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ROBUST H∞ POWER SYSTEM STABILIZER DEVELOPMENT USING LINEAR MATRIX INEQUALITY TECHNIQUE FOR ENHANCED STABILITY OF THE NIGERIAN 330 KV TRANSMISSION NETWORK

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ABSTRACT

This paper presents the development of a robust H∞ Power System Stabilizer (PSS) using a Linear Matrix Inequality (LMI) approach to enhance the dynamic stability of the Nigerian 330 kV transmission network. A detailed 54-bus, 13-generator multi-machine model was developed using real network data and linearised around its operating point obtained through Newton–Raphson load flow analysis. The H∞ control problem was formulated using a mixed-sensitivity framework and solved as an LMI optimisation problem to obtain a centralised dynamic output-feedback controller. The controller was evaluated under small-signal disturbances using time-domain and frequency-domain analyses. Simulation results demonstrated significant improvements in system damping, voltage regulation, and oscillation suppression. The minimum damping ratio was substantially increased, rotor speed deviations were reduced from ±0.05 p.u. to below ±0.02 p.u., and settling times were improved to approximately 3 to 5 seconds. Furthermore, voltage violations observed in the uncompensated network were effectively mitigated, with most bus voltages maintained within acceptable operating limits. The results confirm that the LMI-based H∞ PSS provides superior robustness and stability enhancement compared with conventional stabiliser approaches, making it a viable solution for improving the reliability and operational security of the Nigerian interconnected power system.

KEYWORDS: H∞ Controller, Power System Stabilizer, Linear Matrix Inequality, Nigeria 330 kV Network, Small-Signal Stability.

1.0 INTRODUCTION

The Nigerian power sector faces significant challenges affecting the stability, reliability, and efficiency of the electrical grid, particularly within the 330 kV transmission network (Ogbonna et al., 2021). Rapid industrialisation, urbanisation, and population growth have led to a substantial rise in electricity demand, placing considerable strain on existing infrastructure (Adejumobi et al., 2019). The grid is highly susceptible to disturbances such as load fluctuations, generator outages, and transmission faults, resulting in voltage instability, low-frequency oscillations, and the risk of system collapse (Abdullahi et al., 2020; Etim et al., 2021).

Power System Stabilizers (PSS) play a critical role in enhancing power system stability by regulating the excitation of synchronous generators to damp oscillations and maintain stable voltage and frequency profiles (Oladokun et al., 2021). Despite their importance, conventional PSS designs based on simplified system models often exhibit limited robustness and adaptability under varying operating conditions, particularly in complex systems like Nigerian 330 kV Multi-Machine Transmission Network (Ogundele et al., 2019; Abdullahi et al., 2020). The Linear Matrix Inequality (LMI) approach has emerged as a powerful method for designing robust controllers with guaranteed stability and performance, enabling the incorporation of system uncertainties and parameter variations into the controller design process (Zhao et al., 2020). Although studies have demonstrated the effectiveness of LMI-based PSS, their application to the Nigerian grid remains limited, creating a clear research gap (Oladokun et al., 2021; Ogujor et al., 2020).

This paper addresses this gap by developing a robust $H\infty$ PSS optimised via LMI for the Nigerian 330 kV network. The specific contributions of this paper are: (i) formulation and solution of the $H\infty$ PSS design as an LMI optimisation problem with mixed-sensitivity weighting; (ii) comprehensive evaluation of the proposed controller against conventional PSS methods in both time- and frequency-domain; and (iii) quantification of stability improvement using damping ratio, settling time, rotor speed deviation, and voltage regulation metrics.

2.0 Literature Review

Power system stability refers to the ability of a power system to maintain synchronism and acceptable voltage levels following a disturbance (Liu & He, 2023). It is broadly categorised into transient stability (response within milliseconds to a few seconds), small-signal stability (response to small perturbations over seconds to minutes), and voltage stability (maintenance of acceptable voltage under diverse operational conditions) (Li et al., 2023; Abubakar et al., 2021; Milano et al., 2023). These categories provide the analytical basis for assessing how a network such as Nigeria's 330 kV grid responds to routine and abnormal disturbances.

