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Research Article

Frequency Domain Analysis of Load Frequency Control Using PIDTune Model Standard

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A B S T R A C T

The load frequency control system aims to regulate the frequency in the electric power system at a normal value with a predetermined tolerance limit. In practice, the load frequency control system does not always operate optimally, therefore a controller is needed to be added to the load frequency control system. The controller designed is a variation of the combination of Proportional-Integral-Differential (PID) controllers with the standard model PIDTune method consisting of proportional (P) controller, proportional integral (PI) controller, proportional differential (PD) controller, Proportional Integral Differential (PID) controller, Proportional Differential controller with first-order filter on differential section (PDF), and Proportional Integral Differential controller with first-order filter on differential section (PIDF). This study is aiming to carry out simulation and analysis in the frequency domain and then analyze the robustness of the reheat type power frequency control system and then design a PID controller for the reheat type power frequency control system in basic configuration, filter configuration, feedback configuration, feedforward configuration, and cascade configuration using PIDtune Model Standard on Matlab software. From the results of simulation and analysis, the controller that complies the design criteria and can make the reheat type of load frequency control system work optimally based on frequency domain analysis and robustness analysis is a proportional-integral (PI) controller in a feedback configuration with gain margin (K_g) equals to 38.11 dB, phase margin (γ) equals to 59.6°, infinity bandwidth, peak resonance value (M_r) equals to 1.19, maximum sensitivity peak value (M_S) equals to 1.24, and complementary maximum sensitivity peak value (M_T) equals to 1.17.

INTRODUCTION

In this digital era, electrical energy is a major requirement in all of life aspects, so the availability of a good quality and continuous electrical energy is required. In order to comply the demand for electrical energy, it is necessary to have a stable and reliable electric power system operation. The quality and reliability of the operation of the electric power system is determined by the stability of the voltage and frequency generated by the generating unit [1]. Factors that affect the frequency value of the electric power system are the amount of power generated and the amount of load that exists. Frequency of the electric power system is in normal value when there is a balance between the real power output of the generator and the real power used by the load (load demand) [2]. The active and reactive power requirements of the power system are never stable due to the ever-changing consumer and industrial loads [3]. The normal frequency of the electric power system in Indonesia is 50 Hz with a tolerance limit of ±2% [4]. Larger frequency deviations will have detrimental effects on end consumers and can cause extensive damage to expensive equipment in industry [3]. The electric power frequency control system aims to maintain the frequency of the electric power system within predetermined limits.

In practice, the power frequency control system does not always work optimally. Therefore, it is necessary to have a controller added to the electric power frequency control system to improve its performance. One of the controllers that is commonly used by the industry today is the PID controller. PID controllers are commonly used by the industry because of their simplicity, good functionality, and ease of use [3], [5]. PID controller design can be done through simulation using Matlab software. One of many methods that can be used to design a PID controller in Matlab is by using the PIDtune Model Standard. PIDtune Model Standard is one of the continuous time PID controller representations in Matlab software. Variations of the controller in the PIDtune Model Standard consist of a proportional (P) controller, proportional integral (PI) controller, a proportional differential (PD) controller, a Proportional Integral Differential (PID) controller, a Proportional Differential controller with a first-order filter on the differential section (PDF), and a Proportional Integral Differential controller with a first-order filter on the differential section (PIDF).

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This study is aiming to carry out simulation and analysis in the frequency domain and robustness of the reheat type power frequency control system and to design a PID controller for the reheat type power frequency control system in basic configuration, filter configuration, feedback configuration, feedforward configuration, and cascade configuration using PIDtune Model Standard in Matlab software.

METHOD

The research begins with a mathematical modeling of the load frequency control system for reheat type then simulation and analysis of the system without a controller is carried out, next the criteria for designing controllers is determined, followed by controllers designing, and ended by simulation and analysis of systems with controller. Flowchart of the research is shown in Figure 1.

