Metric Development for Evaluating Inertia's Locational Impacts on System Primary Frequency Response

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***Abstract*—Power systems are changing with the integration of substantial amounts of renewable energy, lightweight turbine generators and electronic devices. This trend results in less resource inertia and may consequently worsen system primary frequency response. This paper develops several metrics to effectively quantify the impacts of resource inertia on power system dynamic performances. Governor and inertial responses are the two primary contributors to alleviate frequency deviations during the first few seconds after the system experiences some contingency events that result in imbalance between the demand and the generation. Burdens on governors caused by inertia reduction are also evaluated. To provide insightful, realistic simulation results, synthetic electric grid models are used to investigate inertia's impacts and their locational dependence.**

***Index Terms*—inertia, governor responses, locational impacts, metric development, large-scale synthetic networks**

I. Introduction

INERTIA is seen by the system as the injection or withdrawal of electrical energy, converted from rotors' kinetic energy, in response to a change of frequency. A significant amount of conventional generation units are replaced by renewable energy resources, whose operations are typically independent from the system frequency [1], [2]. In addition, generators, especially renewable energy, usually operate at maximum power and therefore have no headroom for under-frequency governor responses [3], [4]. With less inertia and governor responses, small events could result in larger frequency excursions. Several reports [5], [6] indicated a declining frequency response in both the Eastern Interconnection (EI) and the Electric Reliability Council of Texas (ERCOT) footprints. Studies [7], [8] performed using models on the footprint of the Western Electricity Coordinating Council (WECC) also observed that lower system inertia due to increased renewable penetration speeds up the change of post-contingency frequency, and therefore may increase the ramp requirements for primary frequency control reserves. Therefore, there is an acute need to study how inertia reduction impacts the system dynamic performances and how its impact varies by location.

Influences of low rotational inertia on system stability and operation were studied in [9]. An energy-function-based transient stability assessment approach was proposed in [10] to study how critical clearing time changes as machine inertia varies. Simulation results from [11]–[13] indicated the locational dependence of inertia reduction on power system frequency responses and oscillations. The system primary frequency response is typically evaluated using the (maximum and minimum) rate of change of frequency (RoCoF) and system frequency during the first several seconds after disturbances [14], [15]. Another commonly used metric is frequency response β, which is defined by β =(generation/load loss in MW)/(frequency deviation in 0.1Hz) [5]–[7]. Different frequencies are used to compute the β. This paper aims to propose and compare several evaluation metrics for the effective quantification of locational impacts of resource inertia on the system primary frequency response. In particular, metrics on governor responses are proposed to study how much burden to generator governors is caused by inertia reduction.

Throughout this paper, all simulation results are performed using synthetic electric grid models [16]–[18]. These synthetic electric grid models are entirely fictitious power flow cases and contain no confidential information, but are designed to be statistically and functionally similar to actual electric grids. A preliminary study is carried out to reveal how inertia and its location come into play in determining the system dynamic responses. Based on simulation results from the preliminary study, several metrics are proposed to quantify the changes of system dynamic performances with respect to varying machine inertia at different locations. Specifically, we develop a set of performance metrics for quantifying the location-dependent impacts of inertia on the system frequency performances and governor responses. Those metrics are then applied to study the locational influences of inertia using a 2000-bus synthetic case, built on the footprint of the ERCOT region. Furthermore, this paper considers both N-1 and N-2 contingency events.

Four more sections follow. First, a preliminary study is presented in Section II to reveal inertia's impacts on system dynamic responses. In Section III, a set of metrics are developed for quantifying inertia's impacts and their locational dependence. Section VI provides simulation results using the 2000-bus test case for illustration, and Section V presents concluding remarks and directions for future work.

978-1-5386-1006-0/18/$31.00 ©2018 IEEE
T. Xu, Y. Liu, T.J. Overbye, "Metric Development for Evaluating Inertia's Locational Impacts on System Primary Frequency Response," Proc. 2018 Texas Power and Energy Conference, College Station, TX, February 2018

II. Preliminary Studies

To reveal variations in the system responses with respect to changing resource inertia, this section uses the ACTIVSg200 case - a 200-bus synthetic network model [19]. As shown in Fig.1, this system is built on the footprint of Central Illinois and serves a load level of 476 MW. All generation units adopt the GENROU, TGOV1 and SEXS_PTI models, with a total inertia of 159 s (Base: 100 MVA). Constant impedance models are used for all loads.

