Investigation of Inertia's Locational Impacts on Primary Frequency Response using Large-scale Synthetic Network Models

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***Abstract*—As more renewable energy resources connected by power electronics and gas-fueled generators are integrated into power grids, total system inertia has been significantly decreasing in recent years. The resulting decline in system primary frequency response threatens the reliability and stability of power grids. This paper aims to study the locational dependence of the impacts of inertia on system primary frequency response. Both transient stability simulations and modal analysis are applied to study the locational effects. Sensitivity analysis is also carried out to provide insights into the extent to which inertia's location impacts the system dynamic behavior. We first use a small-scale test system to illustrate inertia's locational impacts. In order to obtain realistic simulation results, we then perform studies on a large-scale synthetic network dynamic model.**

***Index Terms*—inertia, primary frequency response, synthetic network dynamic model, locational impact, transient stability, time-domain simulation, modal analysis**

I. Introduction

THE ability to maintain frequencies within the desired range is important for a reliable and secure power system. The inertia of a machine is seen by the system as the injection or withdrawal of electrical energy in response to a change of frequency. Inertia mainly contributes to primary frequency response (PFR), occurring in the first several seconds after contingency events. However, the integration of light-weight generation units and the development of renewable energy resources connected via electronic devices cause a significant reduction of total system inertia. With less inertia, small events could result in larger frequency excursions. The minimum/maximum rate of change of frequency (RoCoF) and the minimum/maximum frequency during the first several seconds after disturbances are commonly used to evaluate the system PFR performances [1]. Reports [2], [3] by the North American Electric Reliability Corporation indicated a declining frequency response in both the Eastern Interconnection (EI) and the Electric Reliability Council of Texas (ERCOT) footprints. A simulation-based process was developed in [4] to estimate system inertia constant. Papers [5] and [6] focused on the development of a mathematic, closed-form expression for power system dynamic response using a simplified model without consideration of network effects. In [2], [3], [7], authors evaluated the impact of reduced inertia on system minimum post-contingency frequencies. In references [8], [9], authors performed time-domain simulations to analyze the impact of reduced inertia on frequency stability in consideration of deep wind energy penetration. Modal analysis was also applied in works [10], [11] for studies on inertia. Even though simulation results were presented in [12] to demonstrate locational dependence of the impacts of the virtual inertia services on system dynamic behavior, those studies were performed using small-scale test systems. As presented in [13], actual large-scale system models are used to simulate system frequency response so as to provide realistic, insightful results on impacts of the reduced inertia. Thus, this paper aims to study the locational impacts of the reduced inertia on the PFRs using large-scale synthetic network models that are available at [14].

This paper starts with simulations performed using an illustrative small-scale test system, followed by studies on a large-scale synthetic network model. Some extreme scenarios are constructed to show, for a power system, what aspects the inertia and its location have significant effects on. Several simulation cases with decreased total inertia from different regions are set up to show how the system PFR performance changes as the inertia reduces and the reduction location varies. To provide further insights into the locational impacts, sensitivity analysis is run to quantify the locational dependence of inertia's impacts. Specifically, we perform time-domain simulations and modal analysis for inertia studies.

In this paper, four more sections come as follows. Section II illustrates inertia's locational impacts using a small-scale test system. In Section III, simulations with reduced regional inertia of a large-scale synthetic system model are performed to show the locational dependence of the impacts of inertia on system PFR performance. Sensitivity studies are carried out to further quantify the locational effects in Section IV. Conclusion and future work direction are provided in Section V.

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II. Preliminary Studies: A Small-Scale Test Case

To reveal the system responses to varying resource inertia, this section uses a simple, straightforward 138-kV test system with three generators, as shown in Fig.1. All three transmission lines have reactance of 0.2 p.u.. The three-bus test system supply a load connected to bus 3 with purely real power consumption of 200 MW. Each bus is connected to a generator, modelled with GENCLS (machine) and TGOV1 (governor).