Within the Nigerian context, several studies have documented the specific stresses placed on the transmission network. Ogbonna et al. (2021) and Adejumobi et al. (2019) identify infrastructural strain arising from rapid demand growth as a persistent threat to grid stability, while Abdullahi et al. (2020) and Etim et al. (2021) report recurring voltage instability and low-frequency oscillations linked to load fluctuations, generator outages, and transmission faults. The Nigerian Electricity Regulatory Commission (2020) and the Transmission Company of Nigeria (2021) further note that demand growth projections continue to outpace planned network reinforcement, reinforcing the need for controller-level solutions that can be deployed on the existing network topology.

The Power System Stabiliser (PSS) remains the principal tool for damping electromechanical oscillations by supplementing the Automatic Voltage Regulator (AVR) with a stabilising excitation signal (Oladokun et al., 2021; Taborda et al., 2023). However, conventional PSS designs are typically tuned around a single linearised operating point using fixed lead-lag compensation, and consequently exhibit limited robustness and adaptability when operating conditions deviate from the design point; a recurring limitation in complex, weakly interconnected systems such as Nigerian 330 kV Multi-Machine Transmission Network (Ogundele et al., 2019; Abdullahi et al., 2020; Jamil et al., 2020).

Robust control techniques, particularly those based on $H\infty$ optimisation and Linear Matrix Inequalities (LMI), have emerged as an effective means of overcoming these limitations by explicitly incorporating system uncertainty and disturbance bounds into the controller synthesis process (Zhao et al., 2020; Caverly & Forbes, 2023; Skogestad & Postlethwaite, 2024). The mixed-sensitivity $H\infty$ formulation, solved via the bounded real lemma as a convex LMI feasibility problem, has been successfully applied to multi-machine PSS design by Li and Zhang (2019), Naderi et al. (2020), and Huang et al. (2024), each reporting improved damping and disturbance rejection over conventional stabilisers. Despite this demonstrated effectiveness, none of these studies addressed the specific structural and operational characteristics of the Nigerian 330 kV multi-machine network, leaving a clear gap that motivates the present study (Oladokun et al., 2021; Ogujor et al., 2020).

3.0 MATERIALS AND METHODS

3.1 System Description

The Nigerian 330 kV transmission network has a 54-bus, 13-generator system (TCN, 2021). A Newton–Raphson load flow analysis was conducted to establish the steady-state operating point used for subsequent controller linearisation. The thirteen generating stations included in the model, together with their rated capacities, are: Egbin (1,320 MVA), Sapele (400 MVA), Delta (900 MVA), Afam (1,000 MVA), Shiroro (600 MVA), Kainji (760 MVA), Jebba (578 MVA), Olorunsogo (750 MVA), Omotosho (700 MVA), Alaoji (500 MVA), Geregu (810 MVA), Okpai (1,000 MVA), and Zungeru (700 MVA). Each generator was represented using the IEEE Type ST1A excitation system (Ka = 95–120, Ta = 0.04–0.06 s) together with a two-axis sub-transient generator model.

3.2 Power System Model

Synchronous Generator Dynamic Model

Each synchronous generator was represented in the d-q axis two-axis model. Four governing electromechanical equations describe generator behaviour: the rotor angle dynamics, which represent the variation of rotor angular position with respect to the synchronous reference frame and determine the generator's synchronism with the network; the swing equation, which balances mechanical and electrical torque to determine rotor acceleration or deceleration during disturbances; the governor dynamics, which regulate mechanical input torque in response to speed deviations; and the AVR dynamics, which regulate the field voltage in response to terminal voltage errors. Together these equations provide a comprehensive representation of generator behaviour for transient stability, frequency control, voltage regulation, and dynamic simulation studies.