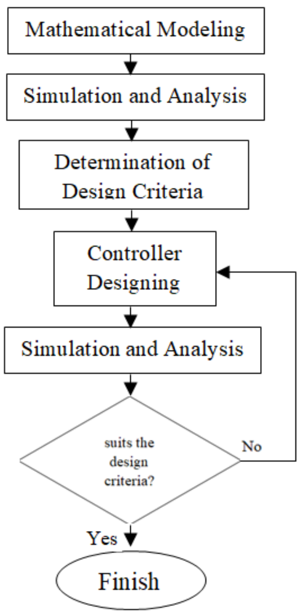

Figure 1. Flowchart of Research

Mathematic Modeling of Load Frequency Control

The Load frequency control system consists of a governor, turbine, and generator. The block diagram of the load frequency control system can be seen in Figure 2 [6].

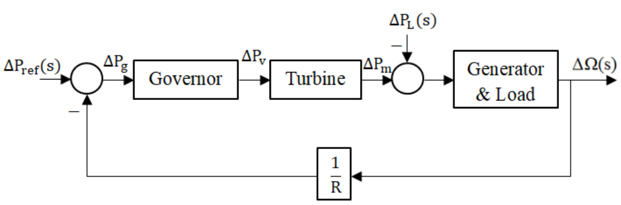

Figure 2. Block Diagram of Load Frequency Control [6]

Governor is a mechanical equipment that functions to regulate the rotation of an engine (turbine, diesel engine) by adjusting the amount of fluid inflow, be it gas, steam, or liquid into the turbine or into combustion chamber. The governor works by reading the parameters used to determine the opening of the control valve which aims to regulate and maintain the turbine rotation speed [7]. The equation of the governor transfer function is shown in equation (1) [6].

$$\Delta P_V(s) = \frac{1}{1+T_g}\Delta P_g(s) \tag{1}$$

Turbine, also known as prime mover, is a generator driving machine that converts primary energy (fuel or hydropower potential) into mechanical energy driving the generator [8]. Based on the type of fluid used and how it works, turbine is divided into several types, including reheat, non-reheat, and hydraulic turbines. Reheat turbine is a steam turbine which consists of several levels and is used to process reheated steam which is usually found in thermal generating units with large capacity. Parameter of the reheat turbine consist of the percentage of energy generated in the reheat section (F_{HP}), time constant of the reheat turbine (T_{RH}), and the non-reheat turbine time constant (T_{CH}) that is usually in the range of 0.2 to 20 s. Equation of the reheat turbine (G_R) transfer function is shown in equation (2) [9].

$$G_R(s) = \frac{F_{HP}T_{RH}s+1}{(T_{RH}s+1)(T_{CH}s+1)} \tag{2}$$

Generator is an equipment that functions to convert mechanical energy into electrical energy. Parameter of the generator consist of generator inertia constant (H) and the load damping coefficient in percent or the percentage change in load that is divided by the percentage change in frequency (D). The transfer function equation of the generator and load is shown in equation (3) [6].

$$\frac{1}{2Hs+D} \tag{3}$$

The closed-loop transfer function equation for the reheat-type load frequency control system based on the block diagram in Figure 2 with $\Delta P_L = 0$ is as follows in equation (4) and (5)

$$\frac{\Delta\Omega(s)}{\Delta P_{ref}(s)} = \frac{(1+F_{HP}T_{RH}s)}{(2Hs+D)(1+T_G s)(1+T_{CH}s)(1+T_{RH}s)+\left(\frac{1+sF_{HP}T_{RH}}{R}\right)} \tag{4}$$

$$\frac{\Delta\Omega(s)}{\Delta P_{ref}(s)} = \frac{as+1}{bs^4+cs^3+ds^2+es+f} \tag{5}$$