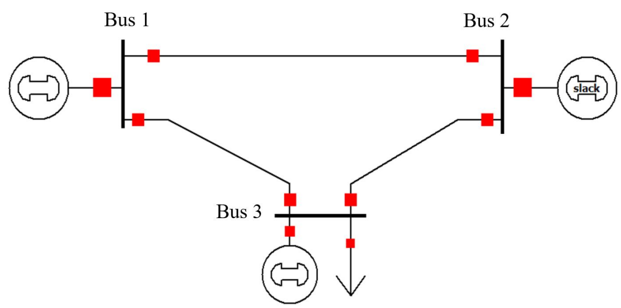

Fig. 1. Oneline diagram of a three-bus test system

The first contingency considers an under-frequency event with a sudden load increase by 10 MW at 1 second. Simulation results are visualized in Fig. 2 with the inertia reduced by a percentage from 0% to 50%. Given a fixed change

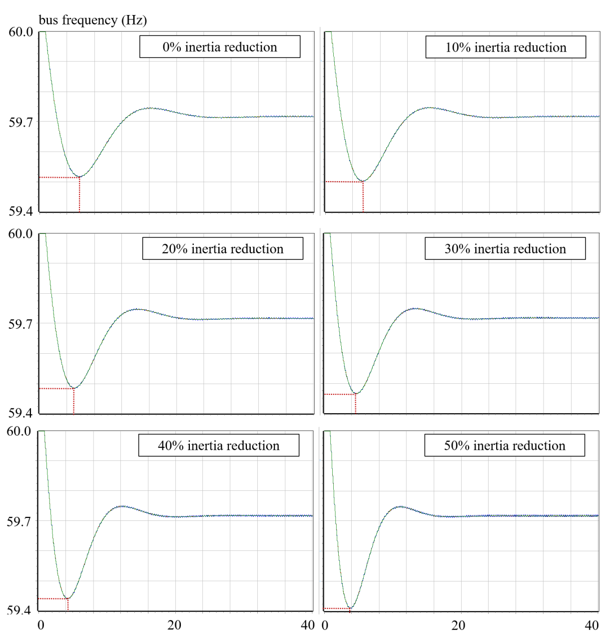

Fig. 2. Simulation results of an under-frequency event on the three-bus test system with varying inertia

rate of frequency, inertia reduction results in less electrical power converted from mechanical energy of rotating parts. Thus, decreasing inertia lowers the post-contingency minimum frequency and makes the frequency reach the minimum value earlier. In this small case, the system is tightly connected and, consequently, the generators swing together and the bus frequencies are very close to each other. Thus, when we consider 100-MWs inertia reduction individually at each generator, the frequency responses shown in Fig. 3 are almost the same for three cases. However, oscillation becomes more obvious when the generator 1 inertia is reduced. Thus, the inertia may also play an important role in the system oscillation modes.

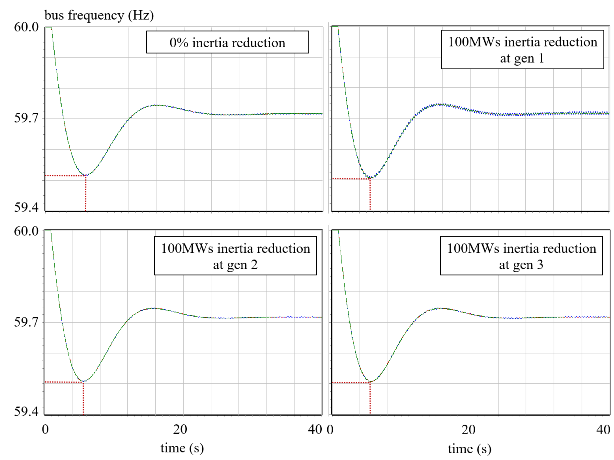

Fig. 3. Simulation results of an under-frequency event on the three-bus test system with inertia reduced at various locations

The impacts of inertia variation on system oscillation modes are studied in the second case, where a balanced 3-phase fault is applied to bus 1 at 1 second and cleared 0.01 second later. Generator speeds are shown in Fig. 4 with the inertia

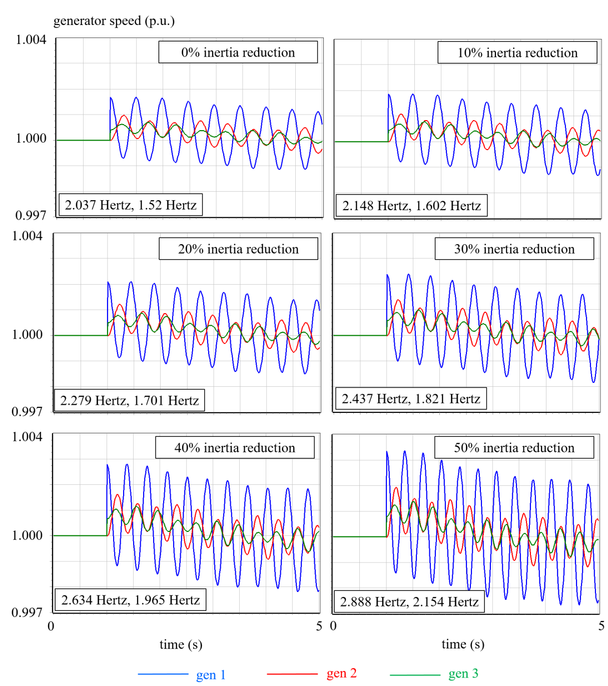

Fig. 4. Simulation results of a bus fault event on the three-bus test system with varying inertia

