



Developing Frequency Stability Constraint for Unit Commitment Problem Considering High Penetration of Renewables

Preprint

Ningchao Gao,^{1,3} Shuan Dong,¹ Xin Fang,² Andy Hoke,¹ David Wenzhong Gao,³ and Jin Tan¹

1 National Renewable Energy Laboratory

2 Mississippi State University

3 University of Denver

Presented at 50th IEEE Photovoltaic Specialists Conference (PVSC 50)

San Juan, Puerto Rico

June 11-16, 2023

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-86622
September 2023



Developing Frequency Stability Constraint for Unit Commitment Problem Considering High Penetration of Renewables

Preprint

Ningchao Gao,^{1,3} Shuan Dong,¹ Xin Fang,² Andy Hoke,¹ David Wenzhong Gao,³ and Jin Tan¹

1 National Renewable Energy Laboratory

2 Mississippi State University

3 University of Denver

Suggested Citation

Gao, Ningchao, Shuan Dong, Xin Fang, Andy Hoke, David Wenzhong Gao, and Jin Tan. 2023. Developing Frequency Stability Constraint for Unit Commitment Problem Considering High Penetration of Renewables: *Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-86622. <https://www.nrel.gov/docs/fy23osti/86622.pdf>.

© 2023 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-86622
September 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Developing Frequency Stability Constraint for Unit Commitment Problem Considering High Penetration of Renewables

Ningchao Gao^{1,3}, Shuan Dong¹, Xin Fang², Andy Hoke¹, David Wenzhong Gao³, and Jin Tan¹

1. *National Renewable Energy Laboratory, Golden, CO, 80401, US*

2. *Department of Electrical and Computer Engineering, Mississippi State University, Starkville, MS, 39762, US*

3. *Department of Electrical and Computer Engineering, University of Denver, Denver, CO, 80210, US*

Abstract—As zero-carbon electricity systems become the trend of future grid, the system inertia provided by conventional synchronous generators (SGs) keeps decreasing. The resultant lower system inertia will inevitably cause frequency stability problem, especially in the first few seconds following disturbance. To tackle this challenge, this paper proposes a frequency stability constraint for power systems unit commitment problem by considering the fast frequency responses (FFRs) from inverter-based resources (IBRs). Our developed frequency stability constraint is grounded on an analytical frequency nadir estimation framework that considers both SG and IBR dynamics. The accuracy of our frequency nadir estimation framework is validated by most severe N-1 contingency simulation result in a real island system. Then, the adaptive inertia frequency stability constraint is derived by performing sensitivity analysis with our frequency nadir estimation framework. Finally, we demonstrate the effectiveness of our developed frequency stability constraint with one year day-ahead unit commitment results of the island system.

Index Terms—Fast frequency response, frequency nadir, inverter-Based Resources, stability constraint, unit commitment.

I. INTRODUCTION

THE increasing penetration of Inverter-Based Resources (IBRs) in power grids, particularly in islanded systems, is necessitating new considerations in unit commitment (UC) problems. The traditional role of synchronous generators (SGs) in providing inherent inertia to resist frequency changes is being disrupted by the influx of IBRs, which have different dynamical response characteristics compared with SGs. However, recent advancements in control strategies and technological solutions have opened up possibilities for IBRs to contribute positively to frequency stability.

With these advancements, understanding how to best incorporate frequency stability constraints into UC while considering IBRs' FFR becomes a complex and challenging problem. It requires the development of advanced mathematical models and optimization algorithms that can handle the complex dynamics and uncertainties associated with these resources, while ensuring the cost-effectiveness and reliability of power system operations [1]–[3]. With the trend towards renewables, how to consider IBRs' contributions in power system scheduling problems like UC is indeed becoming a paramount topic in power systems research and practice [4]–[8].

