Frequency Response Characteristic (FRC) Curve and Fast Frequency Response Assessment in High Renewable Power Systems

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Abstract—This letter introduces a frequency response characteristic (FRC) curve and its application in high renewable power systems. In addition, the letter presents a method for fast frequency response assessment and frequency nadir prediction without performing dynamic simulations using detailed models. The proposed FRC curve and fast frequency response assessment method are useful for operators to understand frequency response performance of high renewable systems in real time.

Index Terms—Frequency response characteristic (FRC) curve, frequency response, renewable generation, governor.

I. INTRODUCTION

Since the increase of renewable penetration decreases system inertia and governor response, power system frequency response has become a major concern of high renewable power systems [1-28]. The common approach to evaluate system steady-state frequency response is a constant value $\beta$ whose unit is MW/0.1 Hz [29-33]. It is also referred to as Frequency Response Obligation (FRO). This value gives a power system’s real power generation increase per 0.1 Hz system frequency decrease. However, this constant value cannot depict the non-linearity caused by governor deadbands and generator headroom limits, as well as various emerging frequency-responsive resources [34-36]. Consequently, operators can hardly evaluate the system frequency response capability over a range of frequency deviations [37-56]. This letter introduces a power system frequency response characteristic (FRC) curve, as a more comprehensive metric for evaluating the frequency response capability accurately and procuring frequency response sources cost-effectively. In addition, a simplified frequency response model is proposed for fast prediction of frequency nadir, which supports the decision of under-frequency remedial strategies.

II. FREQUENCY RESPONSE CHARACTERISTIC CURVE AND FAST FREQUENCY RESPONSE ASSESSMENT

A. Frequency Response Characteristic (FRC) Curve

The proposed FRC curve is defined as the system steady-state frequency response capability at different frequency deviation levels. It is an extension of the commonly used $\beta$ value, which can only represent a linear relation between system response and frequency deviation. Incorporating non-linear characteristics from both governor response and load damping, the FRC curve can help operators easily perceive system frequency response capability after different magnitudes of contingencies and at various frequency deviation levels. The FRC curve can be obtained based on data available in the control centers, including the unit on/off statuses, parameters of governors (such as deadbands, droop ratios, and headroom), and the damping of loads.

$$F_{FRC} = \sum_{i=1,N} x_i \cdot f_i + f_L$$

where $F_{FRC}$ is the system FRC curve. $x_i$ and $f_i$ are the on/off status and each unit’s FRC curve, respectively. $f_L$ is the load damping characteristic. The formulation of the system FRC curve is summarized graphically in Fig. 1. Using the operation

This work was supported by the U.S. Department of Energy SunShot Office SuNLaMP program under award number 30844 and also made use of Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

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plan of each unit, the FRC curve can also be conveniently updated in real time and predicted in short term by superimposing the frequency response characteristic of this unit onto the original FRC curve:

$$ F_{FRC} = F_{FRC} + \sum \Delta f_i $$

(2)

where $F_{FRC}$ is the FRC curve for previous period; $\Delta f_i$ is the frequency response characteristic of newly-turned-on unit $i$. Taking various profiles, $\Delta f_i$ can represent any resource that provides frequency response, including synthetic governors from inverters of renewables and energy storage. Fig. 2 shows an example of updating the system FRC curve after turning on a governor-responsive unit with deadband and headroom.

### B. Fast Frequency Response Assessment (Frequency Nadir Prediction)

For power systems with obvious frequency nadir in frequency response, such as the U.S. Electric Reliability Coordination Council of Texas system (ERCOT) and Western Electricity Coordinating Council (WECC) systems, fast prediction of frequency nadir is very important for taking remedial measures to prevent under-frequency load shedding during frequency transient periods. As a transient attribute, frequency nadir prediction involves system inertia and dynamics of governors and turbines. The block diagram shown in Fig. 3 is proposed for fast assessment of frequency response and prediction of the frequency nadir. In this approach, the inertia $H$ is estimated based on the current operation plan (on/off status) submitted by each generator [57]. The aggregation of governors and turbine models is performed based on clustering governor/turbine dynamic models and associated parameters, which are largely determined by the technology type and capacities of in-service generators. For ‘always-on’ units (continuously operating for more than 24 hours), the clustering and aggregation are performed off line, while shoulder-load and peak-load units are modeled individually for update convenience during operation.

III. CASE STUDIES

This case study is based on the detailed models of two interconnections of the U.S.: the Eastern Interconnection system (EI) and the ERCOT. For each system, a series of models representing high renewable scenarios have been developed [21]. The obtained FRC curves of EI in different renewable penetration scenarios are shown in Fig. 4. In this figure, the turn points of the FRC curves near 59.964 Hz (the dash line) reflect the effects of governor deadbands on system frequency response (0.036 Hz is the common deadband value in the EI system). The green circles represent the EI steady-state frequency obtained using the full dynamic simulation and applying different contingencies. These results show that FRC curve can provide operators an accurate picture of system frequency response capability adequacy at the full frequency band.

