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Modeling, tuning, and validating of exciter and governor in combined-cycle power plants: a practical case study

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ABSTRACT

Exciter and governor systems are critical to regulating power output and maintaining stability in power systems. Despite their significance, there is a lack of practical methodologies that leverage real power plant data for modeling, tuning, and validation. This research paper seeks to fill this gap by presenting a methodology that utilizes a transfer function and control algorithms for tuning and validation. The proposed approach is demonstrated through a case study of a practical combined-cycle power plant in Malaysia. The control algorithm's effectiveness is verified through MATLAB and Simulink simulations. Post-tuning assessments confirm the method's ability to accurately determine tunable control parameter settings, meeting system requirements while ensuring grid stability and reliability. This versatile approach can be applied to various power plant configurations, making it a valuable tool for optimizing operations.

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1. INTRODUCTION

Combined-cycle power plants are power generation systems that combine a gas turbine with a steam turbine to generate electricity. They are a widely used technology for electricity generation, offering high efficiency and flexibility compared to other power plants [1]. Transient stability is the ability of a power system to return to a stable state after a disturbance. In other words, a power system can maintain synchronism and balance between generation and load after a disturbance, such as a short circuit or a sudden change in load [2], [3]. Transient stability is an essential factor in the design and operation of a power system. Therefore, power engineers and system operators need to have a good understanding of transient stability in systems. Transient stability analysis is often performed using dynamic models of power systems [4], [5]. The accuracy of simulation models relies on two crucial factors: appropriate model structures and fitting the proper parameters into those structures [6], [7].

In a technical report [8], six benchmark models with a maximum of 16 generators and 68 buses were presented and used to compare various stabilizer tuning algorithms. In addition, the IEEE created several test cases without dynamics in 1962 to represent a portion of the American Electric Power System in the Midwest, United States [9]. These test cases have since been modified to include dynamic generator models to perform time-domain simulations [10]. A list of power system cases with and without dynamic molds can be found in [11]. There are several proposed methods for tuning the control parameters of a proportional-integral-derivative (PID) controller of exciter and governor, as summarized in [12], including Ziegler–Nichols (ZN), integral of squared time weighted error (ISTE), Kessler-Landau-Voda (KLV), Pessen integral of absolute error (PIAE), some overshoot rule (SO-OV), no overshoot rule (NO-OV), Mantz–Tacconi Ziegler–Nichols (MT-ZN), and refined Ziegler–Nichols (R-ZN). These tuning methods set the values of Kp, Ki, and Kd by using the ultimate gain (Ku) and the oscillation period (Tu). These values are used as initially tuned parameters, and further adjustments are needed to fulfill the control requirements stated by the grid [10].

In previous research, an automated algorithm was developed to generate synthetic cases for steady-state power flow analysis [13]-[18] and dynamic power flow analysis [19]-[22]. This algorithm aimed to capture the complexity of modern electric grids. However, utilizing actual network data, performance criteria, and constraints in dynamic modeling can yield more realistic and insightful simulation results. Therefore, this research paper aims to enhance the understanding of exciter and governor control in combined-cycle power plants, while providing practical guidelines for modeling, tuning, and validating these systems. To achieve this, we employ real measurement data to model both the exciter and generator and fine-tune their controllable parameters to ensure compliance with the requirements of actual grids. Subsequently, the proposed method is validated through a series of simulations conducted in MATLAB and Simulink. The results demonstrate the proposed method's effectiveness in maintaining stable and efficient operation of the power plant. Furthermore, this method can be readily applied to various power plants, as it explores all permissible ranges of control parameters to optimize system performance.

The remaining sections of this article are as follows: i) Section 2 gives an overview of the combined cycle power plant (CCPP), including generator characteristics, selected dynamic models, and network topology; ii) Section 3 describes the methodological approach for modeling, tuning, and validating the exciter and governor systems; iii) Section 4 presents and discusses the results obtained from a simulation in MATLAB and Simulink to assess the system's performance; and iv) Finally, section 5 establishes the conclusion derived from this study, followed by the recommendation for future work.

2. METHOD

Modeling the combined-cycle power plant involves developing mathematical models representing the relationships between input and output variables, such as generator speed, electrical load, and fuel flow. These models can be used to predict the system's performance under different operating conditions and to design control algorithms that can maintain stable and efficient operation. The tuning process involves adjusting the parameters of the control algorithms to achieve the desired performance. This consists of adjusting the gains and other parameters of the control algorithms to optimize the system's response to changes in load or other variables. The validation process involves testing the performance of the control algorithms under a range of operating conditions to ensure that they function as intended and meet the required performance specifications.

The sweep algorithm is used for tuning the control parameters of a proportional-integral-derivative (PID) controller and involves systematically varying the values of the controller's Kp, Ki, and Kd parameters over a range of values and evaluating the system's performance for each set of parameter values. This allows the designer to identify the optimal combination of Kp, Ki, and Kd values that give the best performance for the system. To use the sweep algorithm method, the following steps are typically followed:

- Identify the governor model and exciter model;
- Model the desired control loop in Simulink;
- Add swing equation model after mechanical power output (governor) or add generator model (exciter system);
- Obtain the state space equation of the mod function in MATLAB;
- Convert the state space model to the transfer function;
- Obtain a Bode plot and root locus using the SISOTOOL function in MATLAB; and
- Obtain gain margin (Gm), phase margin (Pm), and oscillation frequency, and perform a parameter sweep for tuning.