The authors in [9], [10] employed differential algebraic equations (DAEs) to capture the dynamic frequency response

of the system, providing a more accurate and realistic representation of system dynamics than traditional steady-state optimal power flow models. Since only a single type of SG turbine governor model is considered, this limits the general applicability of the model. This is because the real-world power systems typically include various types of turbine governor models, each with unique dynamic characteristics.

Thus, this paper proposes an adaptive inertia frequency stability constraint for the UC problems, which considers the largest contingency in power systems analytically. Our key contributions are as follows:

- 1) Validate the accuracy of the dynamic frequency nadir prediction framework in predicting the island system's frequency nadir following disturbances.
- 2) Develop an adaptive inertia frequency stability constraint for UC problem.
- 3) Include our developed stability constraint to the NREL-developed framework Multi-Timescale Integrated Dynamic and Scheduling (MIDAS) and validate its effectiveness on the island system [11].

The rest of this paper is organized as follows: Section II introduces the frequency nadir estimation framework, which predicts the largest time constant of different governor and IBR models, and computes the aggregated parameters of a real island system. Section III proposes adaptive inertia frequency stability constraint. Section IV performs the case study to demonstrate the effectiveness of the added frequency stability constraint in improving frequency dynamics. Section V concludes the paper.

II. FREQUENCY NADIR ESTIMATION

The authors in [12] propose a frequency nadir estimation framework which is summarized in (1)-(3) below:

$$f_{nadir} = f_n + \frac{P_{sus} - P_{genmax}}{D_\Sigma + R_g^{-1}} - \frac{T_g R_g^{-\frac{1}{2}} M e^{\alpha - \phi - \pi \cot \phi}}{(t_2 - t_1)(D_\Sigma + R_g^{-1})^{\frac{3}{2}}}, \quad (1)$$

$$\zeta = \frac{1}{2} \left(\frac{D_\Sigma}{2H_\Sigma} + \frac{1}{T_g} \right) \sqrt{\frac{2T_g H_\Sigma}{D_\Sigma + R_g^{-1}}} = \cos \phi, \quad (2)$$

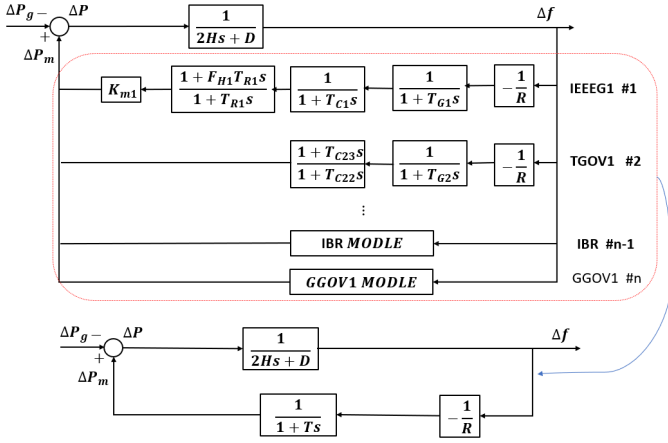


Fig. 1. Low- and Full-order SFR models of Governor and IBR

$$m(t) = P_{sus} e^{\zeta \omega_n t_2} \sin(\omega_d(t - t_2) - \beta - \phi) - P_{sus} e^{\zeta \omega_n t_1} \sin(\omega_d(t - t_1) - \beta - \phi) - \Delta P_{load} \omega_n (t_2 - t_1) \sin(\omega_d t - \beta), \quad (3)$$

where f_{nadir} is the grid frequency nadir in most severe N-1 contingency, f_n is the rated grid frequency, P_{sus} is the IBR step response, P_{genmax} is the active-power output of the largest generation unit, D_Σ is the aggregated damping constant, R_g is the aggregated droop constant, T_g represent the grid's aggregated time constant, and H_Σ is the aggregated system inertia constant [12].

