# Optimization of Frequency Stability in Hydraulic Load Frequency Control Systems Using Controllers with Filters

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## ABSTRACT

This study meticulously investigates the design and analysis of a Load Frequency Control (LFC) system tailored explicitly for hydraulic power systems by employing diverse configurations of PID controllers, namely Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), Proportional-Integral-Derivative (PID), Proportional-Derivative-Fractional (PDF), and Proportional-Integral-Derivative-Fractional (PIDF). The primary objective of this exploration is to improve frequency stability in response to various load fluctuations typical in hydraulic systems. A comprehensive evaluation of each controller's performance is conducted through extensive MATLAB simulations, focusing on critical performance metrics such as rise time, peak time, steady-state time, and maximum overshoot. The findings reveal that the PD and PDF controllers exhibit superior response characteristics, offering the fastest and most stable outcomes regardless of whether droop characteristics are utilized or filtering techniques are introduced. Although the implementation of filters significantly mitigates overshoot, it is evident that controllers incorporating droop characteristics tend to compromise optimal steady-state time stability. The overall analysis underscores the PD and PDF controllers as the preeminent solutions for ensuring frequency stability in hydraulic LFC systems, especially under abrupt and substantial load changes, thus positioning them as vital tools in enhancing hydraulic power system reliability and efficiency.

## INTRODUCTION

Electrical energy can be of good quality because it is essential to life. The generating frequency is considered stable when the active power of the plant is balanced with the active control of the load[1][2]. Changes in the active power demand at the load affect the value of the power system frequency. If the active power demand on the load increases, the system frequency may decrease, but if the plant produces more active power than it consumes, the system frequency will increase more than usual.[3].

Due to variations in production and consumer load in the power system, instability of active and reactive power requirements can cause inappropriate frequency changes during system operation[4][5][6][7]. More significant frequency deviations can cause poor system operation or reduce its performance, endanger consumers, force outages if the frequency is unstable and drops too low, and result in damage[8][9]. The frequency should be stabilized at 50Hz or at a tolerance limit of ±2% of the average frequency to ensure good electricity quality. Therefore, a Load Frequency Control (LFC) control system is required to prevent frequency changes[10][11].

The Load Frequency Control (LFC) system can control energy supply effectively. This system was developed to monitor and

overcome frequency fluctuations due to load changes and can store data on frequency changes.[11][12]. Load Frequency Control (LFC) or frequency control system plays a vital role in controlling frequency changes in the power grid due to load variations. These frequency changes need to be maintained within the allowed range and must be able to recover to normal values quickly. This is important because excessive frequency fluctuations can result in system damage and disruption of electricity supply[14]. In the operation of power and control systems, LFC plays a vital role as the main component that ensures the balance between generated power and the energy needs of customers. This system also plays a role in ensuring stable and high-quality electricity distribution to consumers [15][16].

Designing a robust and easy controller is necessary for frequency deviation. The purpose of the frequency control system is to maintain the stability of the system frequency by regulating the load distribution in each generator. This allows the generators to operate optimally and can produce the required power without experiencing excessive frequency changes[17][18]. To achieve this goal, the active power generated must meet the power requirements of the load so that the system frequency remains stable and within tolerance limits. The mechanical valves required to drive the generator are regulated to control the active power supply. In a power plant, the turbine and the generator rotor

are mechanically connected. The governor system serves to regulate the turbine speed while maintaining the frequency value in the electrical energy frequency control system[19][20][21][22].

Proportional-Integral-Derivative (PID) controllers are one of the methods used by frequency control systems. PID controllers are still the main choice in the power industry today because of their ease of use and good performance[23][24]. The output value of PID controller is calculated by control parameters such as proportional constant (Kp), integral constant (Ki), and derivative constant (Kd). According to the magnitude of the error obtained, the PID controller will provide action to the mechanical valve[25][26].

The purpose of this study is to design and analyze the performance of an LFC control system on a hydraulic-type power system using PID controllers and filters. The analysis is conducted to measure the performance of a single controller in achieving frequency stability and reducing the effect of load changes on the power system. This research also aims to determine the effective controller at rise time, peak time, steady state time, and maximum pass-through simulation using MATLAB software.