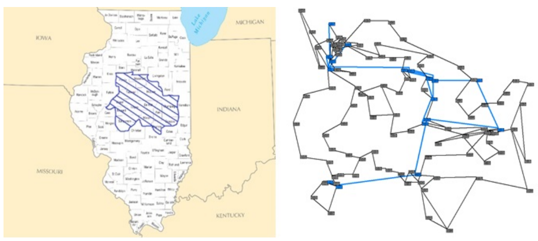

Fig. 1. Geographic footprint and one-line diagram of the 200-bus case

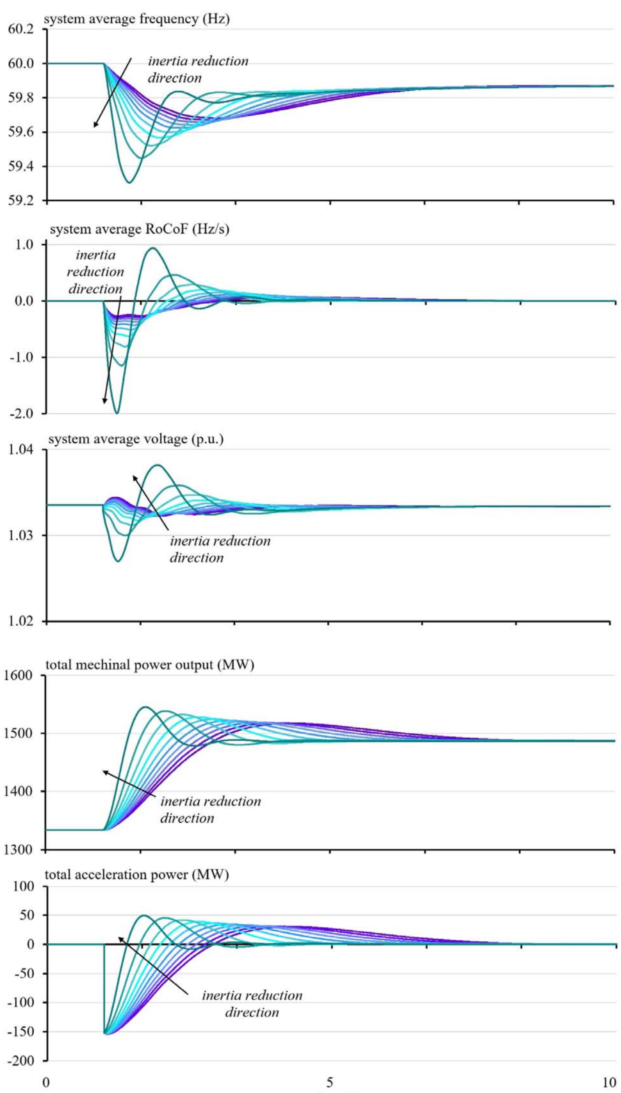

Fig. 2. Simulation results using the ACTIVSg200 case

The test case is subject to a contingency event of 155 MW generation loss. The total system inertia from online units are reduced by an amount from 0% to 90%. Average values of bus frequencies, RoCoFs and voltages, and total mechanical power outputs and acceleration power, are shown in Fig.2. Reducing resource inertia results in faster inertial responses and frequency changes, which in turn casts more burdens on governors. Trivial changes in bus voltages are seen as the inertia is reduced.

For comparison purposes, proportional control coefficients ($\frac{1}{R}$, where R is the droop constant) in the TGOV1 models of all online generations are decreased from 20(100%) to 2(10%). Equivalently, R is increased by a value from 0.05 to 0.5. The maximum and minimum values of bus minimum frequency and RoCoF among all buses are shown in Fig.3 (left). Both increased R and reduced inertia significantly worsen the system primary frequency responses. Inertia reductions lower both bus minimum frequencies and bus minimum RoCoF values, while increasing R has more impacts on bus minimum frequency. Stabilizing frequency means not only to bring frequency back to the nominal value, but also to prevent frequency from changing too fast. Mathematically, inertial response is a differential control[1]. Therefore, the advantage of inertial responses over the typical droop control is that it is able to significantly improve not only the minimum frequencies, but also the maximum RoCoF magnitudes. As shown in Fig.3 (right), we also observe small changes in the maximum and minimum ratios of bus highest and lowest voltages to its original value.