The rotor angle equation is given as:

$$\frac{d\delta}{dt} = \omega - \omega_s \quad \text{... (1)}$$

δ = rotor angle (rad)

ω = rotor angular speed (rad/s)

ω_s = synchronous angular speed (rad/s)

The swing equation, governing rotor motion, is given as:

$$\frac{2H}{\omega_s}\frac{d\delta}{dt} = T_M - T_e - D(\omega - \omega_s) \quad \text{... (2)}$$

H = inertia constant (s)

T_M = *mechanical torque supplied by the prime mover (p.u)*

T_e = *electrical torque produced by the generator (p.u)*

D = damping coefficient

ω = rotor speed (rad/s)

ω_s = *synchronous speed (rad/s)*

The governor dynamics are described by:

$$\frac{dT_m}{dt} = \frac{1}{T_g}\left(T_{m2} - T_m - \frac{\omega_r - \omega_s}{R_{gov}}\right) \frac{dT_m}{dt} = \frac{1}{T_g}\left(T_{m2} - T_m - \frac{\omega_r - \omega_s}{R_{gov}}\right) \quad \text{... (3)}$$

T_m = *mechanical torque output of the governor/turbine*

T_{m2} = *governor torque reference*

T_g = *governor time constant (s)*

R_{gov} = *speed droop coefficient*

ω_r = *rotor speed*

ω_s = *synchronous speed*

The AVR dynamics, regulating the excitation voltage to control generator terminal voltage, are described by:

$$\frac{dE_{fd}}{dt} = \frac{1}{T_a}\left(K_a E_t - K_a V_{ref} - E_{fd}\right) \quad \text{... (4)}$$

Linearised State-Space Representation

The nonlinear multi-machine model was linearised at the operating point to yield a 52-state linear time-invariant (LTI) system:

$$\dot{x}(t) = Ax(t) + Bu(t) + \Gamma p(t) \quad \text{... (5)}$$

with the measured output expressed as:

$$y(t) = Cx(t) \quad \text{... (6)}$$

$$y(t) = \Delta\omega(t) = [\Delta\omega_1(t), \Delta\omega_2(t), \ldots, \Delta\omega_{13}(t)]^T \quad \text{... (7)}$$

where y is the measured output comprising the rotor speed deviations of all thirteen generators. The disturbance matrix Γ was constructed such that disturbances entered only the speed-derivative rows of the swing equations. With an average generator inertia H ≈ 5 s:

$$\Gamma_{(i,j)} = \begin{cases} \frac{1}{2H_j}, & \text{if row } i \text{ corresponded to } \Delta\dot{\omega}_j \\ 0, & \text{otherwise} \end{cases} \quad \text{... (8)}$$

where the entry applies to row i corresponding to Δωj.

3.3 LMI-Based H-infinity Controller Design

3.3.1 H-infinity Control

H∞ optimal control minimises the worst-case disturbance amplification across all frequencies. The H∞ performance objective requires the closed-loop transfer matrix from the disturbance w to the performance output z, T_{wz}, to satisfy:

$$\| T_{wz} \|_{\infty} < \gamma \quad \text{... (9)}$$

where γ is the disturbance attenuation level to be minimised. This framework provides a frequency-domain guarantee of robustness that is independent of the specific operating point at which the network was linearised, making it well suited to a system such as the Nigerian 330 kV grid, which experiences wide variation in loading and generation dispatch.

3.3.2 Linear matrix Inequality

By the bounded real lemma, the existence of a stabilising dynamic output-feedback controller satisfying $\| T_{wz} \|_{\infty} < \gamma$ is equivalent to the feasibility of the following set of Linear Matrix Inequalities (Skogestad & Postlethwaite, 2024):

$$\begin{bmatrix} A_g X + XA_g^T + B_{g2}\hat{C} + ()^T & \hat{A} + A_g^T \cdots B_{g1} & XC_{g1}^T + \hat{C}^T D_{g12}^T \\ ()^T \vdots & YA_g + A_g^T + BC_{g2} + ()^T \ddots YB_{g1} & \vdots C_{g1}^T \\ & \cdots - \gamma I & D_{g11}^T \end{bmatrix}^T < 0 \quad \text{... (10)}$$

$$\begin{bmatrix} X & I \\ I & Y \end{bmatrix} \geq 0 \quad \text{... (11)}$$

where Ag represents the augmented generalised plant matrices. These LMIs were solved using MATLAB's Robust Control Toolbox and LMI Toolbox, yielding a controller that guaranteed closed-loop stability and bounded disturbance amplification.