The study focuses on optimizing frequency stability in hydraulic load frequency control (LFC) systems using various PID controller configurations, including P, PI, PD, PDF, PID, and PIDF. Extensive MATLAB simulations were performed to assess performance metrics such as rise time, peak time, steady-state time, and maximum overshoot. The findings revealed that PD and PDF controllers provide the best response characteristics, offering quick and stable results, even with droop characteristics or filtering techniques. Filters can reduce overshoot, but droop characteristics may negatively impact steady-state stability. Overall, PD and PDF controllers are identified as effective solutions for maintaining frequency stability in hydraulic power systems during significant load changes.

## METHOD

MATLAB simulation is used to analyze the performance of a single controller on a hydraulic LFC system against load inputs. The system block diagram was drawn to show the control flow, including details of the parameters tested, such as rise time, peak time, steady time, and maximum pass rate, as well as the settings for the governor and droop.
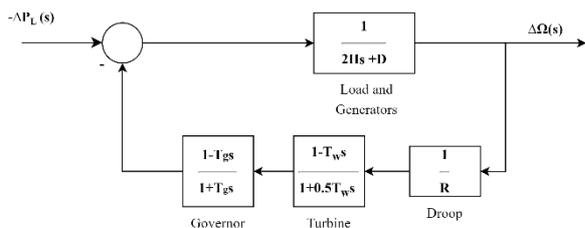


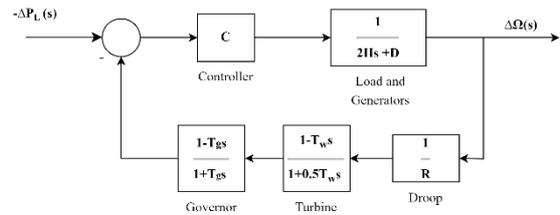Figure 1. Block Diagram of Uncontrolled Hydraulic Type LFC against Load Input [27]



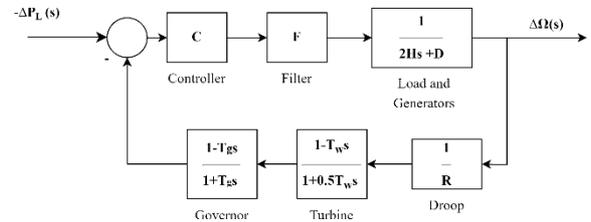Figure 2. Block Diagram of Hydraulic Type LFC with Single Controller against Load Input [27]



Figure 3. Block Diagram of Hydraulic Type LFC with Single Controller Using Filter Against Load Input [27]

Based on Figure 1 - Figure 3, each block diagram 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, the equation can be seen in equation (1):

$$\frac{\Delta\Omega(s)}{-\Delta P_L(s)} = \frac{\left(\frac{1}{2Hs + D}\right)}{1 + \left(\frac{1}{1 + T_G s}\right)\left(\frac{1 - T_w s}{1 + \frac{1}{2}T_w s}\right)\left(\frac{1}{2Hs + D}\right)\left(\frac{1}{R}\right)} \tag{1}$$

Figure 2. is a block diagram of a hydraulic-type LFC with a controller. The equation can be seen in equation (2).

$$\frac{\Delta\Omega(s)}{-\Delta P_L(s)} = \frac{(C)\left(\frac{1}{2Hs + D}\right)}{1 + (C)\left(\frac{1}{1 + T_G s}\right)\left(\frac{1 - T_w s}{1 + \frac{1}{2}T_w s}\right)\left(\frac{1}{2Hs + D}\right)\left(\frac{1}{R}\right)} \tag{2}$$

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

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

Table 1 explains the different types of controllers in the PID (Proportional-Integral-Derivative) approach along with their mathematical representations. Proportional (P) controllers use a control signal that is proportional to the error, where $K_p$ is the proportional gain constant. Furthermore, the Proportional-Integral (PI) controller combines proportional and integral elements to reduce the offset through compensation to the cumulative error, where $T_i$ is the integral time constant. The Proportional-Differential (PD) controller adds a differential component to the proportional controller to speed up the system response by estimating the change in error, with $T_d$ as the differential time constant.

Table 1. PIDTune Controller Types Standard Model [28]

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

A more complex controller is the Proportional-Integral-Differential (PID), which combines all three elements of P, I, and D to provide a more precise system response. To reduce the influence of noise on the differential part, the Proportional-Differential controller with a First Order Filter (PDF) is equipped with a filter. Finally, the Proportional-Integral-Differential controller with a First-order Filter (PIDF) offers a complete combination of P, I, and D with an additional filter on the differential component to improve performance on noise-affected systems. The selection of this controller type depends on the system requirements and the desired performance, where configurations with filters are usually used for systems with high noise interference.

