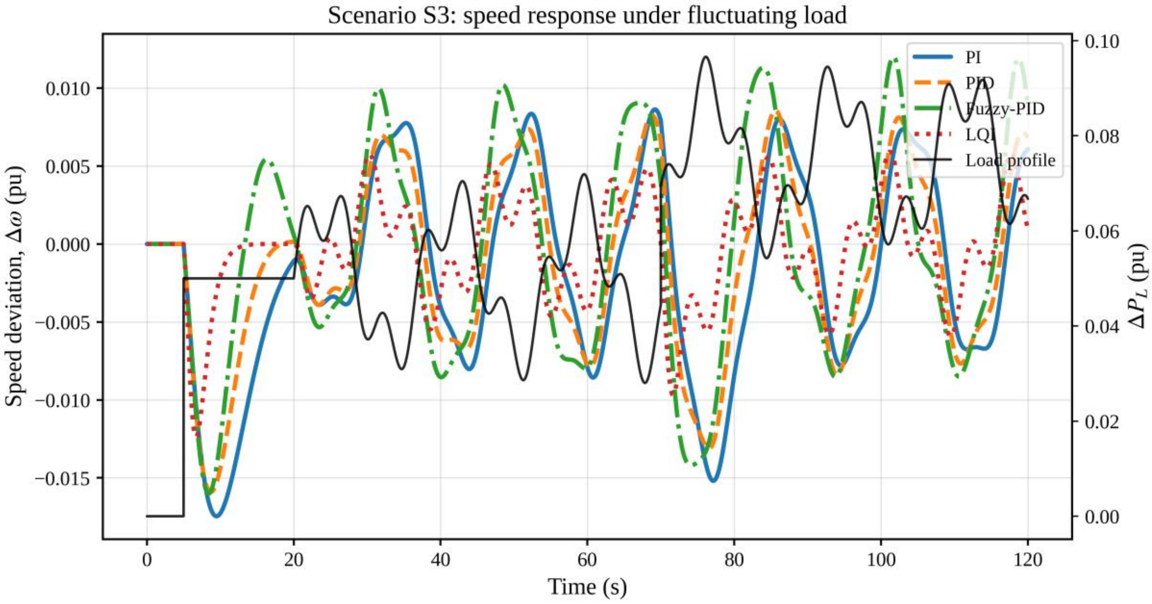

Fig. 8. Scenario S3: speed response under fluctuating load and oscillatory disturbance.