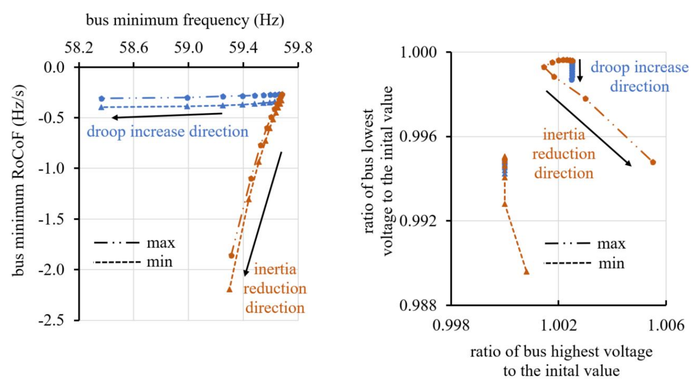

Fig. 3. Comparison studies among simulation results with varying inertia and droop constants

Simulation results presented in this section show that the inertia reduction substantially worsens the system frequencies and RoCoFs, and in turn requires governors to respond faster and more (seen in terms of increases in governor peak values). Therefore, metrics are needed to effectively quantify those changes in system performances with respect to inertia variation. It is essential for such metrics to capture the locational dependence of inertia's impacts.

[1]Differential control is a control action based on the derivative change of the control error.

III. Performance Metric Development

In this section, we develop a set of performance metrics for quantifying the location-dependent impacts of inertia on the system frequency performances and governor responses.

A. Frequency and RoCoF Metrics

Minimum/maximum values of frequency and RoCoF values are commonly used to evaluate the system primary frequency response. The frequency deviation usually deepens in accordance to higher generation loss in a contingency event. To approximate the change in needed demand-supply mismatch to a given frequency deviation, two beta metrics are introduced below:

$$\beta_f = \frac{\text{generation loss or load change in MW}}{\text{frequency deviation in 0.1 Hz}} \tag{1}$$

$$\beta_r = \frac{\text{generation loss or load change in MW}}{\text{RoCoF in 0.1 Hz/s}} \tag{2}$$

For instance, $\beta_f \Delta f$ represents an estimate of generation loss or demand increase that would cause a frequency deviation of Δf. Beta metrics are normalized representations of the system frequency characteristic, and thus can be compared among different contingency events.

A general formulation (3) is used in this paper to represent the system frequency deviation and RoCoF using bus measurements. In small cases, the system is tightly connected and, consequently, generators swing together and bus frequencies are very close to each other. However, bus frequencies may differ by location in large-scale test systems. In addition to a non-weighted (a.k.a. uniformly weighted) average f^n_{sys} (r^n_{sys}) ($w_b = 1$ for $\forall b \in \mathcal{B}$)[2], two other weight combinations are adopted. The first one f^t_{sys} (r^t_{sys}) is to use the worst bus minimum frequency (RoCoF), where $w_b = 1$ if and only if $\underline{f}_b \leq \underline{f}_{b'}$ ($\underline{r}_b \leq \underline{r}_{b'}$) for $\forall b' \in \mathcal{B}$, and other weights are all zero. Another one f^l_{sys} (r^l_{sys}) represents the weight of each bus by its generation and load level ($w_b = 1 + P_b + L_b$), indicating higher importance of a bus with more generation and electricity demands.

$$f_{\text{sys}} = \frac{\sum_{b\in\mathcal{B}} w_b f_b}{\sum_{b\in\mathcal{B}} w_b}, \quad r_{\text{sys}} = \frac{\sum_{b\in\mathcal{B}} w_b r_b}{\sum_{b\in\mathcal{B}} w_b} \tag{3}$$