Table 2. Design Criteria for Hydraulic Type Load Frequency Control Transition Analyzing of Load Input

| Design Criteria | Design Value |
|---|---|
| Rise Time ($T_r$) | <1.150 s |
| Peak Time ($T_p$) | <2.000 s |
| Settling Time ($T_s$) | <4.000 s |
| Peak Value ($y_p$) | <0.055 |
| Maximum Pass Rate ($M_p$) | <20% |

In table 2 shows the design criteria for the transition analysis of load frequency control in hydraulic systems (Hydraulic Type Load Frequency Control) with load input. These design criteria include five main parameters that describe system performance. Firstly, Rise Time ($T_r$) which is the time taken by the system response to increase from the initial condition until it reaches a certain value (usually 10%-90% of the final value), with a design criterion of less than 1.150 seconds. Secondly, Peak Time ($T_p$) which is the time required for the system to reach the first peak of its transient response, which is expected to be less than 2,000 seconds. Furthermore, Settling Time ($T_s$) is the time required for the system response to stabilize within a certain tolerance (usually ±2% or ±5% of the final value), with a target of less than 4,000 seconds. Peak Value ($y_p$) or peak value, refers to the maximum value reached by the system response during transients, which is desired to be less than 0.055. Finally, Maximum Pass Rate ($M_p$) describes the maximum percentage of the system response that passes its target final value, with a criterion of less than 20%.

These criteria are designed to ensure fast, stable and precise system response in coping with load changes in the hydraulic system.

## RESULTS AND DISCUSSION

In this section of the results and analysis describes the results of the hydraulic type LFC control system using a single controller architecture. Analysis of the hydraulic type LFC control system against load input with unit step input. Analysis on a single controller in the form of a Proportional (P) controller, Proportional Integral (PI), Differential Controller (PD), Differential Integral Controller (PID), Differential Controller with First Order Filter Differential Part (PDF), and Differential Integral Controller with First Order Filter Differential Part (PIDF). The results of the analysis obtained a comparison of the criteria set.

Table 3. Information on Analysis of Single Type Hydraulic Type Transition against Load Input without *Droop* Characteristics

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | 1.482 | 1.883 | **0.114** | 104.07 | **0.114** | 101.9 |
| $T_p$ | 5.751 | 4.282 | **0.394** | 362.63 | **0.394** | 475.16 |
| $T_s$ | 70.88 | 12.239 | **0.190** | 217.55 | **0.190** | 213.25 |
| $y_p$ | 0.785 | 1.169 | 0.991 | 0.997 | 0.991 | 0.999 |
| $M_p$ | **14.447** | **16.934** | **0.933** | 0 | **0.933** | 0 |

Based on Table 3. it can be seen that the PD and PDF controllers without droop characteristics fulfil the design criteria in terms of rise time, peak time, steady state time, and maximum skip value. This is because PD and PDF controllers are able to respond faster to changes in input signals and are able to reduce overshoot and improve stability, especially when facing sudden load changes. Meanwhile, in the P, PI, PID, and PIDF controllers, only the maximum skip value fulfils the design criteria. This results in the P, PI, PID, and PID controllers tending to provide slower responses due to the Integral (I) component which can eliminate steady state errors causing longer settling times and often resulting in higher overshoots that can cause dangerous frequency fluctuations.
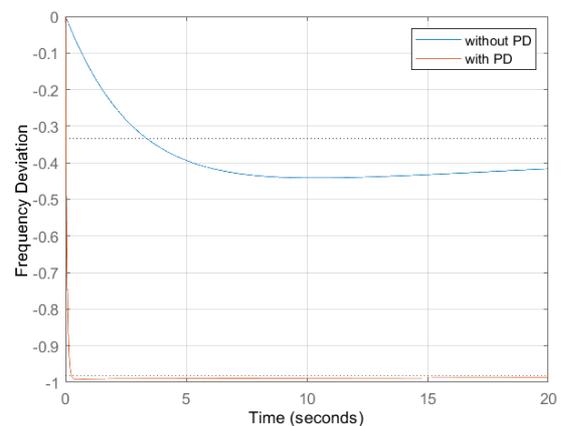


Figure 4. PD Controller LFC Transition Analysis Response to Load Input Without Droop Characteristics