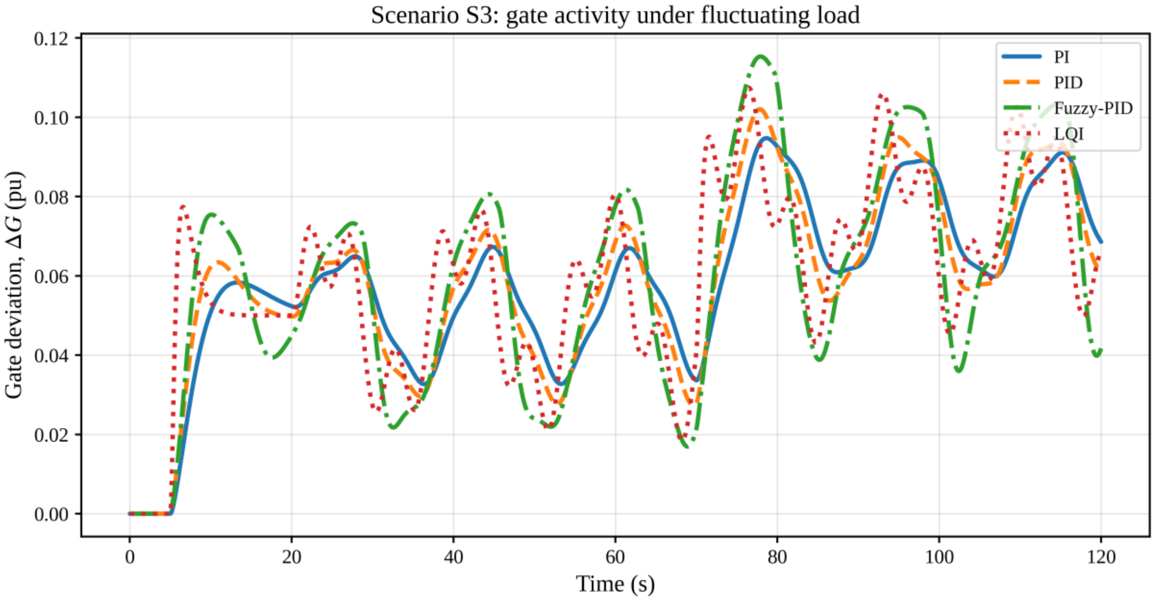

Fig. 9. Scenario S3: gate activity under fluctuating load

Scenario S3 is the most important case for highlighting controller roles under continuous fluctuations. PI produces smooth but relatively large speed oscillations. PID provides additional damping and slightly reduces RMS error. Fuzzy-PID is not uniformly better in this case, because the oscillatory error repeatedly activates the gain-scheduling mechanism and increases gate motion. LQI gives the smallest RMS speed deviation because it uses the waterway state and the integral state to anticipate the effect of the turbine inverse response. The price is higher gate travel, which should be considered when actuator wear is a dominant constraint.

Table 7. Scenario S3 quantitative results

Controller	Peak speed (pu)	IAE	ITAE	RMS	Settling time (s)	Gate travel
PI	0.01746	0.66350	39.04349	0.00673	-	0.45252
PID	0.01590	0.59468	36.52314	0.00605	-	0.57888
Fuzzy-PID	0.01600	0.70445	44.52255	0.00700	-	0.87718
LQI	0.01238	0.30750	19.32588	0.00343	-	1.06948

D. Scenario S4: severe hydromechanical uncertainty

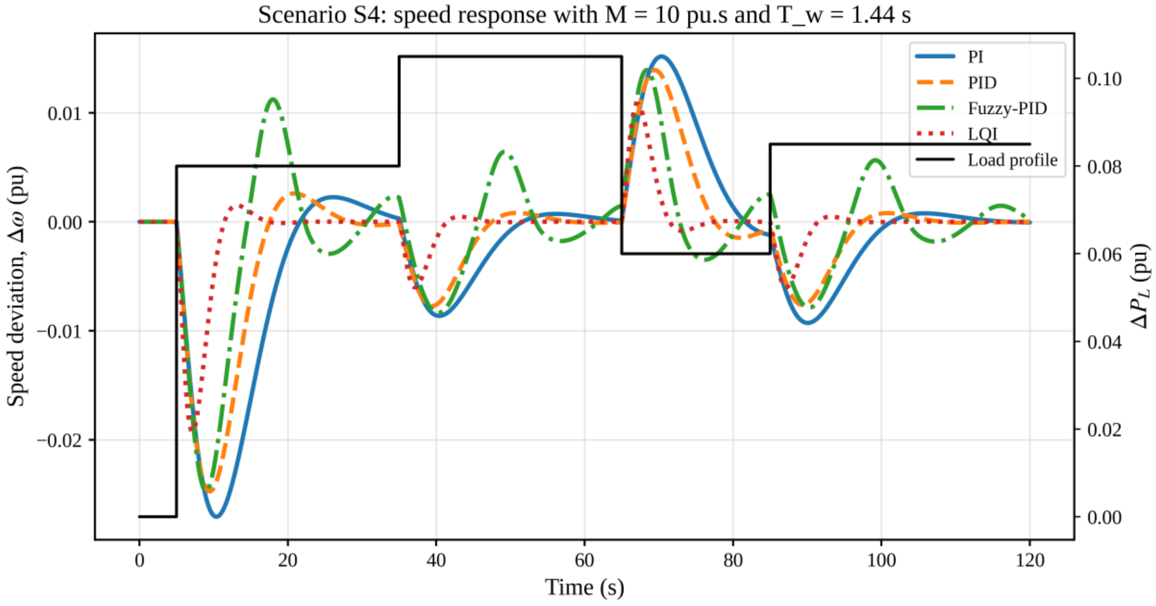

Fig. 10. Scenario S4: speed response with increased inertia and water-starting time.