Where:

$$a = F_{HP}T_{RH}$$
$$b = 2HT_G T_{RH} T_{CH}$$
$$c = 2HT_{RH}T_{CH} + 2HT_G T_{RH} + 2HT_G T_{CH} + T_G T_{RH} T_{CH} D$$
$$d = 2HT_{RH} + 2HT_{CH} + 2HT_G + T_{RH}T_{CH}D + T_G T_{RH} D + T_G T_{CH} D$$
$$e = 2H + T_{RH}D + T_{CH}D + T_G D + \frac{F_{HP}T_{RH}}{R}$$
$$f = D + \frac{1}{R}$$

and equation for the open loop transfer function is as follows in equation (6) and (7)

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$$G(s)H(s)=\frac{1+sF_{HP}T_{RH}}{(2Hs+D)(1+T_Gs)(1+T_{CH}s)(1+T_{RH}s)}\frac{1}{R} \quad (6)$$

$$G(s)H(s)=\frac{as+1}{bs^4+cs^3+ds^2+es+f} \quad (7)$$

Where

$a=F_{HP}T_{RH}$

$b=2HRT_GT_{RH}T_{CH}$

$c=R(2HT_{RH}T_{CH}+2HT_GT_{RH}+2HT_GT_{CH}+T_GT_{RH}T_{CH}D)$

$d=R(2HT_{RH}+2HT_{CH}+2HT_G+T_{RH}T_{CH}D+T_GT_{RH}D+T_GT_{CH}D)$

$e=R(2H+T_{RH}D+T_{CH}D+T_GD)$

$f=RD$

Analysis of System Without Controller and Controller Designing Criteria

The transfer function of the reheat type frequency control system is simulated using Matlab software with the following parameter data included in Table 1.

Table 1. Parameter Value of Reheat Type Load Frequency Control System

Parameter	Value
R	0.05
T_G	0.2 s
F_{HP}	0.3
T_{RH}	7 s
T_{CH}	0.3 s
H	5
D	1

Analysis that is used in the simulation of the reheat load frequency control system consists of frequency domain analysis for the open loop transfer function, frequency domain analysis for the closed loop transfer function, and robustness analysis.

Parameters that are considered in the frequency domain analysis for the open-loop transfer function are gain margin (K_g), frequency of the gain margin, phase margin (γ), and frequency of the phase margin. Gain margin is the amount of gain a system can increase before instability occurs if the phase angle is constant at 180° [10]. The equation of the gain margin is shown in equation (8) and (9) [11].

$$K_g=\frac{1}{\left|G(j\omega_1)\right|} \quad (8)$$

in decibels,

$$K_gdB=20\log K_g=-20\log\left|G(j\omega_1)\right| \quad (9)$$

The phase margin is the amount of phase angle that can be changed before instability occurs if the gain is maintained unity [11]. The equation of the phase margin is shown in equation (10).

$$\gamma=180°+\phi \quad (10)$$

In the frequency domain analysis for the closed loop transfer function, parameters to be considered are the peak resonance value (M_r), frequency of the peak resonance (ω_r), and bandwidth (BW). The peak resonance value (M_r) provides information about the relative stability of the system. The value of the resonance peak is proportional to the overshoot in the transient response [12]. The equation of the peak resonance value (M_r) is shown in equation (11)

$$M_r=\frac{1}{2\zeta\sqrt{1-\zeta^2}} \quad (11)$$

Frequency of the peak resonance (ω_r) is the frequency when the peak resonance occurs. A high value of ω_r indicates that the response time of the output is faster due to the peak time (t_p) in the transient response is inversely equal to ω_r [12].

Bandwidth (BW) is the frequency range where the value of magnitude M in dB is not less than -3 dB. The equation of the bandwidth (BW) is shown in equation (12).

$$BW=\omega_c=\omega_n\left\{\left(1-2\zeta^2\right)+\sqrt{4\zeta^4-4\zeta^2+2}\right\}^{0.5} \quad (12)$$

In the robustness analysis, there is a criterion for the maximum peak value which consists of the maximum sensitivity peak value (MS) and the complementary maximum sensitivity peak value (MT). The equation of the maximum sensitivity peak value (M_S) is shown in equation (13) [13].

$$M_S=\max_{\omega}\left|S(j\omega)\right| \quad (13)$$

and the equation of the complementary maximum sensitivity peak value (M_T) is shown in equation (14) [13].