reduced by a percentage from 0% to 50%. Two significant poor-damped modes (as presented in Fig. 4) exists in the original three-bus system: one at 2.03 Hertz and one at 1.52 Hertz. As the inertia is reduced, these two poorly damped modes oscillate more frequently with higher magnitudes. This is because the inertia reduction causes faster bi-directional conversion between rotor mechanical energy and electricity, and thus the system is less capable to mitigate the oscillation. In addition, different from the observation in Fig. 3, oscillation frequency and magnitude vary when the inertia reduction occurs at different buses, as shown in Fig. 5. Generator 1 inertia mainly contributes to the first mode, while the inertia of remaining two generators impacts more on the second mode.

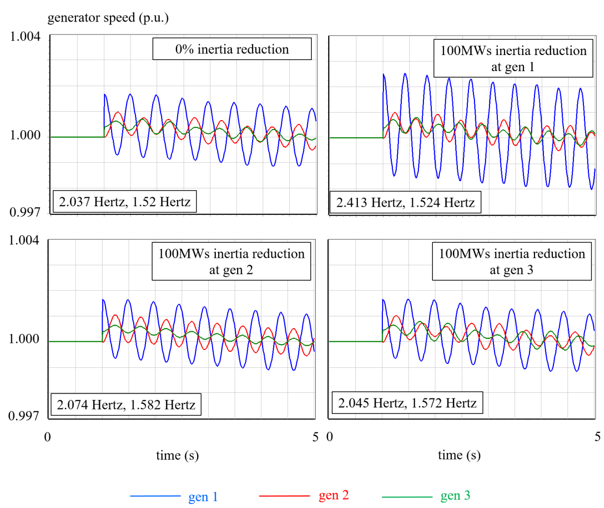

Fig. 5. Simulation results of a bus fault event on the three-bus test system with inertia reduced at various locations

Both cases demonstrate that inertia contributes to not only the frequency response, but also the system oscillation modes. The locational dependence of resource inertia's impacts on power system oscillation models is also observed in this small-test case system. However, inertia reduction at different locations makes indistinguishable impacts on the primary frequency responses for an under-frequency event. Therefore, in the remaining of this paper, we focus our simulations studies on system primary frequency responses after an under-frequency contingency event using synthetic large-scale test systems.

III. Locational Impacts of Inertia on System Primary Frequency Response

In this paper, we adopt a 2000-bus synthetic network that is built based on the ERCOT footprint and available at [14]. As shown in Fig.6, there are eight areas on the ERCOT footprint. Table. I summarizes the total system inertia of online generation units of each area. This paper uses the synthetic high-reserve case created in [15]–[18] to investigate the locational dependency of the impacts of inertia on system PFR performances. The system load is set to 33 GW with 7.2-GW wind capacity and 8-GW reserved capacity. A contingency event with a loss of 2,450-MW generation in area SCENT is considered in this section.

A. Preliminary Studies

This case contains a total moment of inertia to be about 167,000 MWs. This section presents several extreme simulation scenarios, in each of which inertia is set to be 0.1s for all but one generation unit in the specified location where the generation unit collects all the remaining inertia value (around 160,000 MWs). The five selected locations are Manor, Wadsworth, Monahans, Blue Ridge and Dension. Fig.7 shows that Monahans, Blue Ridge and Dension are far away from the contingency location, while Manor and Wadsworth are close to it.

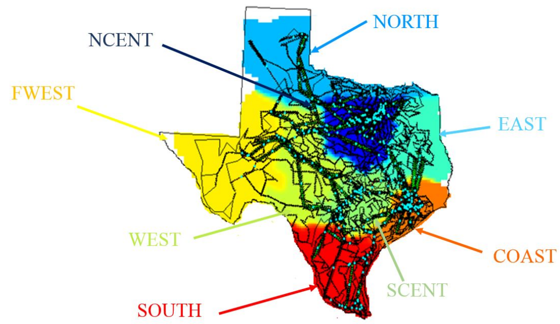

Fig. 6. Eight areas on the ERCOT footprint

TABLE I
Total inertia of online generation units of each area in the synthetic network dynamic model