Furthermore, other than computing the system frequency (RoCoF) over time and finding the minimum value, we could simply approximate the system minimum frequency (RoCoF) by the weighted average of minimum frequencies (RoCoFs) of all buses. Correspondingly, we have the non-weighted average $\tilde{\underline{f}}^n_{\text{sys}}$ ($\tilde{\underline{r}}^n_{\text{sys}}$), weighted average $\tilde{\underline{f}}^t_{\text{sys}}$ ($\tilde{\underline{r}}^t_{\text{sys}}$), and worst-scenario average $\tilde{\underline{f}}^l_{\text{sys}}$ ($\tilde{\underline{r}}^l_{\text{sys}}$). Here, we note that $\tilde{\underline{f}}_{\text{sys}}$ is the weighted average of minimum frequencies $\underline{f}_b$ of all buses using (4), and $\underline{f}_{\text{sys}}$ is the minimum value of system frequency f_{sys} computed using (3).

$$\tilde{\underline{f}}_{\text{sys}} = \frac{\sum_{b\in\mathcal{B}} w_b \underline{f}_b}{\sum_{b\in\mathcal{B}} w_b}, \quad \tilde{\underline{r}}_{\text{sys}} = \frac{\sum_{b\in\mathcal{B}} w_b \underline{r}_b}{\sum_{b\in\mathcal{B}} w_b} \tag{4}$$

[2] $\mathcal{B}$ is the set containing all buses. f_b and r_b are the bus frequency and RoCoF, respectively.

B. Governor Metrics

In addition, we compute two metrics to quantify how governor responds as the inertia is reduced, using mechanical power as the observed measurement. The overshoot ratio α_p denotes as the ratio of the peak value to the steady-state value. τ_+ denotes as how much time a governor takes to ramp from the 10% of its steady-state value to its 90%. Increasing α_p and τ_+ implicitly represent additional tear and wear caused by inertia reduction. Given an area with multiple generators, the aggregated mechanical power is used for metric computation.

$$\alpha_p = \left\{ \begin{array}{c} \text{ratio of the overshoot at the peak} \\ \text{to the steady-state value} \end{array} \right\} \tag{5}$$

$$\tau_+ = \left\{ \begin{array}{c} \text{time duration for signal rising from} \\ \text{10\% to the 90\% of the steady-state value} \end{array} \right\} \tag{6}$$

In the following section, we apply the evaluation metrics introduced in this section to study inertia's locational impacts using a large-scale synthetic network model. Comparisons among weight combinations are also addressed.

IV. Illustrative Simulation Results

This section aims to illustrate the selection and application of the proposed metrics using a synthetic 2000-bus network model - ACTIVSg2000. As shown in Fig.4, this model is built on the ERCOT footprint and has four voltage levels (500/230/161/115 kV). A portion of generators with a total generation capacity of 98 GW is committed and dispatched to supply a load of 67 GW and 19 GVar. Multiple fuel types and various machine/governor/exciter/stabilizer models for each fuel type are included in this case.

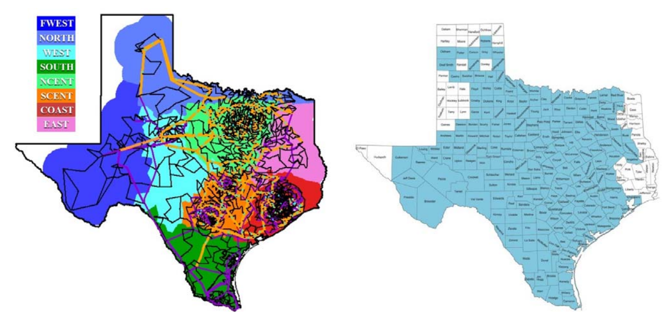

Fig. 4. Geographic footprint and one-line diagram of the 2000-bus model

A. Simulation Setting Up

Among eight areas defined in this test case, there are two regions with similar regional inertia from online generators: R1 with COAST (Case 1), and R2 with NCENT and SCENT (Case 2). For each case, we proportionally reduce the inertia of each unit in the corresponding region such that the regional total inertia is reduced by an amount varying from 0 s to 1,000 s in increment of 200 s. For comparisons, we perform the same simulations using the synthetic case with the system total inertia reduced by a value from 0 s to 1,000 s in increment of 200 s (reference Case 0).