2.1. Modeling, tuning, and validation of the exciter system

Figure 1 outlines the main steps to assess exciter stability and tune exciter parameters. Exciter stability was evaluated in both time and frequency domains with the synchronous machine open-circuited and operating at the rated speed. Time- and frequency-domain characteristics were derived directly from the transfer functions obtained through exact model linearization about the operating point. Exciter stability criteria are assumed to follow IEEE guidelines, as illustrated in Table 1. Figures 2 and 3 illustrate the EXAC1 and AC7B models, respectively, in the MATLAB/Simulink environment, and the models were developed based on the block diagrams provided in [23]-[25].

2.2. Governor modeling, tuning, and validation

Figure 4 outlines the main steps to assess governor stability and tune governor parameters if required. Governor stability was evaluated in both time and frequency domains, with the synchronous machine operating at 80% loading and the rated speed. As the exact model linearization method was not feasible, frequency-domain characteristics were estimated by exciting the model with sine-stream signals after opening the governor speed/frequency feedback loop. In contrast, time-domain characteristics were calculated from simulations with +5% step load changes. The damping ratio was approximated using (1), assuming the system behaves like a second-order system. Governor stability criteria are supposed to follow IEEE guidelines, as illustrated in Table 2. The swing equations only modeled the synchronous machine dynamics for this purpose. Figures 5 and 6 illustrate the GGOV1 and HRSG models, respectively, in the MATLAB/Simulink environment. The GGOV1 model was developed based on the block diagrams provided in [24], [28], while the HRSG model was developed using the provided manufacturer data. For stability analysis purposes, only the speed/frequency and load control paths were modeled.

$$\zeta = \sqrt{\frac{ln^2(\mathrm{OS})}{\pi^2+ln^2(\mathrm{OS})}} \tag{1}$$

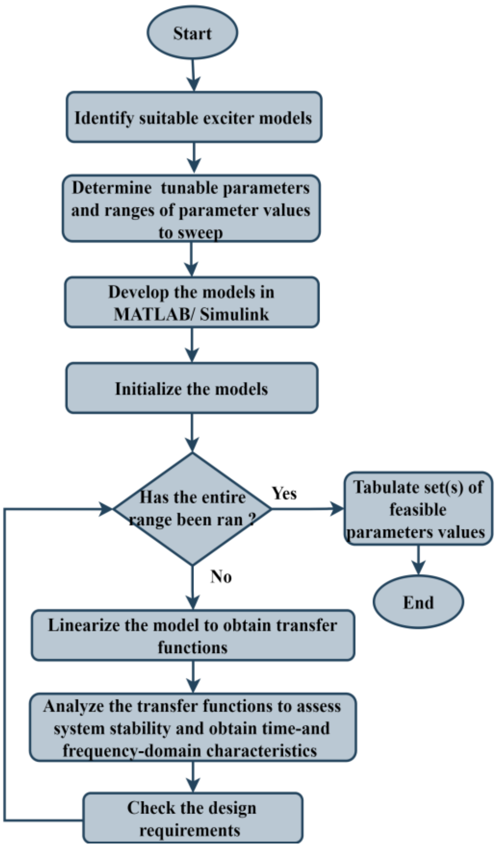

Figure 1. Flowchart of exciter stability study/tuning process

Table 1. Exciter stability criteria [26], [27]

Criteria	Value	Criteria	Value
Gain margin (G_m)	≥ 6 dB	Damping ratio (ζ)	≥ 0.6
Phase margin (P_m)	≥ 40°	Rise time (t_r)	0.025 to 0.6 s
Overshoot (OS)	0 – 15%	Bandwidth (F_B)	0.3 to 5 Hz
Peak amplitude response (M_p)	0.83 to 4 dB	Settling time within 5% (ts)	0.2 to 3 s