The controller graph in Figure 4 is a PD controller without droop characteristics that fulfils the design criteria.
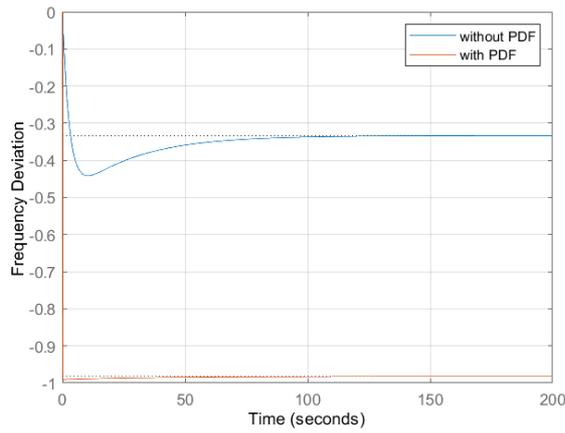
Figure 5. PDF Controller LFC Transition Analysis Response to Load Input Without Droop Characteristics

The controller graph in Figure 5 is a PDF controller without droop characteristics that fulfils the design criteria.

Table 4. Information on the Analysis of Single Type Hydraulic Type Transition against Load Input with *Droop* Characteristics

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | **0.133** | 140.18 | **0.133** | 14660 | **0.133** | 14343 |
| $T_p$ | **0.752** | 447.07 | **0.752** | 48853 | **0.752** | 47797 |
| $T_s$ | 81.604 | 274.44 | 81.604 | 26046 | 81.604 | 25482 |
| $y_p$ | 1.000 | 0.998 | 1.000 | 0.999 | 1.000 | 0.999 |
| $M_p$ | 62.351 | **0** | 62.351 | **0** | 62.351 | **0** |

Based on Table 4, it can be seen that there is no controller that meets the design criteria for the hydraulic type LFC on load input with droop characteristics. At rise time and peak time only P, PD, PDF controllers fulfil the parameters. This happens because P, PD, PDF controllers are effective in providing fast response and good stability. Unlike the PI, PID, PIDF controllers which only fulfil the maximum skip value. Thus, PI, PID, PIDF controllers excel in controlling overshoot due to the presence of integral components that are able to suppress oscillations but the initial response time is slower. At steady state time none of the controllers fulfils the parameters. This results in steady state errors remaining and requires additional controllers to overcome frequency deviation to remain in the Load Frequency Control system.

Table 5. Transition Analysis Information of Single Controller and Filter Hydraulic Types against Load Input without Droop Characteristics (τ=0,025)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | 1.454 | 1.852 | **0.081** | 2.113 | **0.081** | 1.992 |
| $T_p$ | 5.674 | 4.281 | **0.172** | 4.815 | **0.172** | 4.618 |
| $T_s$ | 70.869 | 12.228 | **0.243** | 8.471 | **0.243** | 8.237 |
| $y_p$ | 0.785 | 1.174 | 1.024 | 1.083 | 1.024 | 1.115 |
| $M_p$ | **14.483** | 17.412 | 4.238 | 8.257 | 4.238 | 11.51 |

Based on Table 5. It can be seen that the PD and PDF controllers using *filters* without *droop* characteristics fulfil the design criteria both from the rise time, peak time, steady state time, and maximum skip value. The higher the value, the greater the number obtained. This happens because PD and PDF controllers are optimal in responding to system changes faster thanks to the *Derivative* (D) component that can reduce sudden changes. While for P, PI, PID, PIDF controllers, only the maximum pass value is fulfilled. This is because the Proportional (P) component controller often causes *overshoot* or oscillation and the Integral

(I) component can increase *overshoot* in the initial response phase caused by accumulated *errors*.
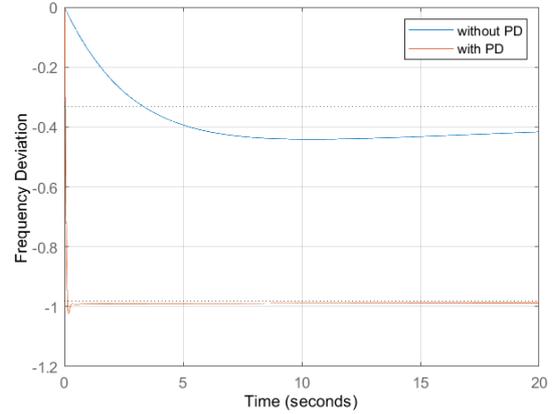