B. Comparisons Among Different Weights for Computing Frequency and RoCoF Metrics

To select an appropriate set of weights, we compare the system minimum frequency and RoCoF using different weights and formulations, after this test system is subject to a N-2 contingency event. As shown in Table.I, the computed system minimum frequencies are close to each other regardless the selected weight combinations and formulations, while this observation does not apply to the system minimum RoCoF.

TABLE I
FREQUENCY AND ROCOF METRICS USING DIFFERENT WEIGHTS

metric	non-weighted	weighted	worst	5% percentile
$\underline{f}_{\text{sys}}$	59.780	59.785	59.745	
$\tilde{\underline{f}}_{\text{sys}}$	59.777	59.780	59.745	59.764
$\underline{r}_{\text{sys}}$	-0.21817	-0.22345	-0.59631	
$\tilde{\underline{r}}_{\text{sys}}$	-0.28137	-0.29312	-0.59631	-0.3292

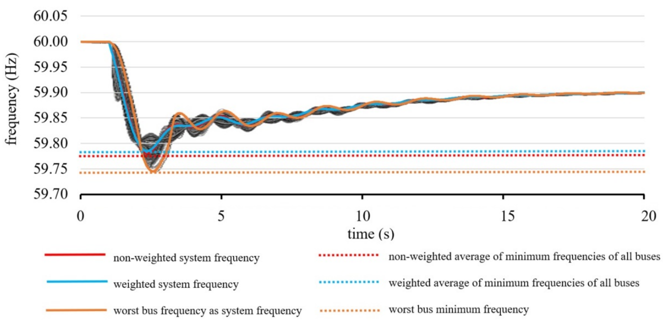

Fig. 5. Computed system frequencies metrics using different weights (Solid color lines for system frequency using (3); Dotted color lines for the system minimum frequency using (4); Grey lines for bus frequencies)

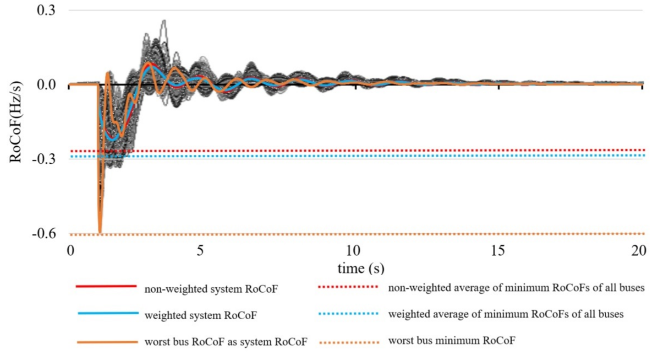

Fig. 6. Computed system RoCoFs using different weights (Solid color lines for system RoCoF using (3); Dotted color lines for the system minimum RoCoF using (4); Grey lines for bus RoCoFs)

Fig.5 (Fig.6) presents the computed system frequencies (RoCoFs) using (3) and the estimated system minimum frequency (RoCoF) using (4). We note that the minimum frequencies and RoCoFs of all buses may occur in different time, thus the average system frequency and RoCoF may be over-smoothed by taking an average of measurements of all buses. As such, the following parts narrow down the comparison studies to $\tilde{\underline{f}}^t_{\text{sys}}$ and $\tilde{\underline{r}}^t_{\text{sys}}$ that are able to appropriately represent both the system change trend and extreme bus values.