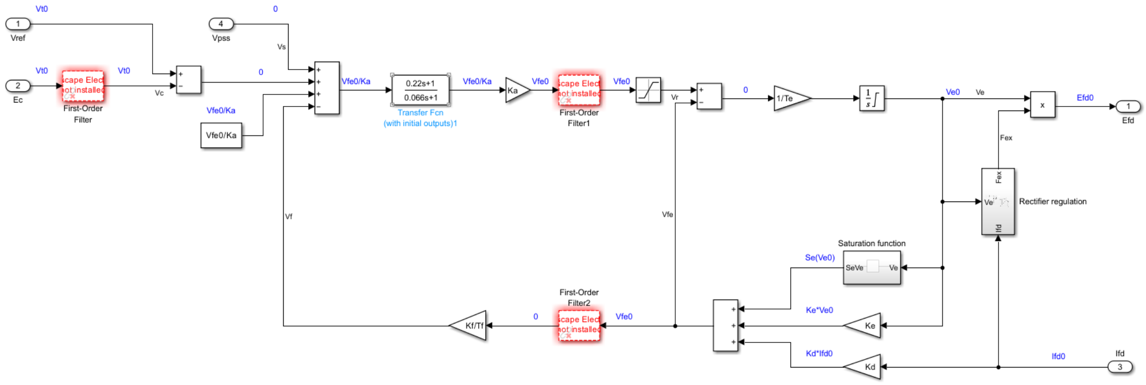

Figure 2. EXAC1 model in MATLAB/Simulink

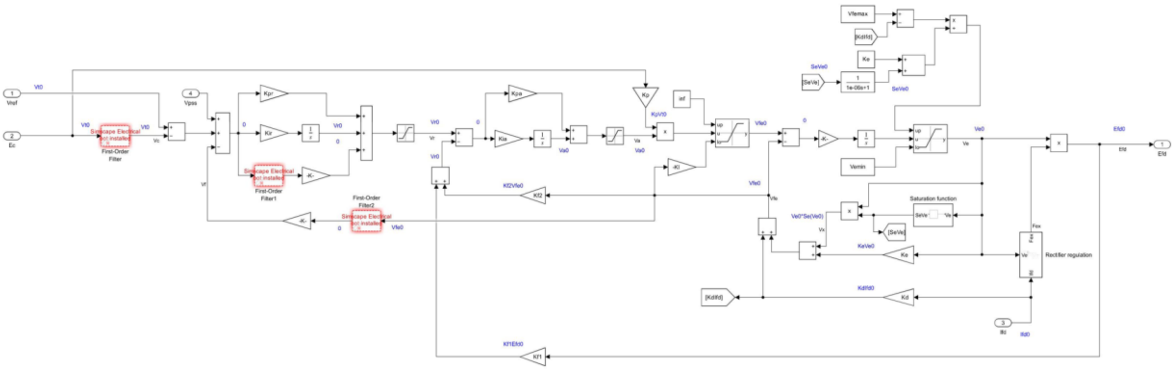

Figure 3. AC7B model in MATLAB/Simulink

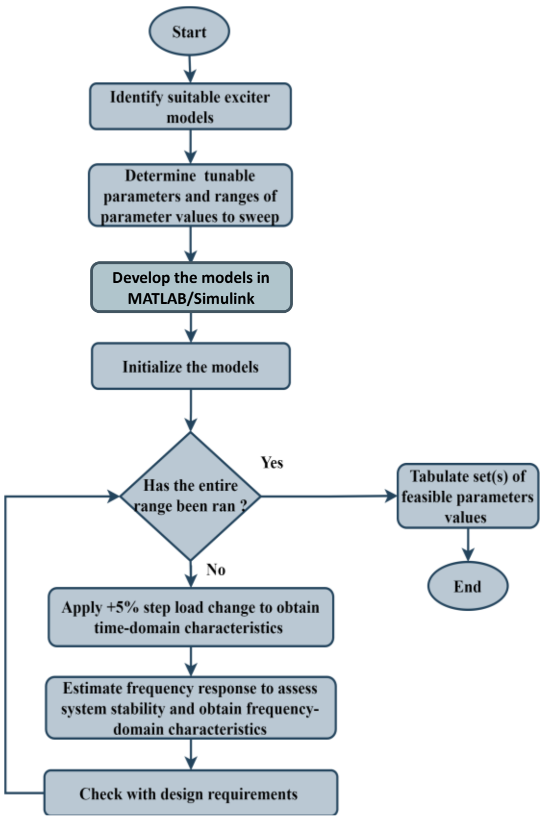

Figure 4. Flowchart of governor stability study/tuning process

Table 2. Governor stability criteria [29]

Criteria	Value	Criteria	Value
Gain margin (G_m)	≥ 3 dB	Damping ratio (ζ)	0.6 to 1.0
Phase margin (P_m)	≥ 40°	Rise time (t_r)	1 to 25 s
Overshoot (OS)	0 – 40%	Bandwidth (F_B)	0.03 to 1 Hz
Peak amplitude response (Mp)	0.83 to 4.0 dB	Settling time within 5% (ts)	2 to 100 s