With less inertia compared with the EI, the ERCOT shows an obvious nadir in frequency response, which is a focus point of ERCOT operators. Fig. 5 is a comparison of the fast frequency response assessment result and the detailed model result of ERCOT. It shows that the proposed model can accurately predict the frequency nadir, alerting the potential need for under-frequency remedial actions. In addition, as a
supplementary of the proposed FRC curve, which addresses frequency response capacity adequacy, the proposed model can help operators and planners evaluate the impact of deployment time of frequency response resources, which is critical for low-inertia systems.

IV. CONCLUSIONS

This letter introduces a frequency response characteristic (FRC) curve and its application in high renewable power systems. In addition, the letter presents a method for fast frequency response assessment and frequency nadir prediction without performing dynamic simulations using detailed models. The effectiveness of the proposed technology in predicting the frequency nadir is verified in the ERCOT study system. The proposed FRC curve and fast frequency response assessment method are useful for operators to understand frequency response performance of high renewable systems in real time.

REFERENCES

1. Li, H., et al., Analytic analysis for dynamic system frequency in power systems under uncertain variability. IEEE Transactions on Power Systems, 2018. 34(2): p. 982-993.
2. You, S., et al., Comparative assessment of tactics to improve primary frequency response without curtailing solar output in high photovoltaic interconnection grids. IEEE Transactions on Sustainable Energy, 2018. 10(2): p. 718-728.
3. You, S., et al., Co-optimizing generation and transmission expansion with wind power in large-scale power grids—Implementation in the US Eastern Interconnection. Electric Power Systems Research, 2016. 133: p. 209-218.
4. You, S., et al. Data architecture for the next-generation power grid: Concept, framework, and use case. in 2015 2nd International Conference on Information Science and Control Engineering. 2015. IEEE.
5. Zhao, J., et al. Data quality analysis and solutions for distribution-level PMU’s. in 2019 IEEE Power & Energy Society General Meeting (PESGM). 2019. IEEE.
6. Liu, Y., et al., A distribution level wide area monitoring system for the electric power grid—FNET/GridEye. IEEE Access, 2017. 5: p. 2329-2338.
7. You, S., et al., Disturbance location determination based on electromagnetic wave propagation in FNET/GridEye: a distribution-level wide-area measurement system. IET Generation, Transmission & Distribution, 2017. 11(18): p. 4436-4443.
8. Hadley, S., et al., Electric grid expansion planning with high levels of variable generation. ORNL/TM-2015/515, Oak Ridge National Laboratory, 2015.
9. You, S., Electromechanical Dynamics of High Photovoltaic Power Grids. 2017.
10. You, S., et al. Energy Storage for Frequency Control in High Photovoltaic Power Grids. in IEEE EUROCON 2019-18th International Conference on Smart Technologies. 2019. IEEE.
11. Guo, J., et al. An ensemble solar power output forecasting model through statistical learning of historical weather dataset. in 2016 IEEE Power and Energy Society General Meeting (PESGM). 2016. IEEE.
12. Yao, W., et al., A fast load control system based on mobile distribution-level phasor measurement unit. IEEE Transactions on Smart Grid, 2019. 11(1): p. 995-904.
13. Li, J., et al., A fast power grid frequency estimation approach using frequency-shift filtering. IEEE Transactions on Power Systems, 2019. 34(3): p. 2461-2464.
14. Wang, J., et al., Flexible transmission expansion planning for integrating wind power based on wind power distribution characteristics. J. Electr. Eng. Technol, 2015. 10: p. 709-718.
15. You, S., et al. FNET/GridEye for Future High Renewable Power Grids—Applications Overview. in 2018 IEEE PES Transmission & Distribution Conference and Exhibition-Latin America (T&D-LA). 2018. IEEE.