3.3.3 Mixed-Sensitivity Framework

A mixed-sensitivity H∞ formulation was adopted to enforce oscillation damping and control-effort limitation simultaneously, with the objective of suppressing low-frequency oscillations while limiting excitation control effort. This objective is formulated as an H∞ performance criterion on the weighted performance outputs z_1 and z_2:

$$\left\| \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} \right\|_{\infty} < \gamma \quad \text{... (12)}$$

where the weighted outputs are defined as:

$$z_1(t) = W_1(s)\, \Delta\omega(t) \quad \text{... (13)}$$

$$z_2(t) = W_2(s)\, u(t) \quad \text{... (14)}$$

The performance weighting function $W_1(s)$ is used to penalise low-frequency oscillations, while the control-effort weighting function $W_2(s)$ constrains excessive control action while preserving the required phase compensation. The PSS controller K(s) is synthesised by solving the H∞ optimisation problem:

$$\min_{K} \left\| \begin{bmatrix} W_1(s)S(s) \\ W_2(s)K(s)S(s) \end{bmatrix} \right\|_\infty \quad \text{... (15)}$$

where the sensitivity function is defined as:

$$S(s) = (I + G(s)K(s))^{-1} \quad \text{... (16)}$$

The weighting functions embed frequency-dependent performance and robustness requirements directly into the state-space model, ensuring effective damping of dominant electromechanical oscillations while maintaining bounded excitation control effort.

3.3.4 Robust PSS Design

Following solution of the LMI feasibility problem, the controller matrices were reconstructed using the standard change-of-variables transformation, yielding a dynamic output-feedback controller realised as:

$$\dot{x}_k = A_k x_k + B_k y \quad \text{... (17)}$$

$$u = C_k x_k \quad \text{... (18)}$$

where x_k is the controller state vector and A_k, B_k, C_k are the controller matrices obtained from the LMI solution. The resulting controller constitutes a centralised, wide-area PSS structure in which all thirteen rotor speed deviations are used to generate thirteen supplementary excitation signals. This coordinated architecture enables simultaneous damping of local and inter-area oscillatory modes across the Nigerian 330 kV Multi-Machine Transmission Network.

4.0 SIMULATION RESULTS AND DISCUSSIONS

This section presents the simulation results of the H∞-based Power System Stabiliser developed using the LMI framework, applied to the linearised 54-bus, 13-generator multi-machine model of the Nigerian 330 kV network, with all assumptions and state-space representations preserved from Section 3.

4.1 Load Flow Analysis

Load flow analysis using the Newton-Raphson method established the steady-state operating point of the Nigerian 330 kV network bus voltages, power flows, and generator outputs converging in 11 iterations. This operating point serves as the linearisation basis for deriving the state-space model, enabling the eigenvalue, modal, and participation-factor analyses used for small-signal stability assessment. Table 1 and Figure 1 present the resulting steady-state load flow analysis for the uncompensated network.

Table 1: Newton-Raphson Load Flow Analysis for the Uncompensated Nigerian 330 kV Multi-Machine Transmission Network.

Bus Number	Voltage (p.u.)	Angle δ (deg)
1	1.0400	0.0000
2	1.0400	-1.1214
3	1.0350	-4.3621
4	1.0328	-4.8140
5	1.0275	-5.0437
6	1.0300	-4.7370
7	1.0643	-2.6699
8	1.0550	-1.1498
9	1.0300	-6.9465
10	1.1983	-13.2456
11	1.1146	-8.5295
12	1.0650	-9.2805
13	1.1327	-9.3109
14	1.1879	-9.9868
15	1.1172	-6.8187
16	1.0503	-8.0057
17	1.0373	-5.0040
18	1.0072	-7.2691
19	1.0367	-3.7446
20	1.0686	-0.9922
21	1.1237	-3.0684
22	1.1227	-4.8996
23	1.1087	-4.1825
24	0.8803	9.0750
25	0.8742	5.5064
26	0.8693	9.7501
27	0.9908	2.6350
28	1.0341	-0.1897
29	1.0568	-2.4586
30	0.8734	3.0227
31	0.9014	-1.9994
32	1.0078	-6.8190
33	1.0065	-6.8543
34	1.1446	-4.4157
35	1.1470	-5.2195
36	1.1514	-5.7220
37	1.1515	-6.0365
38	1.1472	-6.9633
39	1.1539	-5.9891
40	1.1548	-5.7327
41	1.1392	-6.8290
42	1.1500	-5.0123
43	1.1558	-8.1717
44	1.1494	-7.1998