C. Impacts of Inertia Reduction on System Frequency and RoCoF

This subsection studies the impacts of inertia reduction on system frequencies and RoCoFs, after the system is subject to selected N-1 and N-2 generation-loss contingency events. Fig.7 displays the computed beta metrics using $\tilde{\underline{f}}^t_{\text{sys}}$ and $\tilde{\underline{r}}^t_{\text{sys}}$ (Left: Case 0; Middle: Case 1; Right: Case 2). To highlight the locational dependence, Fig.7 also distinguishes the contingency locations using different marker shapes and colors: R1 - circle in orange, R2 - square in blue, and the remaining - hexagram in brown. Overall, inertia reduction typically results in lower $\tilde{\underline{f}}^t_{\text{sys}}$ and $\tilde{\underline{r}}^t_{\text{sys}}$, and thus less β_f and β_r, indicating that small events may cause larger frequency excursion as inertia is reduced. In Case 1 (Case 2), changes of both beta metrics by inertia reduction in R1 (R2) are more significant for those contingency events in the same region R1 (R2) than those in different regions. This observation verifies the locational impacts of inertia: inertia reductions may cause more decreases in frequency and RoCoF metrics when inertia reduction is closer to contingency events. In other words, inertia contributes more to local frequency stability than the global (system) stability. This is because the generators near a contingency event are less capable to prevent the disturbance from spreading over the network and slow down/pick up the decreasing frequencies as the inertia is reduced in those generators.

D. Impacts of Inertia Reduction on Governor Responses

This subsection investigates the changes in governor performances as regional inertia is reduced, in consideration of several large N-1 and N-2 contingency events with over 500-MW generation loss.

TABLE II
THE MAXIMUM AND MINIMUM DIFFERENCE (IN 0.01%) OF REGIONAL GOVERNOR OVERSHOOTS WITH RESPECT TO THOSE WITHOUT INERTIA REDUCTION

case	study region	inertia reduction (s)				
		200	400	600	800	1000
1	R1	1.05	1.88	3.04	3.8	8.75
	R2	0.09	0.18	0.29	0.36	0.40
2	R1	-0.03	0.44	1.35	2.28	2.15
	R2	0.24	1.9	3.8	5.4	6.2
1	R1	-0.23	-0.31	-0.63	-0.84	-0.94
	R2	-0.54	-1.11	-1.544	-1.94	-2.32
2	R1	-2.11	-1.79	-2.25	-3.45	-5.35
	R2	-0.83	-1.82	-2.88	-3.04	-2.79

Table.II summarizes the maximum and minimum differences (in 0.01%) of regional governor overshoots with respect to those computed values before the regional inertia is reduced. Small impacts on governor overshoots by inertia reduction are

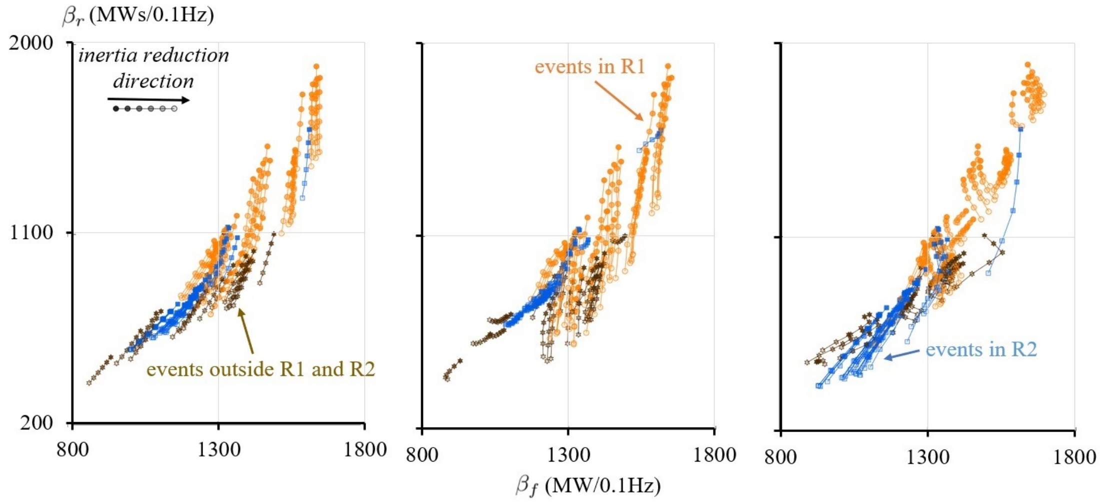

Fig. 7. Computed beta metrics using $\tilde{\underline{f}}^t_{\text{sys}}$ and $\tilde{\underline{r}}^t_{\text{sys}}$ (Left: Case 0; Middle: Case 1; Right: Case 2)

observed in this case. We still notice the locational dependence of inertia's impacts. Inertia reduction in each region usually causes more changes in governor overshoots in the same region. This is consistent with the observations in Section IV.C. Inertia reductions cause faster and deeper frequency deviation, which governors close to contingency events are more sensitive to.