Yuan, Z., et al. Frequency control capability of Vsc-Hvdc for large power systems. in 2017 IEEE Power & Energy Society General Meeting. 2017. IEEE.
Liu, Y., et al., Frequency response assessment and enhancement of the US power grids toward extra-high photovoltaic generation penetrations—An industry perspective. IEEE Transactions on Power Systems, 2018. 33(3): p. 3438-3449.
Tan, J., et al. Frequency Response Study of US Western Interconnection under Extra-High Photovoltaic Generation Penetrations. in 2018 IEEE Power & Energy Society General Meeting (PESGM). 2018. IEEE.
Zhang, X., et al., Frequency Response Study on the ERCOT under High Photovoltaic (PV) Penetration Conditions. IEEE Transactions on Smart Grid, 2019. 10(2): p. 1142-1152.
You, S., et al., Impact of high PV penetration on the inter-area oscillations in the US eastern interconnection. IEEE Access, 2017. 5: p. 4361-4369.
Till, A., S. You, and Y. Liu, Impact of High PV Penetration on Transient Stability—a Case Study on the US ERCOT System. IEEE Transactions on Power Systems, 2017. 32(4): p. 2329-2338.
Sharma, S., et al., Comparative assessment of tactics to improve primary frequency response in high renewable systems in real time. in 2017 IEEE Power & Energy Society General Meeting. 2017. IEEE.
Zhang, Y., et al., Impacts of power grid frequency deviation on time error of synchronous electric clock and worldwide power system practices on time error correction. Energies, 2017. 10(9): p. 1283.
Mu, Y., et al., Primary frequency response from electric vehicles in the Great Britain power system. IEEE Transactions on Smart Grid, 2012. 4(2): p. 1142-1152.
Holdsworth, L., J.B. Ekanayake, and N. Jenkins, Power system frequency response from fixed speed and doubly fed induction generator - based wind turbines. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology, 2004. 7(1): p. 21-35.
Anderson, P.M. and M. Mirheydard, A low-order system frequency response model. IEEE Transactions on Power Systems, 1990. 5(3): p. 720-729.
Sharma, S., et al., Impacts of power grid frequency deviation on time error of synchronous electric clock and worldwide power system practices on time error correction. Energies, 2017. 10(9): p. 1283.
40. Zhang, X., et al. Measurement-based power system dynamic model reductions. in 2017 North American Power Symposium (NAPS). 2017. IEEE.

41. Wu, L., et al. Multiple Linear Regression Based Disturbance Magnitude Estimations for Bulk Power Systems. in 2018 IEEE Power & Energy Society General Meeting (PESGM). 2018. IEEE.

42. You, S., et al., Non-invasive identification of inertia distribution change in high renewable systems using distribution level PMU. IEEE Transactions on Power Systems, 2017. 33(1): p. 1110-1112.

43. Wang, R., et al. A Novel Transmission Planning Method for Integrating Large-Scale Wind Power. in 2012 Asia-Pacific Power and Energy Engineering Conference. 2012. IEEE.

44. You, S., et al., Oscillation mode identification based on wide-area ambient measurements using multivariate empirical mode decomposition. Electric Power Systems Research, 2016. 134: p. 159-166.

45. Liu, Y., et al. Recent application examples of FNET/GridEye. in 2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG). 2018. IEEE.

46. Liu, Y., et al., Recent developments of FNET/GridEye—A situational awareness tool for smart grid. CSEE Journal of Power and Energy Systems, 2016. 2(3): p. 19-27.

47. You, S., et al. Ring-down oscillation mode identification using multivariate empirical mode decomposition. in 2016 IEEE Power and Energy Society General Meeting (PESGM). 2016. IEEE.

48. Lv, C., et al., Short-term transmission maintenance scheduling based on the Benders decomposition. International Transactions on Electrical Energy Systems, 2015. 25(4): p. 697-712.

49. Liu, Y., S. You, and Y. Liu. Smart transmission & wide area monitoring system. Communication, Control and Security for the Smart Grid, 2017.

50. Yao, W., et al., Source location identification of distribution-level electric network frequency signals at multiple geographic scales. IEEE Access, 2017. 5: p. 11166-11175.

51. Wu, L., et al. Statistical analysis of the FNET/grideye-detected inter-area oscillations in Eastern Interconnection (EI). in 2017 IEEE Power & Energy Society General Meeting. 2017. IEEE.

52. Liu, Y., S. You, and Y. Liu. Study of wind and PV frequency control in US power grids—EI and TI case studies. IEEE power and energy technology systems journal, 2017. 4(3): p. 65-73.

53. You, S., et al. A survey on next-generation power grid data architecture. in 2015 IEEE Power & Energy Society General Meeting. 2015. IEEE.

54. You, S., et al. US Eastern Interconnection (EI) Electromechanical Wave Propagation and the Impact of High PV Penetration on Its Speed. in 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D). 2018. IEEE.

55. Zhang, X., et al. US eastern interconnection (EI) model reductions using a measurement-based approach. in 2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D). 2018. IEEE.

56. Medina, D.R., et al., Fast assessment of frequency response of cold load pickup in power system restoration. IEEE Transactions on Power Systems, 2015. 31(4): p. 3249-3256.

57. Du, P. and J. Matevosyan, Forecast System Inertia Condition and Its Impact to Integrate More Renewables. IEEE Transactions on Smart Grid, 2017.