Figure 6. PD Controller LFC Transition Analysis Response to Load Input Without Droop Characteristics

The controller graph in Figure 6 is a PD controller without droop characteristics with a (τ = 0,025) filter that fulfils the design criteria.
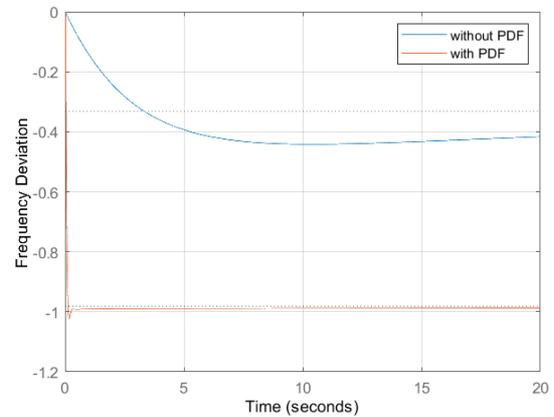


Figure 7. PDF Controller LFC Transition Analysis Response to Load Input Without Droop Characteristics (τ = 0,025)

The controller graph in Figure 7 is a PDF controller without droop characteristics with a (τ = 0,025) filter that fulfils the design criteria.

Table 6. Transition Analysis Information of Single Controller and Filter Hydraulic Types against Load Input without Droop Characteristics (τ=0,05)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | 1.429 | 1.821 | **0.086** | 2.074 | **0.086** | 1.956 |
| $T_p$ | 5.602 | 4.283 | **0.192** | 4.771 | **0.192** | 4.591 |
| $T_s$ | 70.859 | 12.214 | **0.309** | 8.436 | **0.309** | 8.195 |
| $y_p$ | 0.785 | 1.179 | 1.136 | 1.085 | 1.136 | 1.118 |
| $M_p$ | **14.521** | 17.911 | 15.626 | 8.495 | 15.626 | 11.834 |

Based on Table 6. it can be seen that the PD and PDF controllers using *filters* without *droop* characteristics fulfil the design criteria both from the rise time, peak time, steady state time, and maximum skip value. The higher the value, the greater the number obtained. This happens because PD and PDF controllers are optimal in responding to system changes faster thanks to the

*Derivative* (D) component that can reduce sudden changes. While for P, PI, PID, PIDF controllers, only the maximum pass value is fulfilled. This is because the Proportional (P) component controller often causes *overshoot* or oscillation and the Integral (I) component can increase *overshoot* in the initial response phase caused by accumulated *errors*.
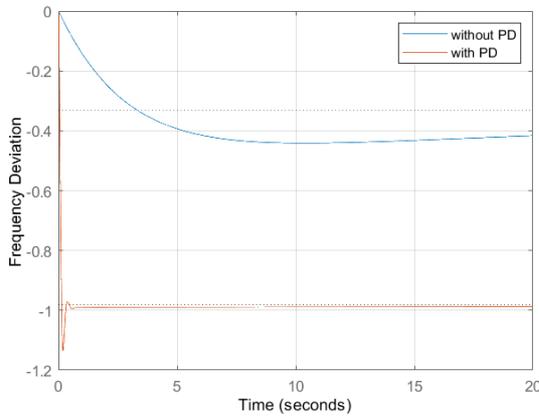


Figure 8. PD Controller LFC Transition Analysis Response to Load Input Without Droop Characteristics

The controller graph in Figure 8 is a PD controller without droop characteristics with a ($\tau = 0,05$) filter that fulfils the design criteria.
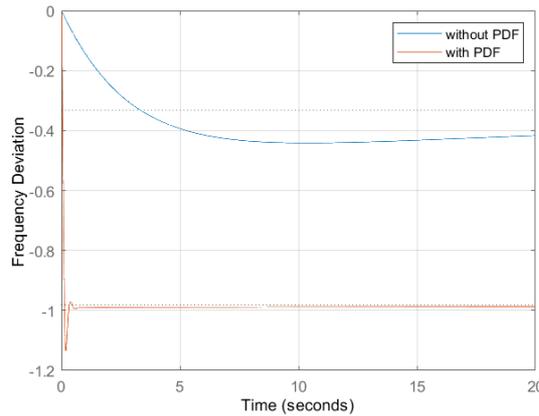


Figure 9. PDF Controller LFC Transition Analysis Response to Load Input Without Droop Characteristics ($\tau = 0,025$)

The controller graph in Figure 9 is a PDF controller without droop characteristics with a ($\tau = 0,05$) filter that fulfils the design criteria.