$$M_T=\max_{\omega}\left|T(j\omega)\right| \quad (14)$$

The controller design criterion in the frequency domain analysis is that it is hoped that the system will provide a gain margin (Kg) greater than 6 dB, phase margin (γ) gives value between 30° and 60°, bandwidth (BW) of the system with controller is greater than the bandwidth of the system without controller, and the peak resonance value ranges from 1 to 1.5 [11]. In robustness analysis, the peak sensitivity (M_S) value is less than 2 and the peak maximum complementary sensitivity (M_T) value is less than 1.25.

Controller Designing

The design of the controller is carried out through a simulation using a continuous time PID controller representation in Matlab software which is known as the PIDtune standard model. The controller used is a combination of PID (Proportional-Integral-Derivative) controllers consisting of proportional controller (P), proportional integral controller (PI), proportional differential controller (PD), Proportional Integral Differential controller (PID), Proportional Differential controller with first order filter on differential section (PDF), and Proportional Integral Differential controller with first order filter on differential section

(PIDF). Equation of the PIDtune standard model is shown in equation (15) [14].

$$C = K_P \left(1 + \frac{1}{T_i s} + \frac{T_d s}{\frac{T_d}{N} s + 1} \right) \tag{15}$$

Where:

K_p = Proportional Gain
T_i = Integral Time
T_d = Derivative Time
N = First-order Derivative Filter Divisor

Simulation and Analysis of System Using Controller

Systems with controllers are simulated in several configurations that are basic, filter, feedback, feedforward, and cascade configurations. System configuration consists of prefilter (F), controller (C), plant (G), and components on the feedback line (H) [15]. The system configuration used is shown in the following figures, Figure 3 for basic configuration, Figure 4 for filter configuration, Figure 5 for feedback configuration, Figure 6 for feedforward configuration, and Figure 7 for cascade configuration.

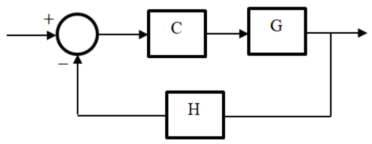

Figure 3. Basic Configuration

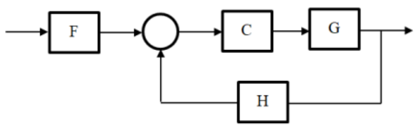

Figure 4. Filter Configuration

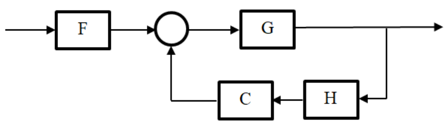

Figure 5. Feedback Configuration

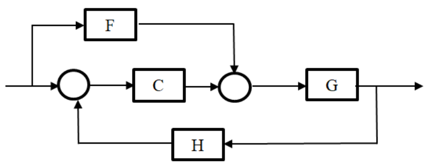

Figure 6. Feedforward Configuration

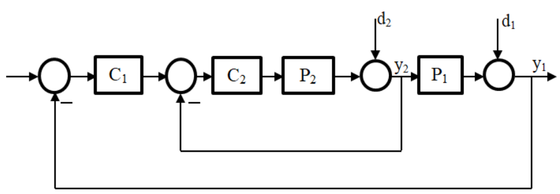

Figure 7. Cascade Configuration [16]

In the reheat type of the load frequency control system, plant (G) consists of a governor, reheat type turbine, generator and speed droop 1/R on the feedback line (H).