A. Low-Order Approximated SG Governor and IBR Models

In the island system model, there are three types of SG governors, i.e., IEEEG1, TGOV1, and GGOV1. Among them, TGOV1 and GGOV1 have particularly complex control models, and this precludes us from analyzing them. In [13] and [14], a low-order system frequency response (SFR) model has been proposed, which neglects nonlinearities and all but the most significant time constants. This low-order SFR model provides a simple but accurate method to estimate complex generator models [15]. This paper uses the low-order SFR model to predict the most prominent time constant of SG governors and the IBR model. As shown in Fig. 1, we build both low- and full-order SFR models of governor and IBR in PSCAD and adjust the most prominent time constant in low order SFR model. In so doing, we expect the frequency response of low-order model to approximate that of the full-order model. From Fig. 2, we can get the low-order model of IEEEG1, and TGOV1 can precisely predict the full-order model dynamics. We note that the low-order model of GGOV1 cannot track the full-order model's steady-state frequency perfectly but can predict the frequency nadir with high precision.

B. Frequency Nadir Estimation

Here, we validate the accuracy of the frequency nadir prediction method with the island system model. To achieve this, we use one-day real-time economic dispatch (RTED) results with 288 snapshots, trip the largest generator, and

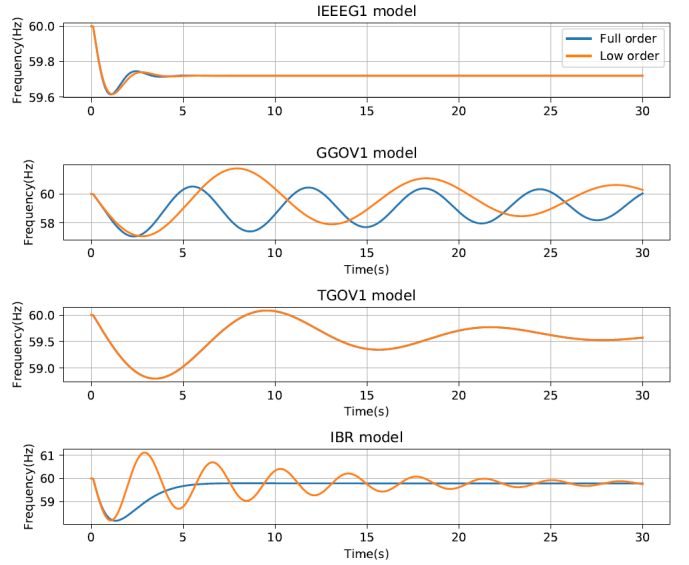


Fig. 2. Comparison between full- and low-order system frequency response.

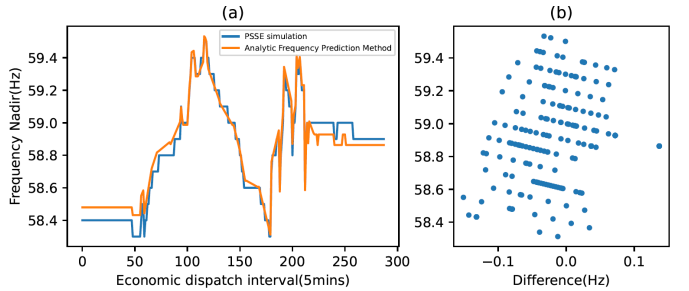


Fig. 3. Comparison between simulated and predicted frequency nadirs following most severe N-1 contingency in island power systems.

compare the frequency nadirs between PSS/E dynamic simulation results and our analytic frequency nadir predictions. Figure. 3(a) shows that our analytical prediction of frequency nadir (orange trace) aligns well with PSS/E simulation results (blue trace). Also, based on Fig. 3(b), the frequency nadir difference between PSS/E simulation and analytic prediction method is very small, and 90 percent of these differences are limited within ± 0.1 Hz.

III. FREQUENCY STABILITY CONSTRAINT

This section leverages the sensitivity analysis method to analyze all the aggregated system frequency response (ASFR) model parameters for the island system. We note that two ASFR model parameters, i.e., the largest generation unit loss $P_{genloss}$ and system inertia H_Σ , have a high correlation with frequency nadir.

