INVOTEK
Jurnal Inovasi Vokasional dan Teknologi
http://invotek.ppj.unp.ac.id/index.php/invotek
Vol. 25, No. 1, Feb 2025
ISSN: 1411 – 3411 (p)
ISSN: 2549 – 9815 (e)

Evaluation of the Impact of Governor-less Control on the Transient Response of Hydraulic Load Frequency Control Systems

Heru Dibyo Laksono[1] *, Dhea Rahmadani Putri[1], Mumuh Muharam[1]

[1] Department of Electrical Engineering, Andalas University
Limau Manih, Pauh, Padang, Indonesia-25163

**Corresponding author:* herudibyolaksono@eng.unand.ac.id Doi: https://doi.org/10.24036/invotek.v25i1.1256

Abstract

This study evaluates the transient performance of a hydraulic Load Frequency Control (LFC) system configured with a single controller and without a governor. The analysis focuses on rise time, peak time, settling time, and overshoot, using various controllers including PI, PD, PID, PDF, and PIDF. Simulation results indicate that eliminating the governor significantly enhances system responsiveness and reduces overshoot, particularly when using the PDF controller. Quantitative analysis shows that the PDF controller achieves 85% faster rise time (0.101s vs 0.607s for P controller) and maintains system stability with minimal overshoot (1.765% for PID vs 59.263% for P controller). This configuration enables for a more direct and efficient control response to load fluctuations, improving system stability. Thus, employing a single controller without a governor presents a promising alternative for frequency regulation in hydraulic LFC systems under dynamic load conditions. The findings of this study offer valuable insights for optimizing controller selection and configuration in practical implementations, providing guidance for engineers and researchers to enhance grid reliability, operational efficiency, and stability in various real-world hydraulic power system scenarios.

Keywords: LFC, Hydraulic, PID Controller, Governor-less, Frequency Stability.

1. Introduction

Maintaining high-quality electrical energy is critical for ensuring the stability and reliability of power systems that support modern infrastructure [1]. Power system frequency remains stable when the active power generation balances the active power demand. Load variations directly affect system frequency: increased load demand causes frequency to decrease, while excess generation leads to frequency elevation beyond acceptable limits [2], [3].

System instability arises form variations in consumer demand and generation patterns, causing inappropriate frequency changes during operation [4]. Significant frequency deviations can result in poor system performance, reduced efficiency, and potential damage to expensive generation equipment. To ensure acceptable power quality, the frequency should be set at 50Hz or at a tolerance limit of ±2% of the normal frequency. This requirement necessitates the implementation of effective LFC systems [5], [6].

Frequency stability is very important in power system operation. Load-induced frequency deviations can lead to cascading effects including performance degradation, equipment damage, or complete system blackouts [6]–[8]. LFC systems serve as the primary defense mechanism against frequency fluctuations, maintaining deviations within acceptable tolerance limits [9]–[11]. LFC is one of the most important parts of the control system. These systems balance power generation with consumer demand to provide stable, high-quality power supply [12], [13]. Modern LFC implementations incorporate advanced technologies such as superconducting magnetic energy storage (SMES) and Flexible AC Transmission Systems (FACTS) to enhance overall system stability and response characteristics [4], [5], [14], [15].

Received date 25/04/2025, Revised date 01/06/2025, Accepted date 16/06/2025

P-ISSN: 1411-3414
E-ISSN: 2549-9815

Conventional LFC systems employ governors to control turbine speed for frequency regulation. The governor detects frequency changes and adjusts the working fluid flow to the turbine, thereby affecting turbine speed and system frequency [16]. Ultimately, this impacts the turbine speed and system frequency. However, governor-based systems can introduce mechanical delays and complexity that may compromise system responsiveness [17], [18]. This research focuses on a hydraulic type LFC system without a governor, where the controller must be able to respond effectively to load changes to maintain frequency stability without the governor's automatic turbine speed regulation [19].

Modern control strategies increasingly utilize Proportional-Integral-Derivative (PID) controllers due to their simplicity and proven performance in industrial applications [9], [20], [21]. PID controllers employ proportional (K_p), integral (K_i), and derivative (K_d) constants to generate appropriate control signals based on system error [22]–[24]. In the PID controller there is a mechanical valve action based on the magnitude of the resulting error. While PI controllers are commonly implemented in LFC systems, they exhibit limitations on dynamic performance and can cause instability with inappropriate gain values [8], [16], [25].