RESULTS AND DISCUSSION

Simulation Results of System Using the P Controller

Frequency Domain Analysis on Open Loop Transfer Function

Table 2. Frequency Domain Analysis of Open Loop Transfer Function with P Controller

Config.	K_g	K_g (dB)	γ(°)	ω K_g	ω γ
Without Controller	12.224	21.744	55.841	3.8392	0.68647
Basic	20.101	26.064	59.98	3.8392	0.47655
Filter	11.909	21.517	57.263	2.8171	0.47616
Feedback	11.909	21.517	57.263	2.8171	0.47616
Feed-forward	0.094746	-20.469	-126.72	0	0.41117
Cascade	0.10633	-19.467	-61.072	8.8271	18.787

Based on the design criteria for frequency domain analysis of open loop transfer function, system configurations with P controller that meet the criteria are basic, filter, and feedback configurations.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 3. Frequency Domain Analysis of Closed Loop Transfer Function with P Controller

Configuration	BW (rad/s)	M_r	M_r (dB)	ω_r (rad/s)
Without Controller	1.1594	0.05732	-24.833	0.49034
Basic	0.75776	0.05395	-25.36	0.34344
Filter	0.75596	0.05392	-25.365	0.343
Feedback	0.5225	0.08122	-21.807	0.24731
Feedforward	5.5178	58.215	35.301	3.8311
Cascade	21.334	0.06389	-23.891	14.395

Based on the design criteria for frequency domain analysis of closed loop transfer function, there is no system configuration with P controller that meets the criteria.

Robustness Analysis

Table 4. Robustness Analysis with P Controller

Config.	M_S	M_T	K_g	K_g (dB)	γ
Without Controller	1.0128	0.05732	79.197	37.974	59.166
Basic	23.79	23.332	1.0439	0.37301	2.4086
Filter	22.528	21.787	1.0465	0.39438	2.5435
Feedback	1.275	0.34369	4.6358	13.322	46.176
Feedforward	58.839	58.215	1.0173	0.14889	0.97378
Cascade	1.0008	0.0639	1	0	0.97378

Based on the design criteria for robustness analysis, system configurations with P controller that meet are feedback and cascade configurations.

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Simulation Results of System Using the PI Controller

Frequency Domain Analysis on Open Loop Transfer Function

Table 5. Frequency Domain Analysis of Open Loop Transfer Function with PI Controller

Configuration	K_g	K_g (dB)	γ (°)	ω K_g	ω γ
Without Controller	12.224	21.744	55.841	3.8392	0.68647
Basic	135.95	42.668	60.001	3.7312	0.12935
Filter	80.41	38.106	59.261	2.7268	0.12934
Feedback	80.41	38.106	59.261	2.7268	0.12934
Feedforward	Inf	Inf	-154.96	Inf	0.1203
Cascade	1.3983	2.9118	0.45641	1.1692	0.99193

Based on the design criteria for frequency domain analysis of open loop transfer function, system configurations with PI controller that comply are filter and feedback configurations.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 6. Frequency Domain Analysis of Closed Loop Transfer Function with PI Controller

Configuration	BW (rad/s)	M_r	M_r (dB)	ω_r (rad/s)
Without Controller	1.1594	0.05732	-24.833	0.49034
Basic	0.19083	0.0529	-25.531	0.0925
Filter	0.1908	0.0529	-25.531	0.09248
Feedback	Inf	1.1914	1.521	0.03761
Feedforward	5.6841	0.86578	-1.2519	0.85116
Cascade	1.5491	6.278	15.956	0.992

Based on the design criteria for frequency domain analysis of closed loop transfer function, system configuration with a PI controller that meets the criteria is feedback configuration.

Robustness Analysis

Table 7. Robustness Analysis with PI Controller

Configuration	M_S	M_T	K_g	K_g (dB)	γ
Without Controller	1.0128	0.05732	79.197	37.974	59.166
Basic	1.0226	0.0685	45.298	33.122	58.545
Filter	1.0267	0.06826	38.392	31.685	58.284
Feedback	1.2394	1.1689	5.1766	14.281	47.583
Feedforward	1.3688	0.86578	3.7119	11.392	42.852
Cascade	6.4491	6.278	1	0	42.852

Based on the design criteria for robustness analysis, system configurations with PI controller that meet the criteria are basic, filter, feedback, and feedforward configurations.