In Fig. 4, the blue points reflect the relationship between $P_{genloss}$ (P_{genmax}) and system inertia H_Σ when the post-disturbance frequency nadir is 59 Hz. By visually checking those blue points, we can find that while increasing the largest output of the generator, a larger system inertia is required to secure the frequency nadir above 59 Hz. So, we select the upper bound of these blue data points (red line) as the

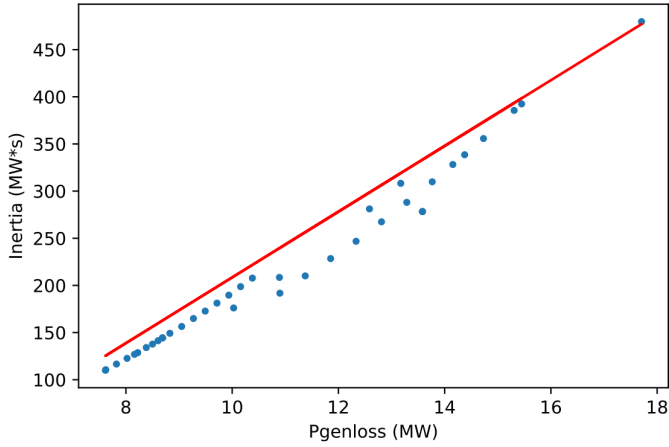


Fig. 4. Approximate linear frequency stability constraint obtained by taking the upper bound of original data points computed from (1)–(3).

frequency stability constraint, which is also expressed in (4) below.

$$H_{\Sigma} \leq k \cdot P_{genmax} + b, \quad (4)$$

where k and b is obtained from the sensitivity analysis of the frequency nadir estimation framework. For the case in Fig. 4, k and b , respectively, take 34.8 and -140. Recall that our frequency stability constraint is developed based on the points when the frequency nadir is precisely 59 Hz. Thus, by including our developed frequency constraint (red trace), we expect that the post-disturbance frequency nadir will not be lower than 59 Hz.

With our developed linear frequency nadir stability constraint (4) in place, we can include it into the UC model in MIDAS framework developed by NREL [11].

IV. CASE STUDIES

In this section, we conduct two case studies to evaluate the effectiveness of our developed frequency stability constraints: the base case without our constraint and the Freq. Const. case with our constraint. In both cases, the SG capacity is 167 MW, and the governor model includes IEEE1, TGOV1, and GGOV1. The total renewable capacity is 375 MW, and the penetration level of renewable is 70%. Figure 5 shows the PV input, wind input, and load time series curve in our two designed case studies. We note that for illustrative purpose, Fig. 5 only plot the first 336 hours (two weeks) of time series data to show the detail.

The proposed adaptive inertia frequency stability constraint unit commitment is considered in day-ahead unit commitment (DAUC) problem. After solving one-year DAUC, we get 8760 generation scheduling results, in which the largest output of generator and battery for base case and Freq. constr. case and are shown in Fig. 6. Based on Fig. 6, it is evident that the largest generator output in the base case is larger than that in the Freq. constr. case. This is because based on our developed frequency stability constraint in (4), the system inertia restricts the generator largest output P_{genmax} .

We plot the N-1 contingency PSS/E simulation result in Fig. 7. Based on Fig. 7(a), 99% of the frequency nadirs in