This study analyzes the performances of a governor-less hydraulic LFC system in maintaining frequency stability under varying load conditions. The research gap addressed is the limited understanding of how eliminating the traditional governor component affects system transient response in hydraulic LFC applications. The novelty lies in the comprehensive of multiple controller configurations (P, PI, PD, PID, PDF, and PIDF) in a governor-less architecture, providing insights into optimal control strategies for modern power systems.

This research aims to evaluate transient performance parameter (rose time, peak time, settling time, overshoot) of governor-less hydraulic LFC systems, compare the effectiveness or different controller types in governor-less configurations, and determine optimal controller configuration for improved system stability and responsiveness. This research scope is limited to ensure focused analysis aligned with the stated objectives:

- Analysis focuses exclusively on hydraulic LFC systems using six controller types (P. PI. PD, PID, PDF, and PIDF).
- MATLAB simulation environment is utilized rather than physical implementation. This approach allows controlled testing of multiple scenarios that would be impractical in real systems due to cost and safety constraints.
- Testing considers condition with and without droop characteristics in governor-less configurations.
- Performance evaluation concentrates on four key transient parameters: rise time, peak time, settling time, and maximum overshoot.

2. Method

MATLAB R2023a with Control System Toolbox was utilized for comprehensive system analysis. The simulation employed a fixed-step solver with 0.01s time step over a 20-second duration capture transient behavior accurately. Load disturbances were implemented as step inputs with 0.1 pu magnitude to evaluate system response under sudden load changes

The hydraulic LFC system was modeled using transfer function representation to analyze control flow and parameter interactions. Three distinct configurations were examined: uncontrolled system, single controller system, and single controller with filter system.

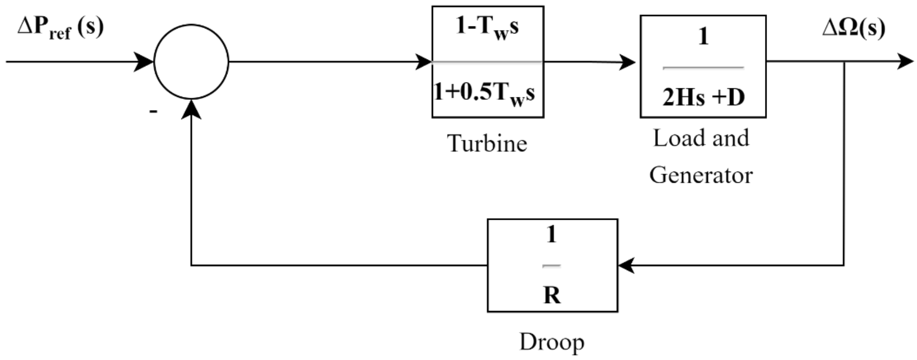

Figure 1. Block Diagram of Uncontrolled Hydraulic Type LFC System

P-ISSN: 1411-3414
E-ISSN: 2549-9815

Figure 1 represents the baseline uncontrolled system where natural system dynamics determine frequency response without any feedback control mechanism. This configuration establishes the reference behavior for comparison with controlled systems.

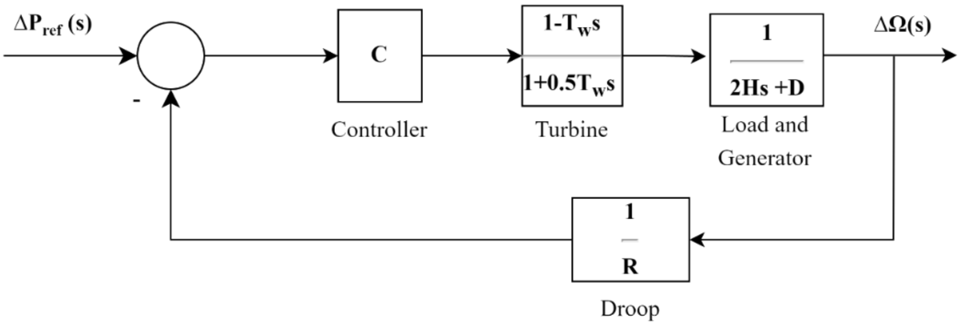

Figure 2. Block Diagram of Hydraulic Type LFC with Single Controller

Figure 2 illustrates the controlled system where a single controlled (C) provides feedback control to regulate frequency deviations. The controller directly interfaces with the hydraulic turbine system without governor intervention, enabling rapid response to frequency changes.