45	1.1367	-6.1615
46	1.1697	-7.2785
47	1.1738	-8.1879
48	1.1807	-9.2382
49	1.1926	-10.3967
50	1.2021	-12.4659
51	1.2640	-14.6366
52	1.0124	1.5303
53	0.9953	-5.5079
54	1.0296	-6.8749

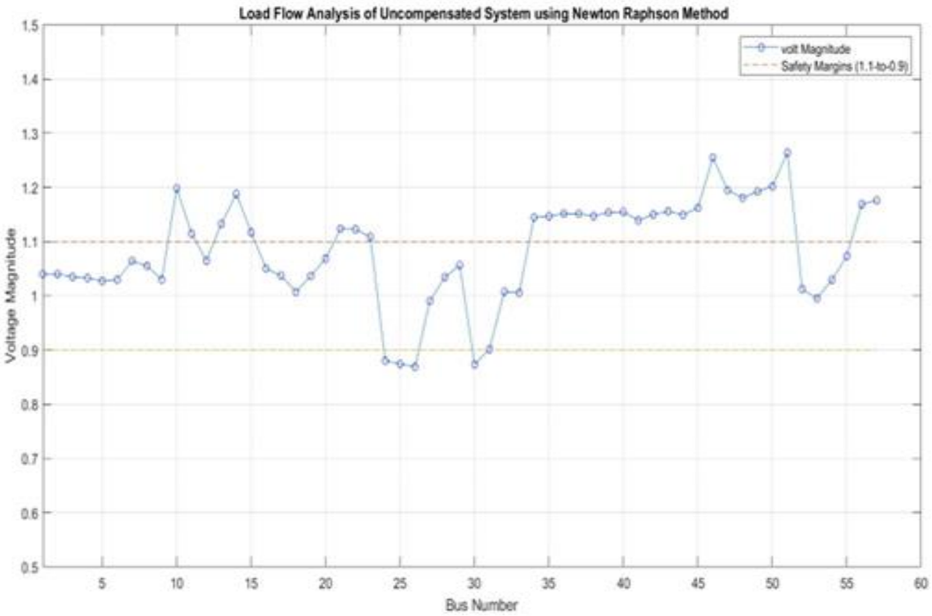

Figure 1: Load Flow Analysis of the Uncompensated Network (Newton-Raphson Method)

The results indicate significant voltage-regulation issues in the uncompensated network, with several buses exceeding the upper limit of 1.1 p.u. (Buses 10-15 and 34-52 reaching approximately 1.25-1.28 p.u.) and others dropping below the lower limit of 0.9 p.u. (Buses 24-26 and 30 at approximately 0.88 p.u.). This wide voltage deviation suggests poor reactive power balance and is associated with weak damping of rotor oscillations, indicating that the system operates close to its stability limits. These observations justify the implementation of an LMI-based H∞ controller to improve both voltage regulation and transient stability.

4.2 H-infinity Power System Stabilizer Performance

The LMI-based H∞ design for the Nigerian 13-generator, 54-bus system achieved a closed-loop disturbance attenuation level of $\gamma = 50.4948$, representing the upper bound on disturbance amplification. Using weighting matrices Wp = 50I13 and Wu = 0.01I13, a centralised dynamic output-feedback PSS was developed to suppress rotor speed deviations and inter-area oscillations.