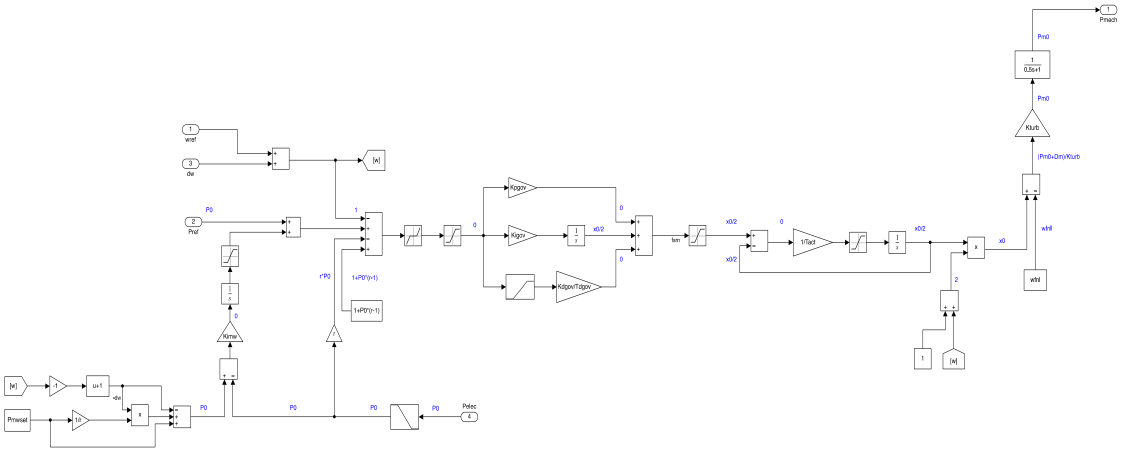

Figure 5. GGOV1 model in MATLAB/Simulink

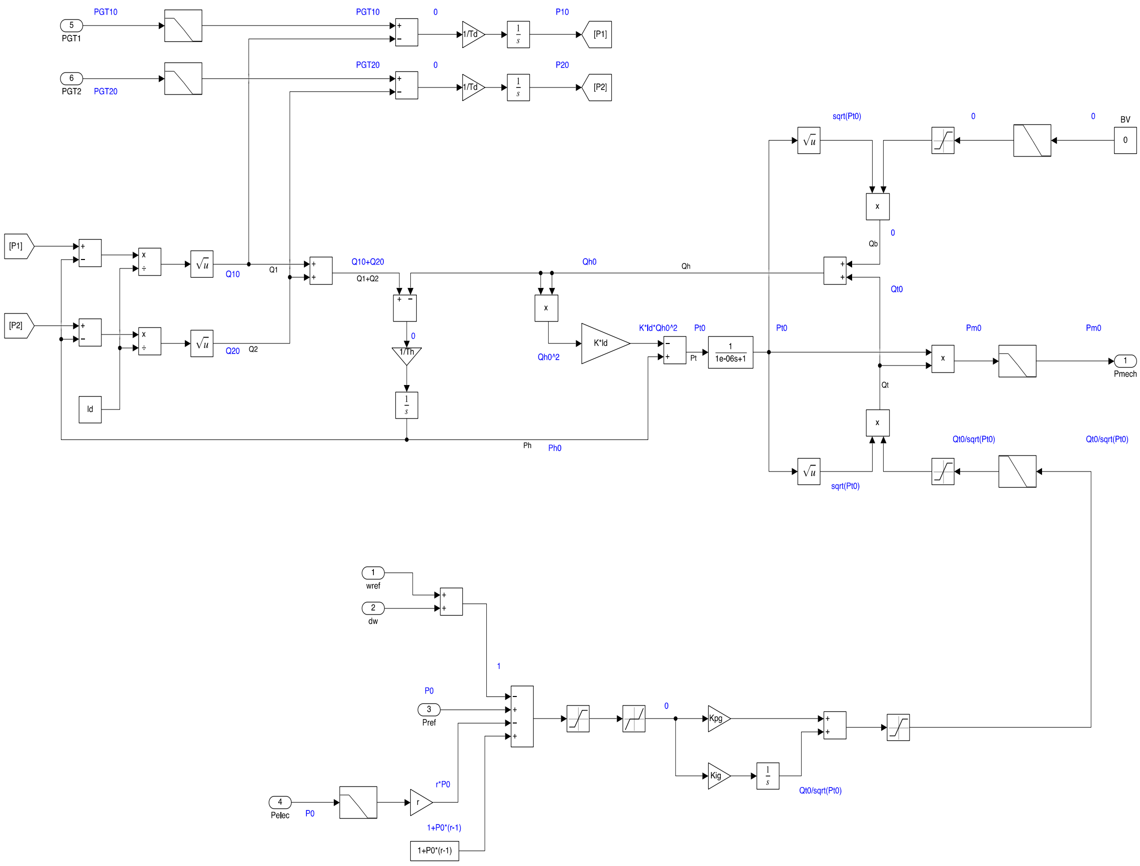

Figure 6. HRSG model in MATLAB/Simulink

3. CASE STUDY

The simulation results presented in this study are based on a modified CCPP in Malaysia as a representative case study. The plant configuration includes two gas turbine units (GTG1 and GTG2) and one steam turbine unit (STG3), as depicted in Figure 7. These components are interconnected to form a single power generation block within the plant. The SG generator ratings for each unit are as follows:

- The steam turbine unit (STG3) is rated at 146.25 MVA, operates at 13.8 kV, and has a power factor of 0.8. It is driven by a steam turbine with a nameplate rating of 117 MW.
- The gas turbine units (GTG1 and GTG2) are both rated at 134.625 MVA, operate at 15 kV, and have a power factor of 0.8. They are driven by either natural gas or distillate oil-fired turbines.