Simulation Results of System Using the PD Controller

Frequency Domain Analysis on Open Loop Transfer Function

Table 8. Frequency Domain Analysis of Open Loop Transfer Function with PD Controller

Config.	K_g	K_g (dB)	γ (°)	ω K_g	ω γ
Without Controller	12.224	21.744	55.841	3.8392	0.68647
Basic	Inf	Inf	60	Inf	2.3982
Filter	5.4034	14.653	47.173	6.9328	2.3452
Feedback	5.4034	14.653	47.173	6.9328	2.3452
Feed-forward	0.01239	-38.139	-119.57	0	2.2204
Cascade	Inf	Inf	3.8966	Inf	75.66

Based on the design criteria for frequency domain analysis of open loop transfer function, system configurations with PD controller that meet are basic, filter, and feedback configurations.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 9. Frequency Domain Analysis of Closed Loop Transfer Function with PD Controller

Configuration	BW (rad/s)	M_r	M_r (dB)	ω_r (rad/s)
Without Controller	1.1594	0.05732	-24.833	0.49034
Basic	3.886	0.05416	-25.327	1.1926
Filter	3.6773	0.0538	-25.384	1.0811
Feedback	2.689	0.01161	-38.705	0.30438
Feedforward	23.437	0.16654	-15.57	15.988
Cascade	113.85	0.73609	-2.6614	75.766

Based on the design criteria for frequency domain analysis of closed loop transfer function, there is no system configuration with PD controller that meets the criteria.

Robustness Analysis

Table 10. Robustness Analysis with PD Controller

Configuration	M_S	M_T	K_g	K_g (dB)	γ
Without Controller	1.0128	0.05732	79.197	37.974	59.166
Basic	1.0764	0.1695	14.092	22.98	55.358
Filter	1.0774	0.09049	13.921	22.873	55.302
Feedback	1.0012	0.01162	827.57	58.356	59.92
Feedforward	1.0762	0.16654	14.126	23	55.369
Cascade	1.4374	0.73609	1	0	55.369

Based on the design criteria for robustness analysis, all system configurations with PD controller meet the criteria of robustness analysis.

Simulation Results of System Using the PID Controller

Frequency Domain Analysis on Open Loop Transfer Function

Table 11. Frequency Domain Analysis of Open Loop Transfer Function with PID Controller

Config.	K_g	K_g (dB)	γ (°)	ω K_g	ω γ
Without Controller	12.224	21.744	55.841	3.8392	0.68647
Basic	Inf	Inf	64.631	Inf	0.12935
Filter	130.97	42.343	63.89	9.0454	0.12934
Feedback	130.97	42.343	63.89	9.0454	0.12934
Feed-forward	71.636	37.103	-150.34	1.8453	0.11722
Cascade	Inf	Inf	85.508	Inf	2.7201

Based on the design criteria for frequency domain analysis of open loop transfer function, there is no system configuration with PID controller that complied.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 12. Frequency Domain Analysis of Closed Loop Transfer Function with PID Controller

Configuration	BW (rad/s)	M_r	M_r (dB)	ω_r (rad/s)
Without Controller	1.1594	0.05732	-24.833	0.49034
Basic	0.17377	0.05237	-25.619	0.07671
Filter	0.17375	0.05237	-25.619	0.0767
Feedback	Inf	1.1835	1.4634	0.04043
Feedforward	5.6399	0.63892	-3.8911	0.29791
Cascade	1.1594	0.05732	-24.833	0.49034

Based on the design criteria for frequency domain analysis of closed loop transfer function, system configuration with a PID controller that meets is a system in feedback configuration.

Robustness Analysis

Table 13. Robustness Analysis with PID Controller

Configuration	M_S	M_T	K_g	K_g (dB)	γ
Without Controller	1.0128	0.05732	79.197	37.974	59.166
Basic	1.0077	0.05275	130.53	42.314	59.494
Filter	1.0128	0.05273	79.025	37.955	59.165
Feedback	1.0153	0.79465	66.397	36.443	59.006
Feedforward	1.0634	0.63893	16.779	24.495	56.095
Cascade	1.0094	0.05469	1	0	56.095

Based on the design criteria for robustness analysis, all system configurations with PID controller meet the criteria of robustness analysis.