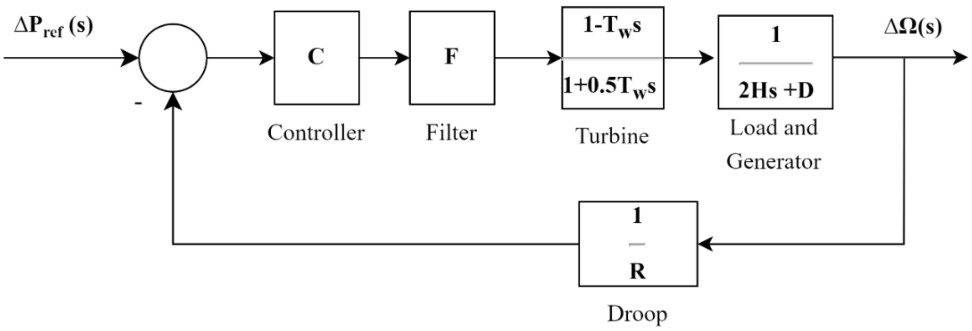

Figure 3. Block Diagram of Hydraulic Type LFC with Single Controller and Filter

Figure 3 shows the enhanced configuration incorporating a derivative filter (F) to improve controller performance by reducing high-frequency noise and enhancing system stability, particularly beneficial for PDF and PIDF controllers.

Based on Figure 1-Figure 3, each of the block diagrams has a transfer function. The transfer function can be seen in the following equation. Figure 1 is a block diagram of a hydraulic type LFC without a controller, where the equation can be seen as follows.

$$\frac{\Delta\Omega(s)}{\Delta P_{ref}(s)} = \frac{\left(\frac{1-T_W s}{1+\frac{1}{2}T_W s}\right)\left(\frac{1}{2Hs+D}\right)}{1+\left(\frac{1-T_W s}{1+\frac{1}{2}T_W s}\right)\left(\frac{1}{2Hs+D}\right)\left(\frac{1}{R}\right)} \tag{1}$$

In Figure 2 is a block diagram of a hydraulic type LFC with a controller where the equation can be seen below.

$$\frac{\Delta\Omega(s)}{\Delta P_{ref}(s)} = \frac{(C)\left(\frac{1-T_W s}{1+\frac{1}{2}T_W s}\right)\left(\frac{1}{2Hs+D}\right)}{1+(C)\left(\frac{1-T_W s}{1+\frac{1}{2}T_W s}\right)\left(\frac{1}{2Hs+D}\right)\left(\frac{1}{R}\right)} \tag{2}$$

In Figure 3 is a block diagram of a hydraulic type LFC with a controller and filter, where the equation can be seen below.

$$\frac{\Delta\Omega(s)}{\Delta P_{ref}(s)} = \frac{(C)(F)\left(\frac{1-T_W s}{1+\frac{1}{2}T_W s}\right)\left(\frac{1}{2Hs+D}\right)}{1+(C)(F)\left(\frac{1-T_W s}{1+\frac{1}{2}T_W s}\right)\left(\frac{1}{2Hs+D}\right)\left(\frac{1}{R}\right)} \tag{3}$$

P-ISSN: 1411-3414
E-ISSN: 2549-9815

where:

T_w = water time constant
H = inertia constant
D = damping coefficient
R = droop characteristic
C = controller transfer function
F = file transfer function

In control systems, there are several types of controllers which can adjust the system response to errors in specific ways. Six controller types were implemented and tuned using MATLAB's PID Tuner tool with emphasis on minimizing rise time and overshoot (Table 1):

Table 1. Controller Transfer Functions [26]

Controller Type	Mathematical Representation
Proportional (P)	K_p
Proportional-Integral (PI)	$K_p + \frac{K_p}{T_i s}$
Proportional-Differential (PD)	$K_p + K_p T_d s$
Proportional-Integral-Differential (PID)	$K_p + \frac{K_p}{T_i s} + K_p T_d s$
Proportional-Differential with a first-order filter on the Differential part (PDF)	$K_p + \frac{K_p T_d s}{\frac{T_d}{N} s + 1}$
Proportional-Integral-Differential with a first-order filter on the Differential part (PIDF)	$K_p + \frac{K_p}{T_i s} + \frac{K_p T_d s}{\frac{T_d}{N} s + 1}$

These controller configurations represent increasing levels of complexity and are commonly employed in LFC applications. The filter time constant τ was varied between 0.025-0.1 to evaluate its impact on system stability and response speed.