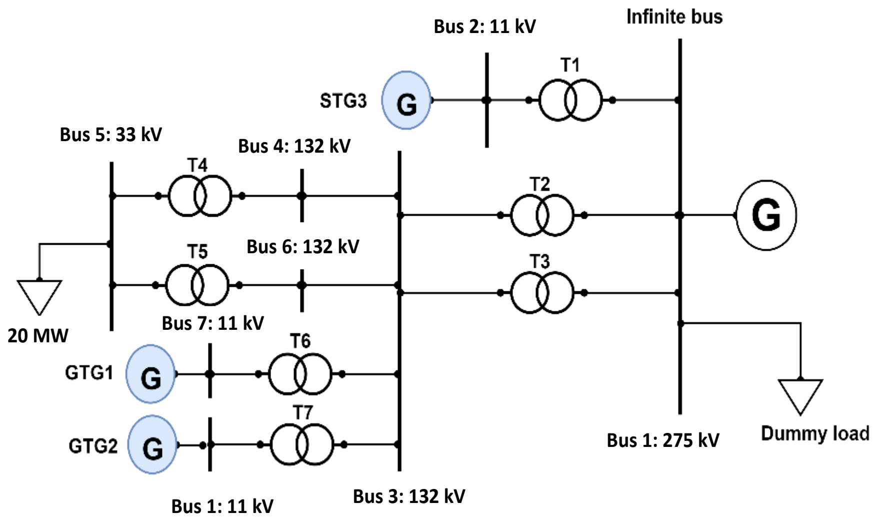

Figure 7. CCPP single-line diagram

The dynamic models, as shown in Table 3, are selected based on the structure of the combined power plant. The selection also considers the measured data obtained from the plant. In addition, the models recommended in [10] for different fuel types or technologies are used as a reference.

Table 3. Governor stability criteria [29]

Unit	GTG1 and GTG2	ST3
Synchronous generator	GENROU	GENROU
Exciter	EXAC1	AC7B
Turbine governor	GGOV1	HRSG
Stabilizer	PSS1A	PSS2B
Minimum exciter model	UEL2	UEL2
Maximum exciter model	MAXEX2	MAXEX2

4. RESULTS AND DISCUSSION

This section describes the results of the parameter tuning process of a power system model to improve its performance. The process begins with initial values for the model parameters collected from the power plant. These initial values may not result in stable behavior for all generators in the model, in which case further tuning is made to the exciters for those generators. A set of criteria guides the tuning and may involve tuning the control system's proportional, integral, and derivative gain parameters. The goal of the process is to obtain a set of model parameters that result in satisfactory control responses, as listed in Tables 2 and 3.

4.1. Tuning and stability analysis of the exciter system

The relative stability of a feedback control system is a crucial aspect that determines its performance and effectiveness. It is commonly evaluated using phase margins and gain margins. To ensure system stability, it is recommended that the exciter system maintain Gm above 6 dB and Pm above 40 degrees, aligning with the requirements set by the power grid. In addition to Gm and Pm, other factors are typically considered when assessing the system's stability. These are, Mp, ζ, OS, tr and ts. Tables 4 and 5 present the original and tuned parameter values of two specific exciters, EXAC1 and AC7B, respectively. As shown in Tables 6 and 7, without the tuning process, some of the criteria are violated, indicating that the control systems do not meet the stability requirements. However, after the tuning process, the results recorded demonstrate that both exciters now fulfill the control requirements specified in [26], [27]. Figures 8 and 9 display the tuned open-loop frequency responses of the exciters, showing the relationship between the voltage reference and the machine terminal voltage, to illustrate the effectiveness of the tuning process visually.

Table 4. EXAC1 original and tuned parameter values

Parameter	Original value
K_A	60

Table 5. AC7B original and tuned parameter values

Parameter	Original value
K_{pr}	100
K_{ir}	40
K_{dr}	40

Table 6. EXAC1 stability analysis results

Comparison	G_m (dB)	P_m (°)	M_p (dB)	f_B (Hz)	ζ	OS (%)	t_r (s)	t_s (s)
Criteria	> 6	> 40	0.83 – 4	0.3 – 5	> 0.6	0 – 15	0.025 – 0.6	0.2 – 3
Original value	46.5	66.0	0.329	1.95	0.604	3.84	0.265	0.290
Tuned value	52.7	81.2	1.096	1.12	0.858	0	0.597	0.791

Table 7. AC7B stability analysis results

Comparison	G_m (dB)	P_m (°)	M_p (dB)	f_B (Hz)	ζ	OS (%)	t_r (s)	t_s (s)
Criteria	> 6	> 40	0.83 – 4	0.3 – 5	> 0.6	0 – 15	0.025 – 0.6	0.2 – 3
Original value	> 46.5	53.6	0.697	1.381	0.555	20.87	0.292	0.926
Tuned value	> 52.4	72.0	1.171	0.680	0.862	4.35	0.595	0.675