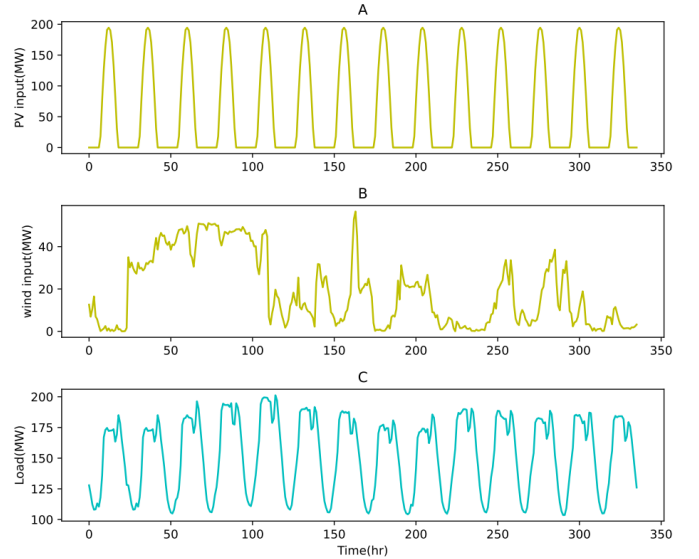


Fig. 5. Time-series data of available PV sources, wind source, and Load demand within two weeks.

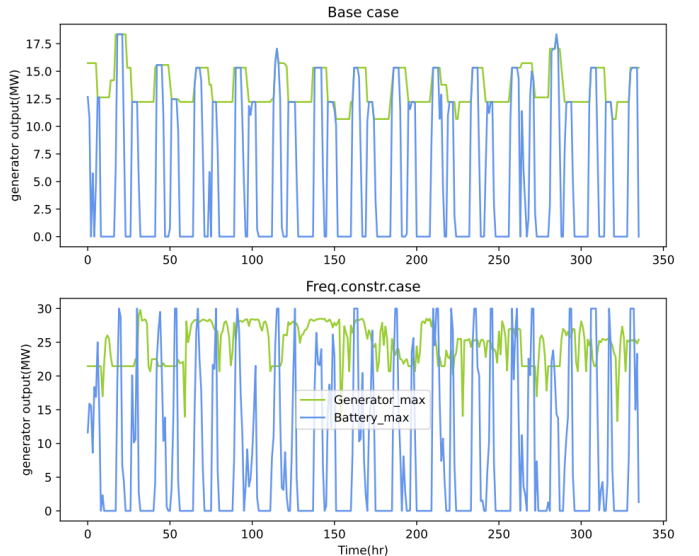


Fig. 6. Largest outputs of generators and batteries in base case and Freq. Const. case.

the base case (blue trace) are below 59 Hz in the period of 8760 hours. While in the freq. constr. case, 98% of frequency nadirs remain above 59 Hz. Specially, figure 7(b) depicts the frequency nadirs within first 100 hours. Similarly, we can find that 97% of the frequency nadirs in the base case are below 59 Hz, but all the frequency nadirs in the Freq. Constr. case are above 59 Hz. In addition, as shown in Table I, the Freq. constr. case's total generation cost increases by 20% compared with the base case. This is because our frequency constraint limits the largest output from the conventional generators and renewables.

V. CONCLUSION

This paper proposes an Adaptive Inertia Frequency Stability Constraint for UC problems. Our developed constraint aims

TABLE I
GENERATION COST COMPARISON OF BASE CASE AND FREQUENCY
CONSTRAINT CASE FOR ONE YEAR DAY-AHEAD UNIT COMMITMENT
(DAUC)

Case	Generation Cost (\$)
Base Case	135,839,782
Freq. Constr. Case	168,386,186

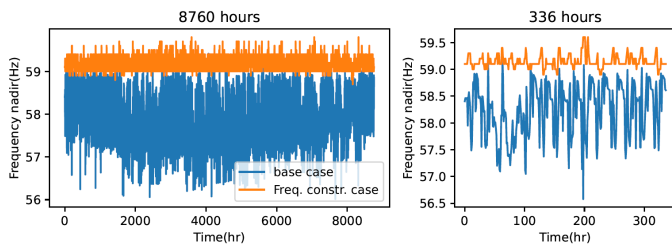


Fig. 7. Comparison of post-disturbance frequency nadir results between base case (blue trace) and Freq. Const. case (orange trace).