Area Name	COAST	EAST	FWEST	WEST
Inertia (MWs)	50487	14364	7753	3931

Area Name	NCENT	NORTH	SCENT	SOUTH
Inertia (MWs)	28106	13221	34245	15189

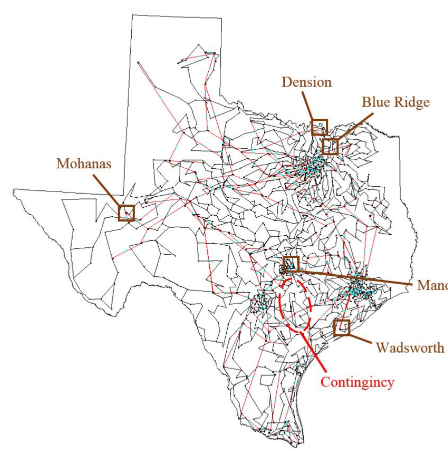

Fig. 7. The location of five selected generators in extreme scenarios

As shown in Fig.8, in terms of minimum frequencies, original $>>$ Manor $\approx$ Wadsworth $>$ Monahans $>$ Blue Ridge $>>$ Dension; in terms of damping performances, original $>>$ Manor $>$ Wadsworth $>$ Monahans $>>$ Blue Ridge $>>$ Dension. In particular, the system in Blue Ridge and Denison scenarios becomes unstable. Therefore, the preliminary study results reveal that the closer the inertia is to the contingency event, the more likely the inertial response could capture and eliminate the impacts of disturbances on the rest of system. In addition, inertia has significant impacts on the system oscillation modes and damping performances. We then perform more simulations to verify what we have observed from these extreme scenarios.

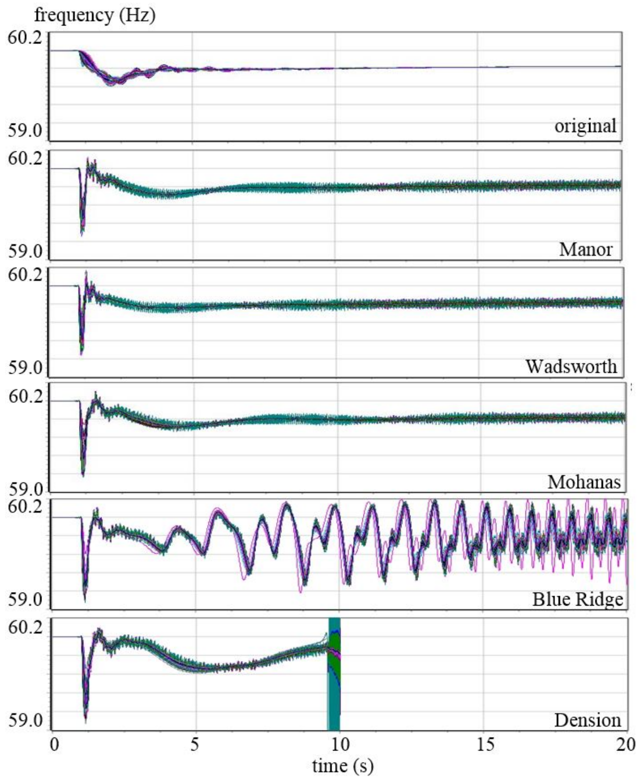

Fig. 8. Primary frequency response of the system in extreme scenarios

B. Simulation Setup

There are three regions with similar total inertia: R1 with COAST (case 1), R2 with SCENT and SOUTH (case 2), and R3 with NORTH, NCENT and FWEST (case 3). For each region, we proportionally reduce the inertia of each unit in that region such that the reduction in the regional total inertia varies from 0 MWs to 25,000 MWs in increment of 5,000 MWs. For comparisons, we perform the same simulations using the synthetic model with the reduced total inertia of the system varying from 0 MWs to 25,000 MWs in increment of 5,000 MWs (reference case 0).

C. Results and Discussions

Fig. 9 presents the range of minimum bus frequencies in each case [1]. As the regional inertia decreases, compared to the reference case, each case has significantly different minimum bus frequency ranges. For regions R1 and R2, the enlarging range of minimum frequency shows that the reduction in inertia results in worse PFR performances in terms of bus minimum frequency. However, different from regions R1 and R2, the reducing inertia in region R3 improves the PFR response. The contingency occurs much closer to generators in R1 and R2 than those in R3. Hence, in the first two cases, the generators near the contingency event are less capable to prevent the disturbance from spreading over the network and pick up the decreasing frequencies as the inertia is reduced in each region. As for the better PFR performance in the third case, this is because these generators from the nearby R1 and R2 regions make progressively more and more contribution as we reduce the inertia in R3. This observation verifies that the inertia changes in different locations not only have distinct impacts on the system PFR performances, but also may drive the system PFR performances to move in opposite directions.