Scenario S4 evaluates robustness under a larger inertia constant and a slower waterway. This condition is challenging because the unit reacts more slowly to gate commands, and the inverse hydraulic response persists longer. PI and PID remain stable, but their recovery is slower. Fuzzy-PID increases the gate action but does not consistently reduce the integrated error. LQI remains the best option because it was designed from the augmented state model and can coordinate all dominant dynamic states.

Table 8. Scenario S4 quantitative results.

Controller	Peak speed (pu)	IAE	ITAE	RMS	Final settling time (s)	Gate travel
PI	0.02706	0.58246	25.66224	0.00802	93.145	0.26766
PID	0.02474	0.41799	17.70922	0.00644	90.030	0.31068
Fuzzy-PID	0.02466	0.48960	22.74794	0.00627	97.235	0.60651
LQI	0.01925	0.15587	6.12678	0.00346	84.745	0.40721

E. Aggregate comparison and recommended controller

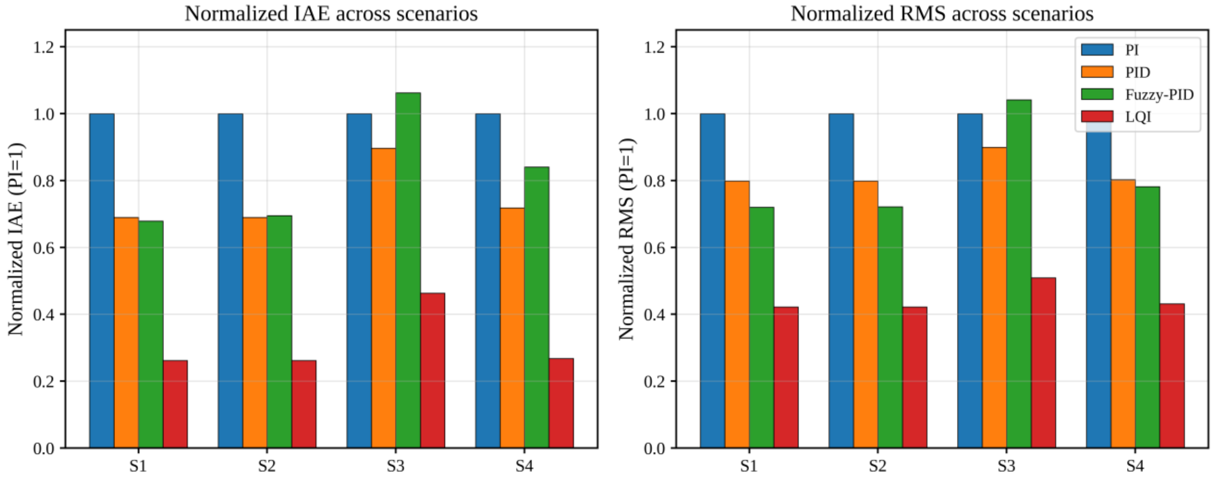

Fig. 11. Normalized IAE and RMS comparison across the four scenarios using PI as reference