Table 2. Design Criteria for Transient Performance Analysis

Design Criteria	Design Value	Justification
Rise Time (T_r)	<2.000 s	Ensures rapid response to load changes
Peak Time (T_p)	<4.000 s	Prevents prolonged frequency excursions
Settling Time (T_s)	<6.000 s	Maintains system stability within acceptable timeframe
Peak Value (y_p)	<0.055	Limits maximum frequency deviation
Maximum Overshoot (M_p)	<20%	Prevents excessive frequency oscillations

Table 2 shows the design criteria used as benchmarks for evaluating the transient performance of the hydraulic LFC system. Each parameter such as rise time, peak time, settling time, and maximum overshoot is accompanied by a design value and a technical justification. These criteria ensure that the system can respond to load changes quickly, keep frequency deviations within safe limits, and maintain operational stability in accordance with standard power grid performance requirements.

3. Results and Discussion

This section presents comprehensive analysis of the governor-less hydraulic LFC system performance using six controller configurations (P, PI, PD, PID, PDF, and PIDF). The analysis examines system behavior under four distinct scenarios: single controller without droop, single controller with droop, single controller with filter without droop, and single controller with filter with droop characteristics.

P-ISSN: 1411-3414
E-ISSN: 2549-9815

Table 3. Performance Analysis of Single Controller Hydraulic LFC System without Droop Characteristics

Transition	P	PI	PD	PID	PDF	PIDF
Rise Time (T_r)	0.607	1.733	0.305	2.328	0.101	1.984
Peak Time (T_p)	3.069	4.618	0	5.618	1.191	5.015
Settling Time (T_s)	11.327	11.126	2.084	4.454	5.748	10.684
Peak Value (y_p)	0.986	1.052	3.275	1.018	1.468	1.039
Maximum Overshoot (M_p)	59.263	5.165	6.417	1.765	140.320	3.875

Table 3 shows the analysis reveals that PD and PDF controllers demonstrate superior performance in meeting design criteria for rise time, peak time, and settling time. The derivative component in these controllers enables faster response to input changes by anticipating system behavior, effectively reducing mechanical delays typically associated with governor systems.

The PD controller achieves exceptional performance with zero peak time and rapid settling (2.084s), demonstrating the effectiveness of derivative action in governor-less configurations. However, it exhibits higher overshoot (6.417%), which remains within acceptable limits.

The PDF controller shows the fastest rise time (0.101s) while maintaining reasonable settling characteristics, though it experiences significant overshoot (140.320%). This behavior results from the aggressive derivative action amplifying high-frequency components.

Controllers incorporating integral action (PI, PID, PIDF) generally exhibit longer response times due to the integral component's inherent lag, but provide better steady-state accuracy and reduced overshoot [27]. The PID controller achieves the lowest overshoot (1.765%) while maintaining acceptable settling time (4.454s), making it a good candidate when minimal deviation is prioritized.

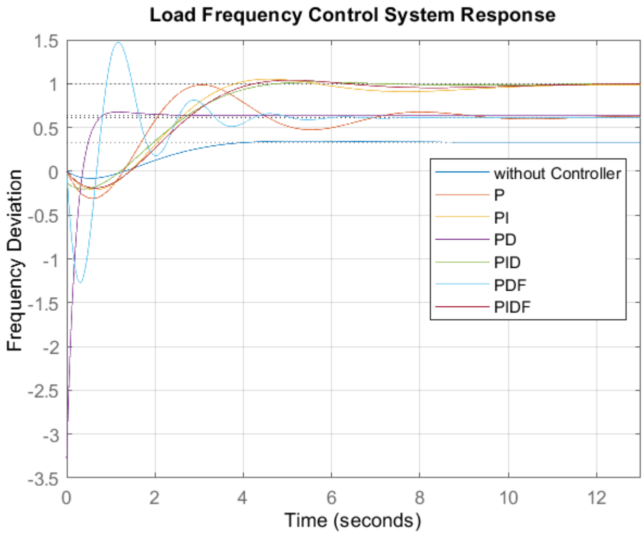

Figure 4. Transient Response Comparison of LFC Controllers Without Droop Characteristics

Figure 4 illustrates the district response characteristics of each controller. The PD and PDF controllers demonstrate rapid initial response with quick rise times, while controllers with integral components show more gradual, stable response with reduced overshoot. The absence of governor mechanical delays allows all controllers to respond more directly to frequency deviations.