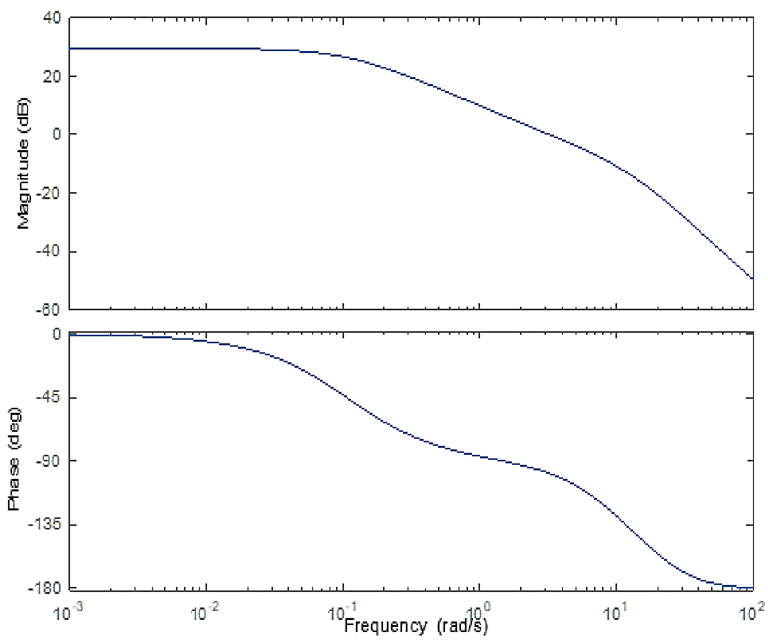

Figure 8. EXAC1 tuned open-loop frequency response Bode plots

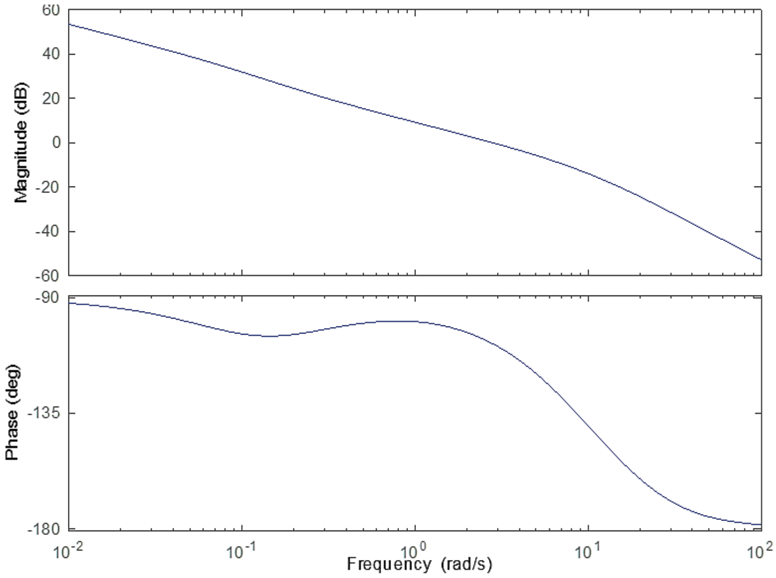

Figure 9. AC7B tuned open-loop frequency response Bode plots

4.2. Tuning and stability analysis of the governor system

The stability of a feedback control system is evaluated based on stability criteria such as Pm, Gm, FB, Mp, ζ , OS, tr and ts. In the context of governor tuning, it is recommended to achieve Gm above 6 dB and Pm above 40 degrees to ensure stability according to the requirements stated in [29]. In the case of the governor system, it is necessary to evaluate and adjust the control parameters to meet these stability criteria. The original parameter values of GGOV1 and HRSG are presented in Tables 8 and 9, respectively. However, as shown in the table, some of the requirements are violated before the tuning process. A tuning process is performed on both governors to rectify the stability issues. The tuned parameter values are tabulated in Tables 10 and 11. These results indicate that both governors fulfill the control requirements specified by the grid after tuning. This implies that the stability of the control system has been improved, and it now meets the recommended stability criteria. Figures 10 and 11 show the tuned open-loop frequency response Bode plots.