to contains the frequency nadir above certain threshold value following the largest N-1 contingency. Then, we validate our frequency stability constraint in DAUC scheduling problems through N-1 PSS/E dynamic simulation results. Specifically, the result shows that our constraint can guarantee 98% of the system frequency nadirs are above the under-frequency load shedding setting point (59 Hz) following most severe N-1 contingency. Compared with the base case, our constraint improves the frequency stability significantly. But we note that the total generation cost will increase by 20% while including our frequency nadir stability constraint. In future work, we will explore how to optimally dispatch more IBRs to provide inertia response instead of pushing more SGs online.

ACKNOWLEDGMENT

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 37772. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

REFERENCES

- [1] X. Fang, Q. Hu, F. Li, B. Wang, and Y. Li, "Coupon-based demand response considering wind power uncertainty: A strategic bidding model for load serving entities," *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1025–1037, 2016.
- [2] X. Liu, J. Xie, X. Fang, H. Yuan, B. Wang, H. Wu, and J. Tan, "A comparison of machine learning methods for frequency nadir estimation in power systems," in *2022 IEEE Kansas Power and Energy Conference (KPEC)*, 2022, pp. 1–5.

- [3] W. Wang, X. Fang, H. Cui, F. Li, Y. Liu, and T. J. Overbye, "Transmission-and-distribution dynamic co-simulation framework for distributed energy resource frequency response," *IEEE Transactions on Smart Grid*, vol. 13, no. 1, pp. 482–495, 2022.
- [4] X. Zhao, H. Wei, J. Qi, P. Li, and X. Bai, "Frequency stability constrained optimal power flow incorporating differential algebraic equations of governor dynamics," *IEEE Trans. Power Syst.*, vol. 36, no. 3, pp. 1666–1676, 2021.
- [5] H. Ahmadi and H. Ghasemi, "Security-constrained unit commitment with linearized system frequency limit constraints," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1536–1545, 2014.
- [6] J. Restrepo and F. Galiana, "Unit commitment with primary frequency regulation constraints," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1836–1842, 2005.
- [7] N. Gao, D. W. Gao, and X. Fang, "Manage real-time power imbalance with renewable energy: Fast generation dispatch or adaptive frequency regulation?" *IEEE Transactions on Power Systems*, pp. 1–12, 2022.
- [8] X. Fang, K. S. Sedzro, H. Yuan, H. Ye, and B.-M. Hodge, "Deliverable flexible ramping products considering spatiotemporal correlation of wind generation and demand uncertainties," *IEEE Transactions on Power Systems*, vol. 35, no. 4, pp. 2561–2574, 2020.
- [9] S. G. Vennelaganti and N. R. Chaudhuri, "Stability criterion for inertial and primary frequency droop control in mtdc grids with implications on ratio-based frequency support," *IEEE Trans Power Syst.*, vol. 35, no. 5, pp. 3541–3551, 2020.
- [10] H. Ahmadi and H. Ghasemi, "Security-constrained unit commitment with linearized system frequency limit constraints," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1536–1545, 2014.
- [11] J. Tan *et al.*, "Final technical report: Multi-timescale integrated dynamics and scheduling for solar (midas-solar)," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2023.
- [12] S. Dong, X. Fang, J. Tan, X. Cui, and A. Hoke, "Analytical frequency nadir prediction considering inverter-based fast frequency responses," <https://arxiv.org/abs/2209.09413>, 2022.
- [13] D. L. H. Aik, "A general-order system frequency response model incorporating load shedding: analytic modeling and applications," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 709–717, 2006.
- [14] P. Anderson and M. Mirheydar, "A low-order system frequency response model," *IEEE Trans. Power Syst.*, vol. 5, no. 3, pp. 720–729, 1990.
- [15] Q. Shi, F. Li, and H. Cui, "Analytical method to aggregate multi-machine sfr model with applications in power system dynamic studies," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6355–6367, 2018.