Simulation Results of System Using the PDF Controller

Frequency Domain Analysis on Open Loop Transfer Function

Table 14. Frequency Domain Analysis of Open Loop Transfer Function with PDF Controller

Config.	K_g	K_g (dB)	γ (°)	ω K_g	ω γ
Without Controller	12.224	21.744	55.841	3.8392	0.68647
Basic	16.381	24.287	64.746	15.101	2.3982
Filter	4.2814	12.632	52.054	6.5078	2.3387
Feedback	4.2814	12.632	52.054	6.5078	2.3387
Feed-forward	0.01403	-37.06	-114.29	0	2.1951
Cascade	1.6074	4.1226	4.1602	99.266	79.028

Based on the design criteria for frequency domain analysis of open loop transfer function, system configurations with PDF controller that comply are filter and feedback configurations.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 15. Frequency Domain Analysis of Closed Loop Transfer Function with PDF Controller

Configuration	BW (rad/s)	M_r	M_r (dB)	ω_r (rad/s)
Without Controller	1.1594	0.05732	-24.833	0.49034
Basic	4.069	0.05282	-25.545	0.75967
Filter	3.7778	0.05267	-25.569	0.72912
Feedback	2.0513	0.0131	-37.656	0
Feedforward	23.268	0.79766	-1.9636	16.49
Cascade	120.71	0.69435	-3.1684	79.372

Based on the design criteria for frequency domain analysis of closed loop transfer function, there is no system configuration with PDF controller that complied.

Robustness Analysis

Table 16. Robustness Analysis with PDF Controller

Configuration	M_S	M_T	K_g	K_g (dB)	γ
Without Controller	1.0128	0.05732	79.197	37.974	59.166
Basic	1.3304	0.80553	4.0264	12.098	44.15
Filter	1	0.41779	Inf	Inf	60
Feedback	1.0007	0.01314	1387.4	62.844	59.952
Feedforward	1.3192	0.79766	4.1327	12.325	44.545
Cascade	1.4359	0.69435	1	0	44.545

Based on the design criteria for robustness analysis, all system configurations with PDF controller meet the criteria.

Simulation Results of System Using the PIDF Controller

Frequency Domain Analysis on Open Loop Transfer Function

Table 17. Frequency Domain Analysis of Open Loop Transfer Function with PIDF Controller

Config.	K_g	K_g (dB)	γ (°)	ω K_g	ω γ
Without Controller	12.224	21.744	55.841	3.8392	0.68647
Basic	63.489	36.054	68.995	4.6999	0.12935
Filter	37.859	31.563	68.255	3.4785	0.12934
Feedback	37.859	31.563	68.255	3.4785	0.12934
Feed-forward	Inf	Inf	-145.95	Inf	0.11369
Cascade	8.733	18.823	78.599	12.652	2.71

Based on the design criteria for frequency domain analysis of open loop transfer function, there is no system configuration with PID controller that complied.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 18. Frequency Domain Analysis of Closed Loop Transfer Function with PIDF Controller

Configuration	BW (rad/s)	M_r	M_r (dB)	ω_r (rad/s)
Without Controller	1.1594	0.05732	-24.833	0.49034
Basic	0.16623	0.0515	-25.763	0.06771
Filter	0.16621	0.0515	-25.763	0.0677
Feedback	Inf	1.0307	0.26258	0.03995
Feedforward	6.3213	0.57732	-4.7717	0.21214
Cascade	5.0397	0.05497	-25.197	0.55488

Based on the design criteria for frequency domain analysis of closed loop transfer function, the system configuration with a PID controller that complies is a feedback configuration.