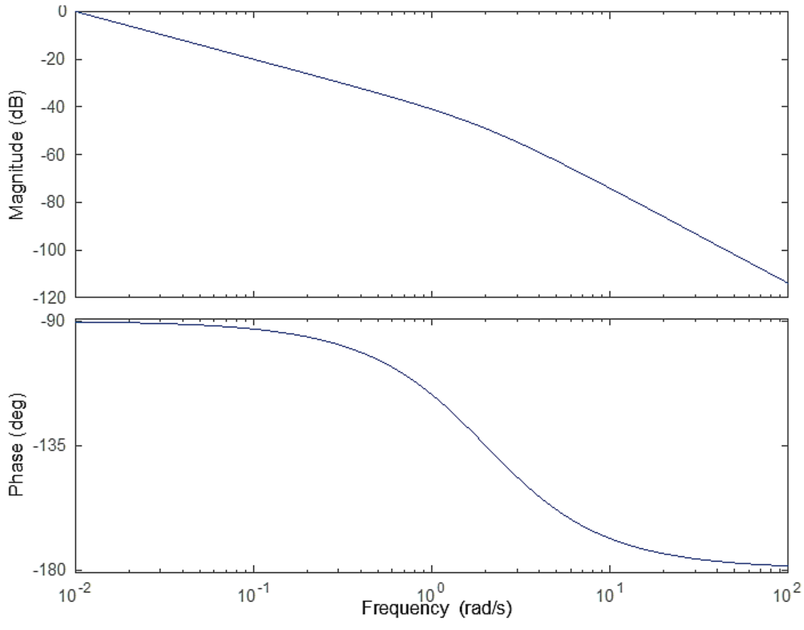

Figure 10. GGOV1 tuned open-loop frequency response Bode plots

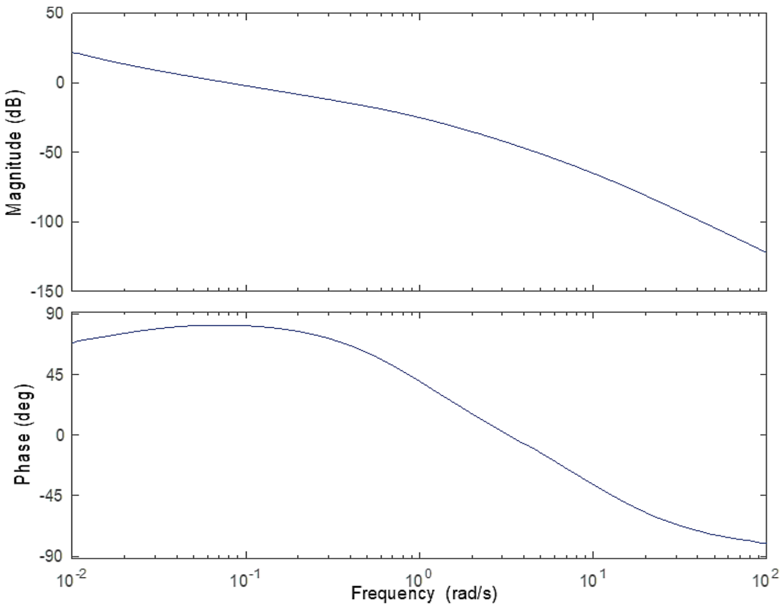

Figure 11. HRSG tuned open-loop frequency response Bode plots

Table 8. GGOV1 original and tuned parameter values

Parameter	Original value	Tuned value
K_{pgov}	30	40
K_{igov}	2.5	10
K_{dgov}	0	5

Table 9. HRSG original and tuned parameter values

Parameter	Original value	Tuned value
K_{pg}	1.5	1
K_{ig}	0.1	0.01

Table 10. GGOV1 stability analysis results

Comparison	G_m (dB)	P_m (°)	ζ	OS (%)
Criteria	≥ 3	≥ 40	> 0.6	0 – 40
Original value	> 114.0	90.0	0.180	56.24
Tuned value	> 114.0	90.0	0.384	27.12

Table 11. HRSG stability analysis results

Comparison	G_m (dB)	P_m (°)	ζ	OS (%)
Criteria	> 3	> 40	> 0.6	0 – 40
Original value	> 118.4	238.6	0.127	149.46
Tuned value	> 122.2	261.8	1	0

5. CONCLUSION

Exciters and governors are critical components in the control systems of combined-cycle power plants. They regulate generator speed and output to ensure stable and efficient plant operation. This study introduced a sweep algorithm for tuning the turntable control parameters, which was validated through simulations using MATLAB and Simulink. The results demonstrate the method's effectiveness in identifying optimal tunable control settings that meet system requirements. The proposed sweep algorithm can be broadly applied to other power plants, as it systematically explores the range of allowable control parameters to deliver the best performance. This flexibility makes the method particularly useful for a wide range of control systems where tuning is necessary. It is most beneficial in systems that require precise control tuning over large parameter spaces, where traditional methods may struggle to converge on optimal settings. Future work could enhance the robustness of the model by incorporating a power system stabilizer (PSS), allowing for a more comprehensive study of modeling, tuning, and validation in combined cycles and other types of power plants. This would extend the method's applicability to more complex scenarios involving dynamic stability and grid interactions.

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AUTHOR CONTRIBUTIONS STATEMENT

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Renuga Verayiah		✓				✓	✓	✓	✓		✓	✓		
Tan Yi Xu	✓		✓	✓					✓		✓		✓	
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [RV]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

REFERENCES

[1] M. P. Boyce, "Combined cycle power plants," in *Combined Cycle Systems for Near-Zero Emission Power Generation*, Elsevier, 2012, pp. 1–43. doi: 10.1533/9780857096180.1.
[2] P. Kundur, *Power system stability and control*. New York, 1993.
[3] S. Khalid, "e-Prime - Advances in electrical engineering, electronics and energy a novel algorithm adaptive autarchoglossans lizard foraging (AALF) in a shunt active power filter connected to MPPT-based photovoltaic array," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 3, no. November 2022, p. 100100, 2023, doi: 10.1016/j.prime.2022.100100.
[4] T. Xu, A. B. Birchfield, K. S. Shetye, and T. J. Overbye, "Creation of synthetic electric grid models for transient stability studies," *The 10th Bulk Power Systems Dynamics and Control Symposium (IREP 2017)*, no. Irep, pp. 1–6, 2017.
[5] S. Khalid, "Optimized aircraft electric control system based on adaptive tabu search algorithm and fuzzy logic control," *Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*, vol. 4, no. 3, Sep. 2016, doi: 10.11591/ijeei.v4i3.221.
[6] L. N. Hannett and J. W. Feltes, "Testing and model validation for combined-cycle power plants," in *2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194)*, vol. 2, pp. 664–670. doi: 10.1109/PESW.2001.916933.
[7] A. Mugarra, J. M. Guerrero, K. Mahtani, and C. A. Platero, "Synchronous generator stability characterization for gas power plants using load rejection tests," *Applied Sciences*, vol. 13, no. 20, p. 11168, Oct. 2023, doi: 10.3390/app132011168.