Small-signal stability was assessed using the damping ratios of the closed-loop electromechanical modes, $\zeta = -\sigma/\sqrt{(\sigma^2 + \omega^2)}$. With the LMI-based H∞ controller, the minimum damping ratio increased from 1.1869 to 7.55, indicating overdamped, non-oscillatory behaviour. All dominant local and inter-area modes were shifted further into the left-half plane, ensuring strong oscillation suppression. This is consistent with the time-domain results, which show fast settling time (3-5 s), negligible speed deviations, and no sustained oscillations.

Figure 2 presents the compensated steady-state bus voltage magnitude profile of the network after incorporating the LMI-based H∞ PSS into the generator excitation systems. The results show that bus voltages are maintained largely within the acceptable operating range of 0.9-1.1 p.u., with only minor deviations observed at a few buses. Compared with the uncompensated case, the voltage profile exhibits significant improvement, indicating enhanced reactive power support and more effective voltage regulation throughout the network. The smooth and coordinated voltage distribution demonstrates the ability of the LMI-based H∞ controller to mitigate voltage instability, improve damping of electromechanical oscillations, and enhance overall system robustness.

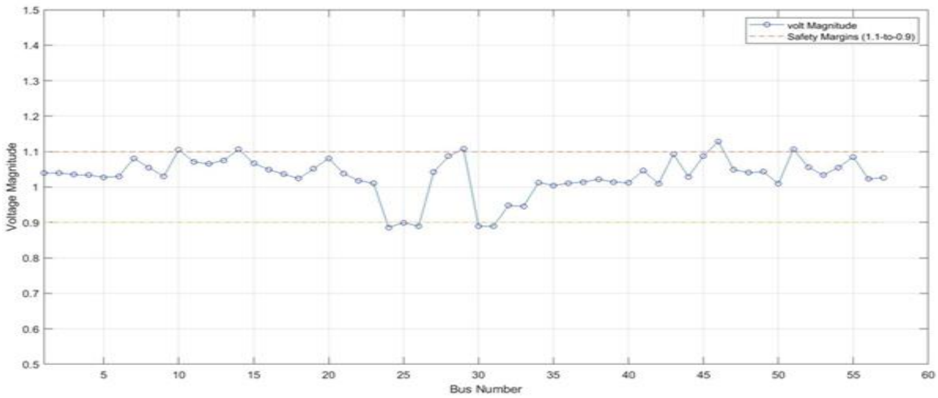

Figure 2: Voltage Magnitude Deviations of the Compensated Power System.

Figure 3 compares rotor speed deviations for the Nigerian multi-machine system in open loop and with the LMI-based H∞ controller. The open-loop case shows sustained, poorly damped oscillations and severe voltage violations (0.88 p.u. to 1.28 p.u.), indicating weak reactive power support and marginal stability. With the LMI-based H∞ controller, both local and inter-area oscillations were effectively damped, peak deviations were reduced from ±0.05 p.u. to below ±0.02 p.u., and the system settled within 3-5 s. By enforcing left-half-plane pole placement, the controller stabilised voltage, ensured global system stability, and restored all generators to equilibrium within two oscillation cycles.