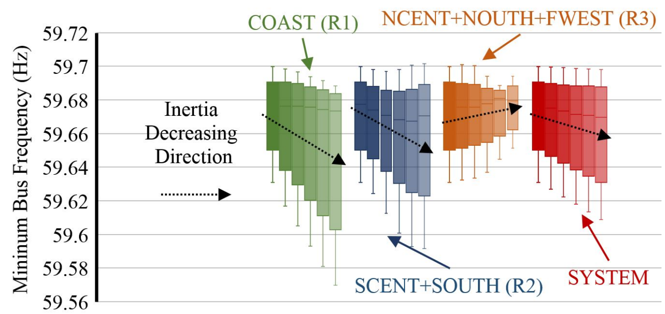

Fig. 9. Range of Nadir frequencies for all buses on the ERCOT footprint

We also compute the minimum system RoCoF [2], displayed in Fig. 10. With the reduction of the regional inertia, the minimum RoCoF value decreases correspondingly. This result is reasonable since the system with less inertia has less capability to resist the deviation of bus frequencies from the nominal value after contingencies. Since the contingency events occur in the region R2, the inertia reduction in region R2 has more significant impacts on the minimum system RoCoF.

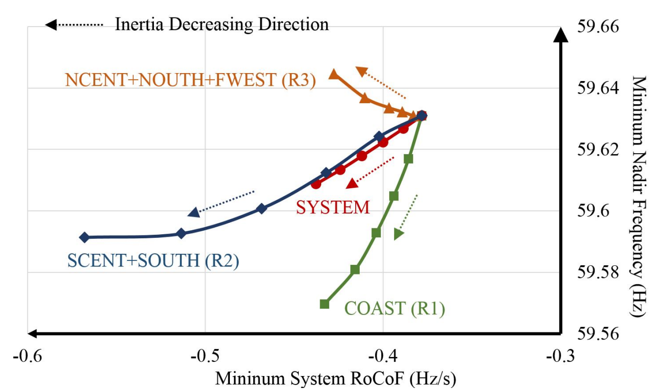

Fig. 10. Minimum bus Nadir frequency v.s. minimum system RoCoF

In addition, modal analysis [19] is performed to study what role the location plays in the modes of system frequency response. The locational dependency of the impacts of inertia on the system modes is clearly shown in Fig. 11. Compared to the results for the original case without any reduction in inertia, the regional inertia reduction significantly changes the

[1]For each boxplot, the upper and the lower bars correspond to the maximum and the minimum values of the Nadir frequencies, which the filled box covers the Nadir frequencies ranging from 10% to 90%.

[2]System RoCoF is computed by the average value of the RoCoF for each bus.

damping ratio for the two well-damped modes (enclosed in the dotted circle) and the fluctuation frequency for the three poorly-damped modes (enclosed in the solid circle). However, we also note that the inertia reduction in different regions have distinguishable impacts on the system modes. For instance, for the 0.8-Hz mode, the inertia reduction in region R3 has the most significant impacts (oscillation frequency increases) than those in other regions.

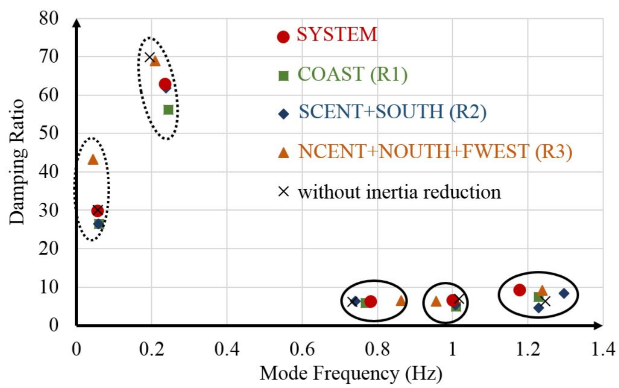

Fig. 11. Modal analysis results with 20000-MWs inertia reduction

To further study the effects of the locations on the system modes, we perform sensitivity studies on the inertia's locational impacts in the next section.

IV. Sensitivity Studies on Inertia's Locational Impacts using Modal Analysis

In this section, sensitivity studies are performed to assess the locational impacts of system inertia. The modal analysis is based on variable projection method (VPM) developed for industry use to determine the characteristic modes observed from time series analysis. For each region of R1, R2 and R3, modal analysis on bus frequencies is applied to see the movement of damping versus frequency, and the real part versus the imaginary part of eigenvalues. The total inertia in each region is decreased up to 70% (about 35,000 MWs) with 1% decrement. We consider a loss of 2,450-MW generation in area SCENT as in the previous section and five different cases as shown in Table II.