Table 4. Performance Analysis of Single Controller Hydraulic LFC System with Droop Characteristics

Transition	P	PI	PD	PID	PDF	PIDF
Rise Time (T_r)	NaN	0.001	0.002	0.001	0.002	0.001
Peak Time (T_p)	Inf	0.002	0.005	0.003	0.005	0.002
Settling Time (T_s)	NaN	0.006	0.003	0.008	0.003	0.006
Peak Value (y_p)	Inf	1.244	1.002	1.117	1.002	1.186

P-ISSN: 1411-3414
E-ISSN: 2549-9815

Maximum Overshoot (M_p)	NaN	24.402	0	11.706	0	18.595

NaN = Not a Number (non-converging response); Inf = Infinite (unstable response)

Table 4 shows that droop characteristics introduce additional complexity. The P controller becomes unstable (indicated by NaN and Inf values), unable to compensate for the feedback from droop without damping support.

However, PD and PDF controllers remain effective, exhibiting zero overshoot and fast responses. This highlights the importance of derivative action in dampening oscillations induced by droop. While PI and PID controllers maintain reasonable performance, their overshoots (24.402% and 11.706% respectively) suggest limited damping capacity under droop influence.

The droop characteristic provides natural load-sharing capability but introduces additional feedback that can destabilize simple proportional control. The derivative component in PD, PDF, PID, and PIDF controllers provides necessary damping to maintain stability under droop conditions.

PD and PDF controllers achieve zero overshoot with droop characteristics, demonstrating excellent stability. The derivative action effectively counters the destabilizing effects of droop feedback, maintaining system equilibrium.

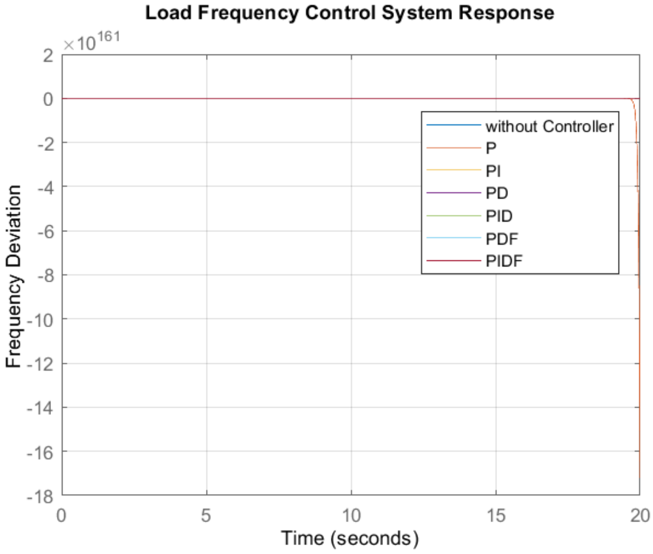

Figure 5. Transient Response Comparison of LFC Controllers with Droop Characteristics

Figure 5 shows the stabilizing effect of derivative components when droop characteristics are present. Controllers without derivative action struggle to maintain stability, while those incorporating derivative terms demonstrate well-damped responses.

Table 5 performance analysis results for the hydraulic LFC system with a single controller and a filter, without droop characteristics, across various filter time constants. The data includes rise time, peak time, settling time, peak value, and maximum overshoot for each controller type. It highlights how variations in the filter time constant influence response speed, system stability, and overshoot, emphasizing that selecting an appropriate filter value can balance rapid response with effective oscillation damping.

Table 5. Performance Analysis of Single Controller Hydraulic LFC System and Filter without Droop Characteristics

Parameter	Filter (τ)	P	PI	PD	PID	PDF	PIDF
T_r	0.025	0.609	1.707	0.125	2.276	0.110	1.952
	0.050	0.611	1.684	0.120	2.228	0.122	1.923
	0.075	0.614	1.665	0.135	2.186	0.137	1.900
	0.100	0.622	1.652	0.154	2.149	0.152	1.883
T_p	0.025	3.137	4.608	0.147	5.602	1.281	5.146
	0.050	3.199	4.598	0.212	5.586	1.423	5.129