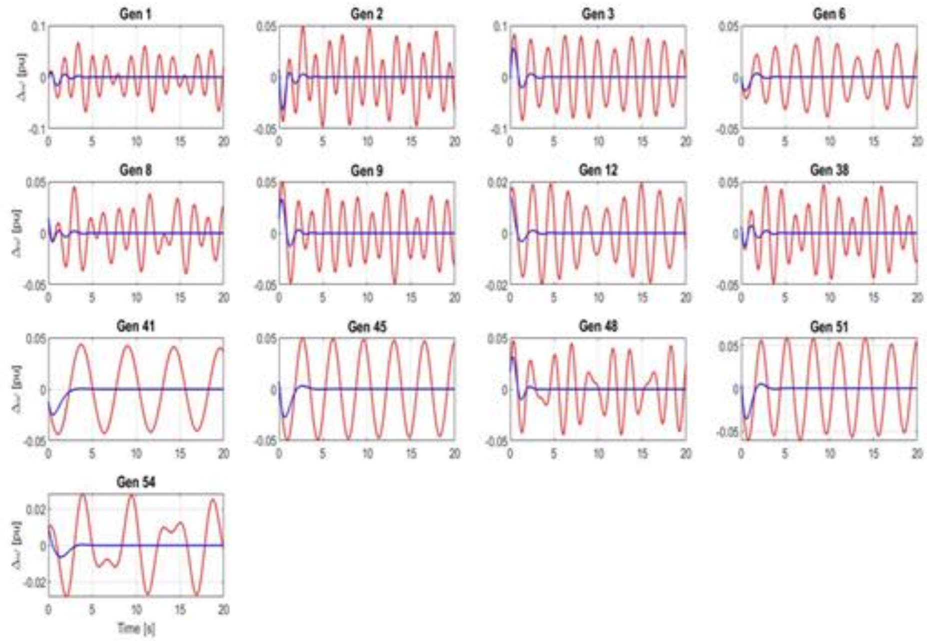

Figure 3: Open- and Closed-Loop Rotor Speed.

Figure 4 presents the Bode magnitude plots comparing the open-loop and closed-loop rotor angle ($\Delta\delta$) responses of the Nigerian 54-bus, 13-generator system. In open loop, prominent low-frequency resonance peaks (0.5-2 rad/s) indicate weak damping and high sensitivity to disturbances. With the LMI-based $H\infty$ controller, these peaks were significantly suppressed across all generators, demonstrating effective damping of oscillatory modes. The improved high-frequency roll-off also indicates enhanced robustness and reduced amplification of fast dynamics, confirming improved small-signal stability of the system.

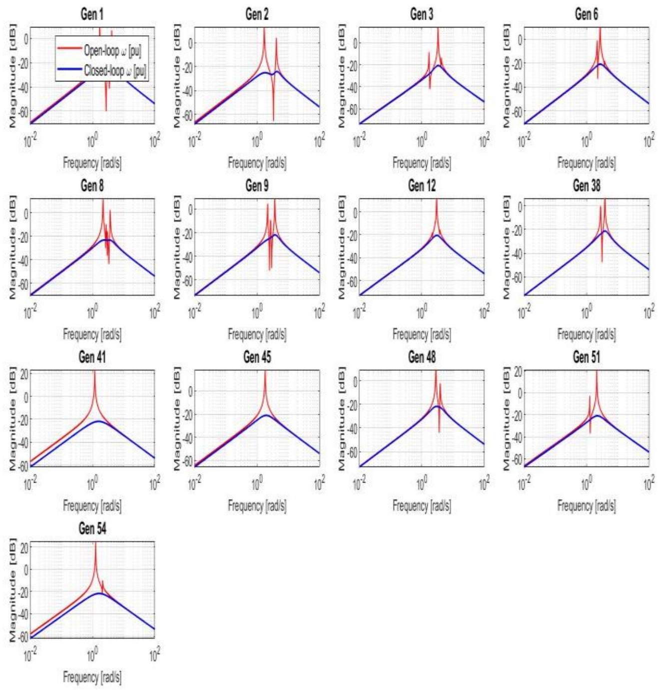

Figure 4: Frequency Response - Rotor Angle.

5.0 CONCLUSION

This study developed and implemented a robust H∞ Power System Stabilizer based on Linear Matrix Inequality (LMI) optimisation for the Nigerian 330 kV transmission network. A comprehensive 54-bus, 13-generator dynamic model was employed and linearised to facilitate controller synthesis. The proposed mixed-sensitivity H∞ controller successfully achieved robust damping of both local and inter-area oscillatory modes while maintaining acceptable control effort. Simulation results showed significant improvements in voltage regulation, damping characteristics, rotor speed stability, and disturbance-rejection performance. The controller reduced oscillation amplitudes, improved settling times to approximately 3 to 5 seconds, and maintained bus voltages largely within the acceptable range of 0.9 to 1.1 p.u. Frequency-domain analysis further confirmed enhanced robustness through the suppression of low-frequency resonance peaks and improved attenuation of disturbances. Overall, the results demonstrate that the LMI-based H∞ PSS is an effective and reliable solution for enhancing the stability, robustness, and operational security of the Nigerian 330 kV Multi-Machine Transmission Network under varying operating conditions and system uncertainties.

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