TABLE II
Case Summary in Sensitivity Study

Case	Contingency Location	Inertia Reduction Location
1	R2	R1
2	R2	R2
3	R2	R3
4	R1	R1
5	R3	R3

Fig.12 and Fig.13 show how the modes and roots change with respect to the inertia reduction from 0% (black circle) up to 70% (white circle), respectively, in the first three cases. For each mode, unique relationships between the four parameters are observed: a) when damping of a mode decreases, the real part moves to the right and vice versa; b) when frequency of a mode increases, the imaginary part increases and vice versa. The inverse relationship between damping and the real part is reasonable because as the damping decreases, the system becomes less stable hence the real part should move to the right. Also, frequency of a mode is in a proportional relationship with its imaginary part that corresponds to oscillations. These relationships are valid as the damping ratio is calculated as $-\frac{100\sigma_i}{\sqrt{\sigma_i^2+\omega_i^2}}$, where σ_i and $\omega_i = 2\pi f_i$ are the real and imaginary parts of the eigenvalue λ_i associated with each mode i.

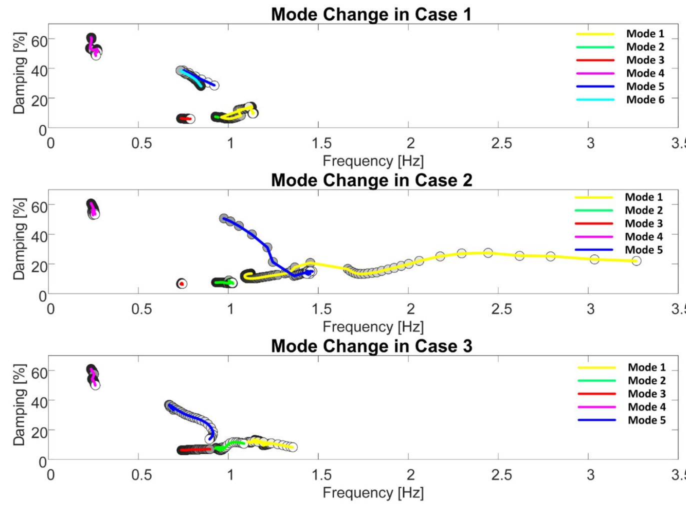

Fig. 12. Mode change with respect to inertia reduction in each region for a contingency in R2

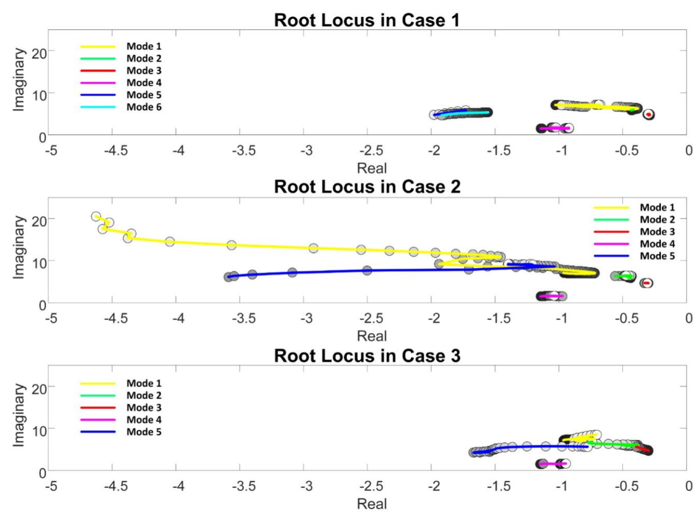

Fig. 13. Root locus with respect to inertia reduction in each region for a contingency in R2

In addition, inertia reduction in R2 where the contingency occurs has resulted in larger frequency changes in some modes and hence larger imaginary part movements. Real part movements of the same modes are bigger than those of other cases and the damping changes are more dramatic when inertia in R2 is reduced. This observation is reasonable because R2 has a shorter distance to the contingency location than other regions. Further simulations are needed to see if this applies when the contingency occurs in other regions.

Fig.14 and Fig.15 show the trend of mode changes and root locus when a contingency with a similar generation loss occurs in COAST and NORTH regions, respectively. The inertia of each region decreases from 0% (black circle) up to 70% (white circle). Here, Fig.14 (case 4) and Fig.15 (case 5) are compared with cases 1 and 3 in Fig.12 and Fig.13, respectively. As expected, the relationships between the four parameters are consistent for all simulations regardless of the location of the contingency. When a contingency occurs in a region with decreasing inertia, it tends to have more significant impacts on its modes. Especially, the frequency and the real part of some modes are more sensitive to the inertia reduction.