P-ISSN: 1411-3414
E-ISSN: 2549-9815

	0.075	3.250	4.779	0.255	5.570	1.535	5.113
	0.100	3.289	4.768	1.295	5.555	1.637	5.242
T_s	0.025	11.571	11.052	1.959	6.134	7.997	10.746
	0.050	13.686	11.007	21.243	6.455	9.640	10.817
	0.075	14.111	10.988	3.337	6.687	10.563	10.898
	0.100	14.456	10.993	3.843	6.879	11.314	10.987
y_p	0.025	1.002	1.064	1.851	1.025	1.537	1.049
	0.050	1.018	1.077	1.463	1.033	1.549	1.060
	0.075	1.031	1.089	1.239	1.041	1.533	1.071
	0.100	1.043	1.101	1.173	1.049	1.505	1.081
M_p	0.025	61.940	6.425	30.182	2.482	151.630	4.933
	0.050	64.378	7.652	63.012	3.250	153.660	6.011
	0.075	66.573	8.855	77.812	4.065	150.980	7.080
	0.100	68.488	10.125	84.573	4.923	146.400	8.144

The filter analysis reveals several critical insights:

Rise Time Performance: Controllers with derivative components (P, PI, PD, PDF, PIDF) consistently meet the rise time criteria (<2.000s) across all filter values. The PID controller fails this criterion due to the integral component's inherent lag, which becomes more pronounced when combined with derivative filtering.

Filter Time Constant Effect: As τ increases from 0.025 to 0.1, there is a general trend toward slightly slower rise times but improved stability. This occurs because larger filter time constants provide more aggressive noise filtering at the expense of response speed.

Peak Time Analysis: The combination of derivative components with appropriate filtering (PD, PDF) enables rapid peak attainment, with the PD controller showing exceptional performance across all filter values. The derivative action provides anticipatory control that accelerates the approach to steady-state.

Overshoot Control: Controllers with integral components (PI, PID, PIDF) demonstrate superior overshoot performance, with the PID controller achieving the lowest overshoot values across all filter settings, this behavior results form the integral component's ability to eliminate steady-state error while providing natural damping against excessive transient responses.

Table 6 shows the performance analysis results for the hydraulic system with a single controller, a filter, and droop characteristics, evaluated across different filter time constants. The results indicate that only PD and PDF controllers with smaller filter time constants maintain system stability under sroop conditions. The table illustrates how the addition of droop characteristics affects stability margins, showing that increasing the filter time constant generally degrades performance and beyond a critical point, can lead to system instability.

Table 6. Performance Analysis of Single Controller Hydraulic LFC System and Filter with Droop Characteristics

Parameter	Filter (τ)	P	PI	PD	PID	PDF	PIDF
T_r	0.025	NaN	NaN	0.005	NaN	0.005	NaN
	0.050	NaN	NaN	0.006	NaN	0.006	NaN
	0.075	NaN	NaN	0.008	NaN	0.008	NaN
	0.100	NaN	NaN	NaN	NaN	NaN	NaN
T_p	0.025	Inf	Inf	0.013	Inf	0.013	Inf
	0.050	Inf	Inf	0.018	Inf	0.018	Inf
	0.075	Inf	Inf	0.022	Inf	0.022	Inf
	0.100	Inf	Inf	Inf	Inf	Inf	Inf
T_s	0.025	NaN	NaN	0.208	NaN	0.208	NaN
	0.050	NaN	NaN	0.473	NaN	0.473	NaN
	0.075	NaN	NaN	0.843	NaN	0.843	NaN

P-ISSN: 1411-3414
E-ISSN: 2549-9815

	0.100	NaN	NaN	NaN	NaN	NaN	NaN
y_p	0.025	Inf	Inf	1.796	Inf	1.796	Inf
	0.050	Inf	Inf	1.866	Inf	1.866	Inf
	0.075	Inf	Inf	1.901	Inf	1.901	Inf
	0.100	Inf	Inf	Inf	Inf	Inf	Inf
M_p	0.025	NaN	NaN	78.758	NaN	78.758	NaN
	0.050	NaN	NaN	85.708	NaN	85.708	NaN
	0.075	NaN	NaN	89.231	NaN	89.231	NaN
	0.100	NaN	NaN	NaN	NaN	NaN	NaN

The results reveal that only PD and PDF controllers with smaller filter time constants ($\tau \leq 0.075$) maintain stability. This occurs because:

Phase Margin Reduction: The combination of droop feedback and derivative filtering reduces the system's phase margin to critical levels. Damping Requirement: Only controllers with unfiltered or lightly filtered derivative action provide sufficient damping to maintain stability under droop conditions. Critical Filter Value: At $\tau = 0.1$, even PD and PDF controllers become unstable, indicating a critical threshold where filtering degrades system stability beyond acceptable margins.