Table 7. Transition Analysis Information of Single Controller and Filter Hydraulic Types against Load Input without Droop Characteristics ($\tau$=0,075)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | 1.406 | 1.792 | **0.095** | 2.036 | **0.095** | 1.923 |
| $T_p$ | 5.485 | 4.150 | **0.218** | 4.726 | **0.218** | 4.453 |
| $T_s$ | 70.85 | 12.197 | **0.687** | 8.390 | **0.687** | 8.152 |
| $y_p$ | 0.785 | 1.184 | 1.214 | 1.087 | 1.214 | 1.122 |
| $M_p$ | **14.563** | 18.436 | 23.657 | **8.749** | 23.657 | **12.185** |

Based on Table 7, it can be seen that no controller fulfils the design criteria. At rise time, peak time, and steady state time only the PD and PDF controllers fulfil the parameters. This happens because these controllers are optimal in providing a fast response but are prone to uncontrolled *overshoot*. While the maximum pass

only P, PI, PID, and PIDF controllers fulfil the parameters. This is due to the presence of the Integral (I) component in reducing *overshoot* but not as fast as PD and PDF in reaching the initial response.

Table 8. Transition Analysis Information of Single Controller and Filter Hydraulic Types against Load Input without Droop Characteristics ($\tau$=0,1)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | 1.386 | 1.767 | **0.104** | 2.002 | **0.104** | 1.892 |
| $T_p$ | 5.429 | 4.165 | **0.244** | 4.680 | **0.244** | 4.426 |
| $T_s$ | 70.839 | 12.177 | **0.837** | 8.363 | **0.837** | 8.109 |
| $y_p$ | 0.786 | 1.190 | 1.272 | 1.090 | 1.272 | 1.126 |
| $M_p$ | **14.608** | 19.01 | 29.495 | **9.021** | 29.495 | **12.558** |

Based on Table 8, it can be seen that no controller fulfils the design criteria. At rise time, peak time, and steady state time only the PD and PDF controllers fulfil the parameters. This happens because these controllers are optimal in providing a fast response but are prone to uncontrolled *overshoot*. While the maximum pass only P, PI, PID, and PIDF controllers fulfil the parameters. This is due to the presence of the Integral (I) component in reducing *overshoot* but not as fast as PD and PDF in reaching the initial response.

Table 9. Information Analysis of Single Controller and Filter Type Hydraulic Transition against Load Input with *Droop* Characteristics ($\tau$=0,025)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | **0.125** | 140.13 | **0.125** | 140.14 | **0.125** | 140.13 |
| $T_p$ | **0.700** | 445.36 | **0.700** | 445.56 | **0.700** | 445.36 |
| $T_s$ | 81.607 | 274.39 | 81.617 | 274.4 | 81.607 | 274.39 |
| $y_p$ | 1.009 | 0.997 | 1.009 | 0.997 | 1.009 | 0.997 |
| $M_p$ | 63.831 | **0** | 63.831 | **0** | 63.831 | **0** |

Based on Table 9, it can be seen that none of the controllers fulfils the design criteria. At rise time and peak time only P, PD, PDF controllers fulfil the parameters. This happens because P, PD, PDF controllers are effective in providing fast response and fairly good stability. Unlike the PI, PID, PIDF controllers which only fulfil the maximum skip value. Thus, PI, PID, PIDF controllers excel in controlling overshoot due to the presence of integral components that are able to suppress oscillations but the initial response time is slower. At steady state time none of the controllers fulfils the parameters. This results in steady state errors remaining and requires additional controllers to overcome frequency deviation to remain in the Load Frequency Control system.

Table 10. Information Analysis of Single Controller and Filter Type Hydraulic Transition against Load Input with *Droop* Characteristics ($\tau$=0,05)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | **0.132** | 140.09 | **0.132** | 140.09 | **0.132** | 140.09 |
| $T_p$ | **0.633** | 627.96 | **0.633** | 628.24 | **0.633** | 627.96 |
| $T_s$ | 81.611 | 274.35 | 81.611 | 274.35 | 81.611 | 274.35 |
| $y_p$ | 1.024 | 0.999 | 1.024 | 0.999 | 1.024 | 0.999 |
| $M_p$ | 66.305 | **0** | 66.305 | **0** | 66.305 | **0** |

Based on Table 10, it can be seen that none of the controllers fulfils the design criteria. At rise time and peak time only P, PD, PDF controllers fulfil the parameters. This happens because P, PD, PDF controllers are effective in providing fast response and

fairly good stability. Unlike the PI, PID, PIDF controllers which only fulfil the maximum skip value. Thus, PI, PID, PIDF controllers excel in controlling overshoot due to the presence of integral components that are able to suppress oscillations but the initial response time is slower. At steady state time none of the controllers fulfils the parameters. This results in steady state errors remaining and requires additional controllers to overcome frequency deviation to remain in the Load Frequency Control system.