[8] C. Canizares *et al.*, "Benchmark models for the analysis and control of small-signal oscillatory dynamics in power systems," *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 715–722, Jan. 2017, doi: 10.1109/TPWRS.2016.2561263.
[9] U. of Washington, "Power systems test case archive," 1996. https://labs.ece.uw.edu/pstca/ (accessed Jan. 04, 2023).
[10] T. Xu, A. B. Birchfield, and T. J. Overbye, "Modeling, tuning, and validating system dynamics in synthetic electric grids," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6501–6509, Nov. 2018, doi: 10.1109/TPWRS.2018.2823702.
[11] J. Bialek *et al.*, "Benchmarking and validation of cascading failure analysis tools," *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 4887–4900, Nov. 2016, doi: 10.1109/TPWRS.2016.2518660.
[12] A. S. McCormack and K. R. Godfrey, "Rule-based autotuning based on frequency domain identification," *IEEE Transactions on Control Systems Technology*, vol. 6, no. 1, pp. 43–61, 1998, doi: 10.1109/87.654876.
[13] E. Schweitzer *et al.*, "Medium voltage radial distribution systems," *IEEE Transactions on Smart Grid*, vol. 1, no. 1, pp. 28–39, 2010.
[14] S. H. Elyas and Z. Wang, "Improved synthetic power grid modeling with correlated bus type assignments," *2017 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2017*, 2017, doi: 10.1109/ISGT.2017.8085975.
[15] Z. Wang, S. H. Elyas, and R. J. Thomas, "Generating synthetic electric power system data with accurate electric topology and parameters," in *2016 51st International Universities Power Engineering Conference (UPEC)*, Sep. 2016, pp. 1–6. doi: 10.1109/UPEC.2016.8114145.
[16] S. Soltan and G. Zussman, "Generation of synthetic spatially embedded power grid networks," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, Jul. 2016, pp. 1–5. doi: 10.1109/PESGM.2016.7741383.
[17] D. Ciechanowicz, D. Pelzer, B. Bartenschlager, and A. Knoll, "A modular power system planning and power flow simulation framework for generating and evaluating power network models," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 2214–2224, May 2017, doi: 10.1109/TPWRS.2016.2602479.
[18] N. Hutcheon and J. W. Bialek, "Updated and validated power flow model of the main continental European transmission network," in *2013 IEEE Grenoble Conference*, Jun. 2013, pp. 1–5. doi: 10.1109/PTC.2013.6652178.
[19] S. Ba-swaimi, R. Verayiah, V. K. Ramachandaramurthy, and A. K. ALAhmad, "Long-term optimal planning of distributed generations and battery energy storage systems towards high integration of green energy considering uncertainty and demand response program," *Journal of Energy Storage*, vol. 100, p. 113562, Oct. 2024, doi: 10.1016/j.est.2024.113562.
[20] S. Ba-swaimi, R. Verayiah, V. K. Ramachandaramurthy, A. K. AlAhmad, and S. Padmanaban, "Two-stage strategic optimal planning of distributed generators and energy storage systems considering demand response program and network reconfiguration," *Energy Conversion and Management: X*, vol. 24, p. 100766, Oct. 2024, doi: 10.1016/j.ecmx.2024.100766.
[21] A. K. ALAhmad, R. Verayiah, S. Ba-swaimi, H. Shareef, A. Ramasam, and A. Abu-Rayash, "Optimized two-stage planning model for integrating compressed air energy storage with uncertain correlated wind farms in power systems," *Energy Conversion and Management: X*, vol. 25, p. 100838, Jan. 2025, doi: 10.1016/j.ecmx.2024.100838.
[22] A. K. ALAhmad, R. Verayiah, H. Shareef, A. Ramasamy, and S. Ba-swaimi, "Optimizing renewable energy and green technologies in distribution systems through stochastic planning of distributed energy resources," *Energy Conversion and Management: X*, vol. 25, p. 100834, Jan. 2025, doi: 10.1016/j.ecmx.2024.100834.
[23] R. Gunasekara *et al.*, "A novel virtual synchronous machine implementation and verification of its effectiveness to mitigate renewable generation connection issues at weak transmission grid locations," *IET Renewable Power Generation*, vol. 17, no. 10, pp. 2436–2457, Jul. 2023, doi: 10.1049/rpg2.12558.
[24] S. I. Inc, "PSSE 34.2.0 model library," 2017.
[25] K. S. Shetye, T. J. Overbye, S. Mohapatra, R. Xu, J. F. Gronquist, and T. L. Doern, "Systematic determination of discrepancies across transient stability software packages," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 432–441, 2016, doi: 10.1109/TPWRS.2015.2393813.
[26] "IEEE guide for identification, testing, and evaluation of the dynamic performance of excitation control systems." IEEE, Piscataway, NJ, USA, Mar. 27, 2014. doi: 10.1109/IEEESTD.2014.6845300.
[27] "IEEE Recommended Practice for Preparation of Equipment Specifications for Speed-Governing of Hydraulic Turbines Intended to Drive Electric Generators," *IEEE Std 125-2007*, Oct. 26, 2007, IEEE Standards Association. Available [Online]: https://standards.ieee.org/ieee/125/3394/.
[28] A. S. Menon, R. Babu, and S. Desabhatla, "Study on the impact of turbine controls on transient stability of synchronous machine," *Journal of Green Engineering*, vol. 6, no. 2, pp. 1–22, 2016, doi: 10.13052/jge1904-4720.624.
[29] "IEEE Guide for the Application of Turbine Governing Systems for Hydroelectric Generating Units," May 16, 2011, *IEEE, Piscataway, NJ, USA*. doi: 10.1109/IEEESTD.2011.5936081.

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