4. Conclusion

This research demonstrates that governor-less hydraulic LFC systems provide superior transient performance compared to traditional governor-based configurations. The elimination of mechanical delays inherent in governor systems enables more responsive and efficient frequency control. Among the evaluated controllers, the PDF controller emerges as the optimal choice, achieving the fastest rise time while maintaining system stability. The derivative component effectively compensates for the absence of governor damping, providing anticipatory control that enhances system response. The study establishes that governor-less operation with appropriately designed controllers represents a viable and advantageous approach for frequency regulation in hydraulic power systems. This configuration is particularly beneficial under dynamic load conditions where rapid frequency response is critical for system stability. Future research should investigate the implementation of these control strategies in real hydraulic power systems and explore adaptive control techniques that can optimize controller parameters in real-time based on operating conditions.

References

[1] D. P. Kothari and I. J. Nagrath, *Modern Power Systems Analysis*. 2022. doi: 10.1201/9781003207429-6.

[2] F. R. Ningsih, "Simulasi Dan Analisa Sistem Kendali Frekuensi Tenaga Listrik Dengan Pilot Servo Dan Kombinasi Pengendali PIDTune Model Standar (Model Hidraulik)," *J. Ilmu Pendidik.*, vol. 7, no. 2, pp. 809–820, 2020.

[3] V. T. W. Vina, "Analisis Setting Speed Droop dan Deadband Governor Unit 1 PLTA Maninjau Sebagai Pengaturan Frekuensi pada Sistem 150 KV," *J. Tek. Energi*, vol. 11, no. 2, pp. 25–29, 2023, doi: 10.35313/energi.v11i2.3912.

[4] S. Asgari, M. B. Menhaj, A. A. Suratgar, and M. G. Kazemi, "A disturbance observer based fuzzy feedforward proportional integral load frequency control of microgrids," *Int. J. Eng. Trans. A Basics*, vol. 34, no. 7, pp. 1694–1702, 2021, doi: 10.5829/IJE.2021.34.07A.13.

[5] H. D. Laksono and W. H. bin Mohd Saad, "Frequency Domain Analysis of Load Frequency Control Using PIDTune Model Standard," *Andalas J. Electr. Electron. Eng. Technol.*, vol. 3, no. 1, pp. 44–51, 2023, doi: 10.25077/ajeeet.v3i1.38.

[6] A. J. Pakpahan and Herlambang Setiadi, "Optimal Control Design for Frequency Regulation in Electric Power System With Low Inertia," *J. Adv. Technol. Multidiscip.*, vol. 3, no. 1, pp. 26–36, 2024, doi: 10.20473/jatm.v3i1.59984.

P-ISSN: 1411-3414
E-ISSN: 2549-9815

[7] A. D. Novfowan, M. Mieftah, and W. Kusuma, "Analisis Stabilitas Transien Tegangan dan Frekuensi pada Sistem Pembangkit Listrik Tenaga Uap," *ELPOSYS J. Sist. Kelistrikan*, vol. 8, no. 1, pp. 28–33, 2021.

[8] N. A. Orka, S. S. Muhaimin, M. N. S. Shahi, and A. Ahmed, *An Enhanced Gradient Based Optimized Controller for Load Frequency Control of a Two Area Automatic Generation Control System*, vol. 1069. 2023. doi: 10.1007/978-3-031-16832-1_5.

[9] P. Kundur, "Power System Stability and Control," *Power System Stability and Control*. 2007. doi: 10.1201/9781420009248.

[10] D. Marsudi, "Operasi Sistem Tenaga Listrik," *Graha Ilmu*, no. April, pp. 2–5, 2006.

[11] M. Kusriyanto, H. S. Utama, and I. Effendi, "Prototype of Automatic Frequncy Control in Microhydro Power Plant with Dummy Load Based on Arduino Uno and Labview," *Teknoin*, vol. 27, no. 1, pp. 1–8, 2021, doi: 10.20885/teknoin.vol27.iss1.art1.

[12] S. Y. Bhuran and S. P. Jadhav, "Design of PID, IMC and IMC based PID Controller for Hydro Turbine Power System of Non-minimum Phase Dynamics," *J. Robot. Control*, vol. 5, no. 2, pp. 416–426, 2024, doi: 10.18196/jrc.v5i2.21342.

[13] A. K. Baliarsingh, S. K. Mohapatra, and P. M. Dash, "Fractional Order PD(1+ PI) Controller for Frequency Control of Power System with Renewable Sources and Electric Vehicle," *Electrica*, vol. 24, no. 2, pp. 406–424, 2024, doi: 10.5152/electrica.2024.23143.

[14] N. G. Hingorani dan L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission System*. Library of Congress Cataloging-in-Publication Data, 2000.