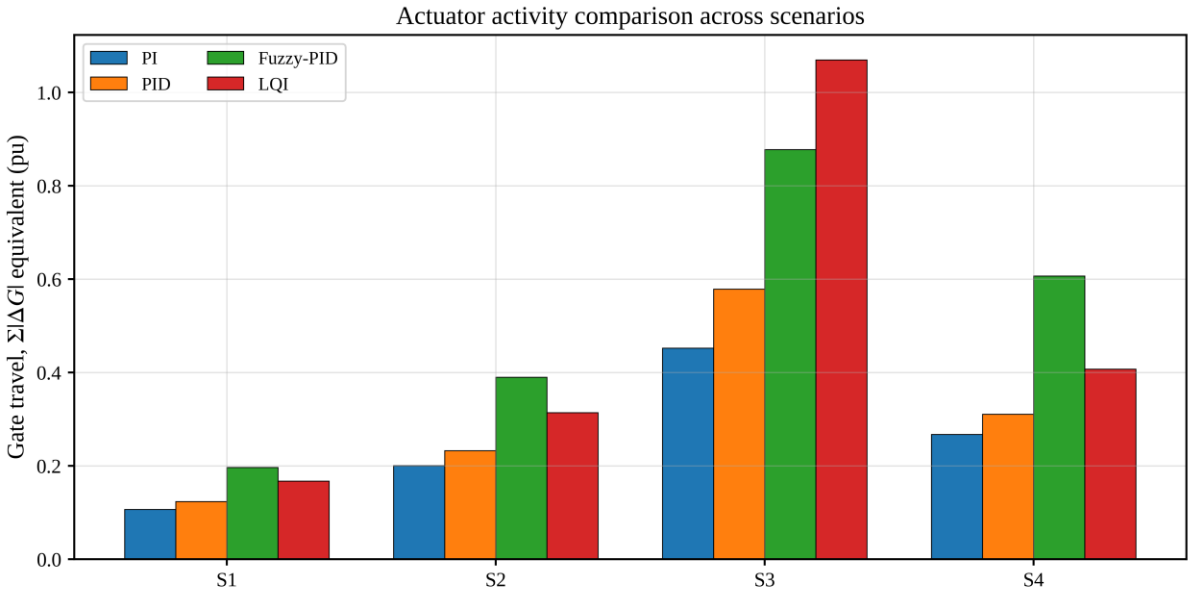

Fig. 12. Actuator activity comparison across the four scenarios

Figure 11 summarizes the speed-regulation performance across all scenarios. LQI is consistently the best controller in terms of IAE and RMS speed deviation. This is not merely a numerical advantage in one step test; it is repeated under multi-step disturbances, fluctuating loads, and severe hydromechanical uncertainty. PID is the best low-complexity alternative because it improves PI without requiring a state model. Fuzzy-PID is useful when adaptive response is desired, but the chosen gain-scheduling rule must be designed carefully to avoid unnecessary gate motion.

Figure 12 shows the actuator-side trade-off. PI has the smallest gate travel because it reacts slowly. PID adds moderate gate activity. Fuzzy-PID increases gate movement significantly because its gains increase during transients. LQI uses more gate motion than PI and PID in fluctuating scenarios, but the motion is effective because it produces the largest reduction in speed error. Therefore, LQI is recommended for high-performance hydropower speed regulation when state information or reliable state estimation is available.

Table 9. Main performance reductions of LQI relative to PI.

Scenario	IAE reduction	RMS reduction	Settling-time reduction	Interpretation
S1	73.8%	57.8%	61.9%	LQI gives the fastest recovery after a single step.
S2	73.8%	57.8%	9.9%	LQI maintains the smallest total error under repeated changes.
S3	53.7%	49.1%	-	LQI best suppresses continuous speed oscillations but uses the highest gate travel.
S4	73.2%	56.9%	9.0%	LQI remains best under larger inertia and slower waterway dynamics.

VI. CONCLUSIONS AND FUTURE WORK

This paper has developed a scenario-based comparative assessment of hydropower speed-governor controllers. Four controllers were tested on the same hydropower benchmark: PI, PID, Fuzzy-PID, and LQI. The model includes the servo, hydraulic water-starting effect, inverse mechanical-power response, swing dynamics, saturation, and gate-rate limits. Four scenarios were used to evaluate different operating roles.

The results show that each controller has a clear role. PI is reliable and simple but produces the slowest recovery. PID improves transient damping and is a good low-complexity practical solution. Fuzzy-PID improves some indices under step disturbances but may cause larger gate activity under fluctuating loads. LQI gives the best overall speed-regulation performance and is the recommended strategy for the considered benchmark. Future work should extend the benchmark to nonlinear turbine characteristics, measurement noise, governor dead bands, and multi-unit hydropower plants participating in wide-area load-frequency control.

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