Table 11. Information Analysis of Single Controller and Filter Type Hydraulic Transition against Load Input with *Droop* Characteristics (τ=0,075)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | **0.142** | 140.04 | **0.142** | 140.05 | **0.142** | 140.04 |
| $T_p$ | **0.573** | 598.88 | **0.573** | 599.15 | **0.573** | 598.88 |
| $T_s$ | 81.614 | 274.3 | 81.614 | 274.31 | 81.614 | 274.3 |
| $y_p$ | 1.055 | 1.00 | 1.055 | 1.00 | 1.055 | 1.00 |
| $M_p$ | 71.201 | **0** | 71.201 | **0** | 71.201 | **0** |

Based on Table 11, it can be seen that none of the controllers fulfils the design criteria. At rise time and peak time only P, PD, PDF controllers fulfil the parameters. This happens because P, PD, PDF controllers are effective in providing fast response and fairly good stability. Unlike the PI, PID, PIDF controllers which only fulfil the maximum skip value. Thus, PI, PID, PIDF controllers excel in controlling overshoot due to the presence of integral components that are able to suppress oscillations but the initial response time is slower. At steady state time none of the controllers fulfils the parameters. This results in steady state errors remaining and requires additional controllers to overcome frequency deviation to remain in the Load Frequency Control system.

Table 12. Information Analysis of Single Controller and Filter Type Hydraulic Transition against Load Input with *Droop* Characteristics (τ=0,1)

| Transition | P | PI | PD | PID | PDF | PIDF |
|---|---|---|---|---|---|---|
| $T_r$ | **0.152** | 140 | **0.152** | 140 | **0.152** | 140 |
| $T_p$ | **0.572** | 553.13 | **0.572** | 553.39 | **0.572** | 553.13 |
| $T_s$ | 81.617 | 274.26 | 81.617 | 274.27 | 81.617 | 274.26 |
| $y_p$ | 1.094 | 0.999 | 1.094 | 0.999 | 1.094 | 0.999 |
| $M_p$ | 77.632 | **0** | 77.632 | **0** | 77.632 | **0** |

Based on Table 12, it can be seen that none of the controllers fulfils the design criteria. At rise time and peak time only P, PD, PDF controllers fulfil the parameters. This happens because P, PD, PDF controllers are effective in providing fast response and fairly good stability. Unlike the PI, PID, PIDF controllers which only fulfil the maximum skip value. Thus, PI, PID, PIDF controllers excel in controlling overshoot due to the presence of integral components that are able to suppress oscillations but the initial response time is slower. At steady state time none of the controllers fulfils the parameters. This results in steady state errors remaining and requires additional controllers to overcome frequency deviation to remain in the Load Frequency Control system.

## CONCLUSIONS

This study shows that the PD and PDF controllers exhibit faster and more stable response in the face of load changes, especially

without droop characteristics. The use of filters in the controllers improves the response and reduces overshoot, but the steady state time stability is not ideal with droop. Overall, PD and PDF controllers are more effective in maintaining frequency stability in hydraulic LFC systems especially in the face of sudden and large load changes.

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## NOMENCLATURE

| | |
|---|---|
| $\Delta\Omega$ | meaning of Frequency Change |
| H | meaning of Constant of Inertia |
| $\Delta P_L$ | meaning of Changes in Expenses |
| D | meaning of Load Damping Constant |
| R | meaning of *Speed Regulation* |
| $T_w$ | meaning of Hydraulic Turbine Time Constant |
| C | meaning of Controller |
| F | meaning of *Filter* |
| $T_r$ | meaning of Rising Time |
| $T_p$ | meaning of Peak Time |
| $T_s$ | meaning of Steady State Time |
| $y_p$ | meaning of Peak Value |
| $M_p$ | meaning of Maximum Leakage Rate |

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