[15] T. Mustarin, "Desain Optimal Load Frequency Control (LFC) dengan Superconducting Magnetic Energy Storage (SMES) pada Sistem Pembangkit Listrik Tenaga Mikro Hidro Menggunakan Metode Firefly Algorithm," p. 84, 2015, [Online]. Available: http://repository.its.ac.id/52255/

[16] Z.- Abidin, "Pemodelan Matematis Pengaturan Frekuensi Beban Sistem Tenaga Hibrid Turbin Angin-Diesel-PV," *JE-Unisla*, vol. 5, no. 2, p. 392, 2020, doi: 10.30736/je.v5i2.497.

[17] A. Kumar, O. P. Malik, and G. S. Hope, "Effect of Governor Dead-Band on Variable Structure Controller Performance for Lfc of Interconnected Power Systems.," *IFAC Proc. Vol.*, vol. 18, no. 7, pp. 255–260, 1986, doi: 10.1016/s1474-6670(17)60443-9.

[18] A. Kiswantono, "Peningkatan Kinerja Pltb Melalui Kendali Frekuensi Fuzzy Logic," *J. Inform. dan Tek. Elektro Terap.*, vol. 12, no. 1, pp. 137–147, 2024, doi: 10.23960/jitet.v12i1.3948.

[19] C. S. M. Da Silva, N. J. F. Da Silva, F. A. D. C. Ayres Junior, R. L. P. De Medeiros, L. E. S. E. Silva, and V. F. De Lucena, "Experimental Implementation of Hydraulic Turbine Dynamics and a Fractional Order Speed Governor Controller on a Small-Scale Power System," *IEEE Access*, vol. 12, no. March, pp. 40480–40495, 2024, doi: 10.1109/ACCESS.2024.3375349.

[20] E. D. Cahyono, "Simulasi Rancang Bangun Alat pH Balancer Berbasis Logika Fuzzy Menggunakan Arduino Uno," *Prosiding Seinar Nasional Forum Pendidikan Tinggi Teknik Elektro Indonesia (FORTEI) Regional VII,* vol.7, no. 4, pp. 296–301, 2021, [Online]. Available: http://download.garuda.kemdikbud.go.id/article.php?article=2811419%5C&val=25026%5C&title=Simulasi Rancang Bangun Alat pH Balancer Berbasis Logika Fuzzy Menggunakan Arduino Uno

[21] B. Maharmi, I. Cholid, Syafii, and E. H. Arya, "Optimization of speed droop governor operation at the gas turbine cogeneration unit," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 33, no. 1, pp. 20–30, 2024, doi: 10.11591/ijeecs.v33.i1.pp20-30.

[22] D. V. Doan, K. Nguyen, and Q. V. Thai, "Load-Frequency Control of Three-Area Interconnected Power Systems with Renewable Energy Sources Using Novel PSO~PID-Like Fuzzy Logic Controllers," *Engineering, Technology and Applied Science Research*, vol. 12, no. 3. pp. 8597–8604, 2022. doi: 10.48084/etasr.4924.

P-ISSN: 1411-3414
E-ISSN: 2549-9815

[23] A. Fernández-Guillamón, E. Muljadi, and A. Molina-García, "Frequency control studies: A review of power system, conventional and renewable generation unit modeling," *Electr. Power Syst. Res.*, vol. 211, no. January, 2022, doi: 10.1016/j.epsr.2022.108191.

[24] M. Mokhtar, M. I. Marei, M. A. Sameh, and M. A. Attia, "An Adaptive Load Frequency Control for Power Systems with Renewable Energy Sources," *Energies*, vol. 15, no. 2, pp. 1–22, 2022, doi: 10.3390/en15020573.

[25] I. A. Khan, H. Mokhlis, N. N. Mansor, H. A. Illias, L. Jamilatul Awalin, and L. Wang, "New trends and future directions in load frequency control and flexible power system: A comprehensive review," *Alexandria Eng. J.*, vol. 71, pp. 263–308, 2023, doi: 10.1016/j.aej.2023.03.040.

[26] H. D. Laksono, *Pidtune Model Paralel Dan Model Standard*. LPPM - Universitas Andalas, 2021.

[27] S. Datta and D. Chakraborty, "An LMI based PID controller for load frequency control in power system," *Proc. IEEE Int. Conf. Control Appl.*, no. August 2013, pp. 655–660, 2013, doi: 10.1109/CCA.2013.6662824.