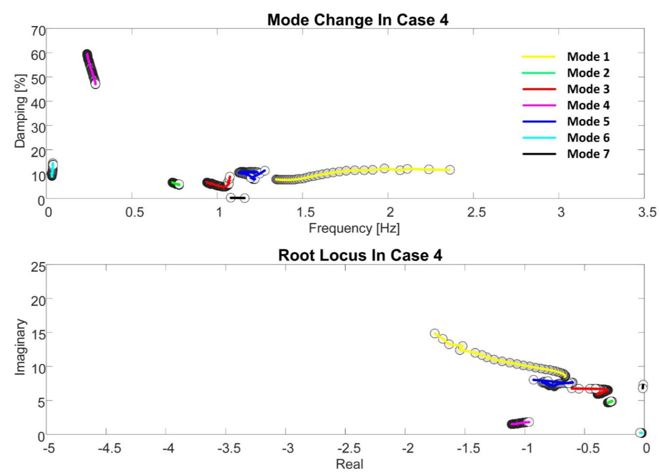

Fig. 14. Mode change and root locus with respect to inertia reduction in R1 for a contingency in R1 (case 4)

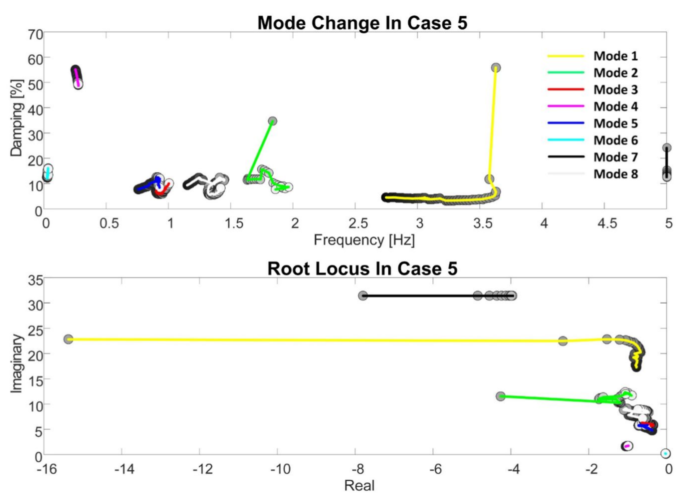

Fig. 15. Mode change and root locus with respect to inertia reduction in R3 for a contingency in R3 (case 5)

Another point to note is discontinuity characteristic of mode change and root locus as the inertia reduces. Some modes always exist from 0% all the way up to 70% of inertia reduction while other modes only show up in a particular period of inertia reduction. This may be due to the inertia decrement being too big so the subtle changes are not observed. However, reducing the resolution of inertia reduction (such as to 0.1%) does not reveal the vanishing modes. The VPM is a measurement-based approach and hence the modes with a trivial magnitude are not observable for a certain period of inertia reduction. For example, Mode 2 in case 1 (Fig.12) covers inertia reduction from 0% to 49% and Mode 5 covers from 65% to 70%. As shown in Fig.12 and Fig.13, the end of Mode 2 and the beginning of Mode 5 in case 1 almost collide, but there is a period of inertia reduction where the mode does not appear. These two modes could be continuous, but the magnitude of the mode in the period becomes too small to be observed. Further simulations are run to show that a threshold value in modal analysis can have obvious impacts on the observability of modes. The modal analysis method used in the paper has Singular Value Threshold which is set to 0.025 for all simulations. When the value is lowered, more modes are observable and all the existing modes with the original threshold have slightly different parameter values in order to match the original signal with more number of modes.

In this section, we carried out several studies to reveal the sensitivity of modal analysis results with respect to the inertia reduction in different regions. Simulation results further demonstrate that the impacts of inertia on system dynamic behavior vary by its location from the oscillation mode prospective of view.

V. Conclusion

In this work, we apply an illustrative small-scale test system and a large-scale synthetic dynamic model to investigate the location-dependent impacts of inertia on power system primary frequency response. Both time-domain simulation and modal analysis results indicate that the impacts of inertia on power systems vary by location. As such, inertia should be an important factor to be taken into consideration during power system planning, generator sitting and some other applications related to power system transient stability.