Robustness Analysis

Table 19. Robustness Analysis with PIDF Controller

Configuration	M_S	M_T	K_g	K_g (dB)	γ
Without Controller	1.0128	0.05732	79.197	37.974	59.166
Basic	1.0427	0.07308	24.431	27.759	57.31
Filter	1.0501	0.07047	20.961	26.428	56.868
Feedback	1.0398	0.66856	26.14	28.346	57.485
Feedforward	1.2464	0.57732	5.0584	14.08	47.301
Cascade	1.0162	0.05497	1	0	47.301

Based on the design criteria for robustness analysis, all system configurations with PIDF controller meet the criteria.

Results of Load Frequency Control System Analysis for All Controllers

Frequency Domain Analysis on Open Loop Transfer Function

Table 20. Frequency Domain Analysis Results on Open Loop Transfer Function for All Controllers and Configurations.

Configuration	Controller					
	P	PI	PD	PID	PDF	PIDF
Basic	✓	×	✓	×	×	×
Filter	✓	✓	✓	×	✓	×
Feedback	✓	✓	✓	×	✓	×
Feedforward	×	×	×	×	×	×
Cascade	×	×	×	×	×	×

Based on simulation results, the design criteria for the frequency domain analysis of the open loop transfer function are fulfilled by the P and PD controllers in basic configuration as well as the P, PI, PD, and PDF controllers in filter and feedback configurations.

Frequency Domain Analysis on Closed Loop Transfer Function

Table 21. Frequency Domain Analysis Results on Closed Loop Transfer Function for All Controllers and Configurations.

Configuration	Controller					
	P	PI	PD	PID	PDF	PIDF
Basic	×	×	×	×	×	×
Filter	×	×	×	×	×	×
Feedback	×	✓	×	✓	×	✓
Feedforward	×	×	×	×	×	×
Cascade	×	×	×	×	×	×

Based on simulation results, the design criteria for frequency domain analysis of closed loop transfer function are met by PI, PID, and PIDF controllers in feedback configuration.

Robustness Analysis

Table 22. Robustness Analysis Results for All Controllers and Configurations.

Configuration	Controller					
	P	PI	PD	PID	PDF	PIDF
Basic	×	✓	✓	✓	✓	✓
Filter	×	✓	✓	✓	✓	✓
Feedback	✓	✓	✓	✓	✓	✓
Feedforward	×	✓	✓	✓	✓	✓
Cascade	✓	×	✓	✓	✓	✓

Based on simulation results, the design criteria for robustness analysis are met by the P controller in feedback and cascade configurations; systems with PI controllers other than cascade configurations; and PD, PID, PDF, and PIDF controllers in all configurations.

CONCLUSIONS

In the reheat type of load frequency control system, controller that provides more optimal performance and meets all the design criteria in the frequency domain analysis of the open loop transfer function, frequency domain analysis on closed loop transfer function, and robustness analysis is the PI controller with feedback configuration for power input reheat model system with droop characteristics.

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NOMENCLATURE

ΔP_V	The change position of the input steam valve
ΔP_{ref}	Reference set power
T_g	Time constant of the governor
ΔP_g	Difference between ΔP_{ref} and power ($\Delta\Omega / R$)
F_{HP}	The percentage of energy generated in the reheat section
T_{RH}	Time constant of the reheat turbine
T_{CH}	The non-reheat turbine time constant that is usually in the range of 0.2 to 20 s
D	The load damping coefficient in percent or the percentage change in load that is divided by the percentage change in frequency
H	Generator inertia constant
R	Governor speed regulation that is usually measured in Hz/MW
K_g	Gain margin
$G(j\omega_1)$	Equation of the open loop transfer function of the system in the frequency domain at the phase crossover frequency
γ	Phase margin
M_r	Resonance peak value
ω_r	Frequency of the resonance peak
ϕ	Phase angle of the system at *gain crossover frequency*
ζ	Damping ratio
ω_n	Natural frequency
BW	*Bandwidth*
$S(j\omega)$	Sensitivity transfer function in the frequency domain
$T(j\omega)$	Complementary sensitivity transfer function in the frequency domain
M_S	The sensitivity maximum peak value
M_T	Complementary sensitivity maximum peak value