Further studies may focus on investigating the impacts of concentrated solar plants on power system dynamics due to its inherent cheap storage thermal devices and conventional steam generator, compared to other renewable energy resources. Influences of deepening penetration of both wind and solar energy resources on power system dynamic performances are of interest as well. Replacement of conventional units by light- or zero-inertia units will be considered to study the locational impacts of inertia. Given the location-dependent values and impacts of inertia, it is also of interest to construct a comprehensive market simulation tool with integration of dynamic performance security constraints. We will report these studies in future work.

References

[1] W. Freitas, W. Xu, C. M. Affonso, and Z. Huang, "Comparative analysis between rocof and vector surge relays for distributed generation applications," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1315–1324, April 2005.

[2] NERC, “Balancing and frequency control,” January 2011. [Online]. Available: http://www.nerc.com/docs/oc/rs/NERC\%20Balancing\%20and\%20Frequency\%20Control\%20040520111.pdf.
[3] ——, “Frequency response initiative report,” October 2012. [Online]. Available: http://www.nerc.com/docs/pc/FRI_Report_10-30-12_Master_w-appendices.pdf.
[4] P. Wall, F. Gonzlez-Longatt, and V. Terzija, “Demonstration of an inertia constant estimation method through simulation,” in *Universities Power Engineering Conference (UPEC), 2010 45th International*, Aug 2010, pp. 1–6.
[5] P. M. Anderson and M. Mirheydar, “A low-order system frequency response model,” *IEEE Transactions on Power Systems*, vol. 5, no. 3, pp. 720–729, Aug 1990.
[6] D. L. H. Aik, “A general-order system frequency response model incorporating load shedding: analytic modeling and applications,” *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 709–717, May 2006.
[7] W. Winter, K. Elkington, G. Bareux, and J. Kostevc, “Pushing the limits: Europe’s new grid: Innovative tools to combat transmission bottlenecks and reduced inertia,” *IEEE Power and Energy Magazine*, vol. 13, no. 1, pp. 60–74, Jan 2015.
[8] D. Gautam, V. Vittal, and T. Harbour, “Impact of increased penetration of dfig-based wind turbine generators on transient and small signal stability of power systems,” *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1426–1434, Aug 2009.
[9] J. McLoughlin, Y. Mishra, and G. Ledwich, “Estimating the impact of reduced inertia on frequency stability due to large-scale wind penetration in australian electricity network,” in *Power Engineering Conference (AUPEC), 2014 Australasian Universities*, Sept 2014, pp. 1–6.
[10] S. Eftekharnejad, V. Vittal, G. T. Heydt, B. Keel, and J. Loehr, “Impact of increased penetration of photovoltaic generation on power systems,” *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 893–901, May 2013.
[11] ——, “Small signal stability assessment of power systems with increased penetration of photovoltaic generation: A case study,” *IEEE Transactions on Sustainable Energy*, vol. 4, no. 4, pp. 960–967, Oct 2013.
[12] T. Xu, W. Jang, and T. Overbye, “Application of set-theoretic method to assess the locational impacts of virtual inertia services on the primary frequency responses,” in *2016 IEEE Power and Energy Conference at Illinois (PECI)*, Feb 2016, pp. 1–6.
[13] P. Mackin, R. Daschmans, B. Williams, B. Haney, R. Hunt, and J. Ellis, “Dynamic simulation studies of the frequency response of the three U.S. interconnections with increased wind generation report,” December 2010. [Online]. Available: http://www.nerc.com/FilingsOrders/us/FERCOrdersRules/Dynamic_Simulation_Studies.pdf.
[14] “Texas 2000-bus case.” [Online]. Available: http://icseg.iti.illinois.edu/synthetic-power-cases/texas2000-june2016/
[15] A. B. Birchfield, K. M. Gegner, T. Xu, K. S. Shetye, and T. J. Overbye, “Statistical considerations in the creation of realistic synthetic power grids for geomagnetic disturbance studies,” *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–1, 2016.
[16] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye, “Grid structural characteristics as validation criteria for synthetic networks,” *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–1, 2016.
[17] T. Xu, A. B. Birchfield, K. M. Gegner, K. S. Shetye, and T. J. Overbye, “Application of large-scale synthetic power system models for energy economic studies,” in *2017 50th Hawaii International Conference on System Sciences (HICSS)*, Jan 2017.
[18] T. Xu, A. B. Birchfield, K. S. Shetye, and T. J. Overbye, “A statistical approach to create synthetic network dynamic cases,” *submitted to 10th Bulk Power Systems Dynamics and Control Symposium*.
[19] J. G. A. Borden, B.C. Lesieutre, “Power system modal analysis tool developed for industry use,” in *Proc. 2013 North American Power Symposium*, Sept 2013.

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