Fig.8 displays the computed τ_+ of aggregated governor responses in different regions with X-axis and Y-axis for Case 1 and Case 2, respectively. As shown in each sub-figure, inertia variation causes additional burdens on governors. As the regional inertia is reduced, governors usually respond faster, corresponding to faster frequency changes. In addition, such impacts vary as the inertia reduction region is changed. For instance, the decrease in R1 governor rising time is more severe as R1 inertia is reduced than that as R2 inertia is reduced. In contrast, governors outside R1 and R2 are more sensitive to changes in R2. However, governor responses in R2 are almost equally sensitive to inertia reduction in R1 and R2.

In summary, simulation results in this section clearly demonstrate that the proposed metrics are capable of investigating the locational impacts of inertia on both frequency stability and governor performances.

V. Conclusion

This paper applied two synthetic network dynamic models to study inertia's location-dependent impacts on system primary frequency responses and governor performances. Several metrics were developed for evaluations. Selected N-1 and N-2 contingency events over a certain amount of generation loss were applied to disturb the system. Simulation results clearly indicated that inertia reduction causes larger and faster frequency excursions, and then requires faster governor responses. Overall, the impacts of inertia on power systems vary by location. Regional inertia reduction usually causes larger impacts on local metrics than on other regions. As such, inertia should be an important factor to be taken into consideration during power system planning, generator siting and some other applications related to power system transient stability.

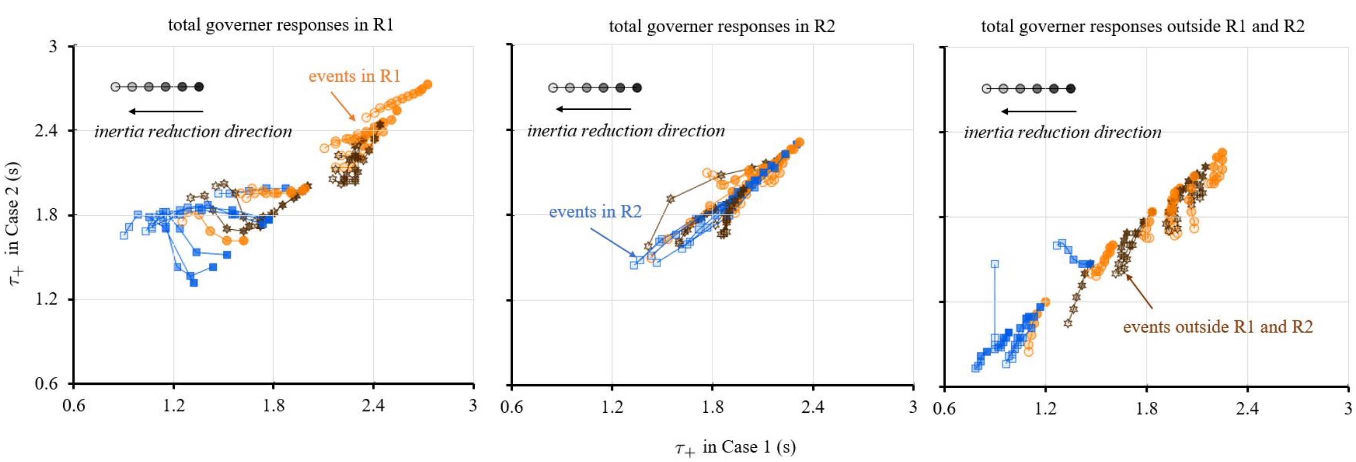

Fig. 8. Computed τ_+ of aggregated governor responses in different regions (X-axis: Case 1, and Y-axis: Case 2)

A continued research effort should be developing and testing some extreme cases, such as those with extra-high renewable energy penetrations, where inertia is substantially reduced in one region or even the whole grid. It is of of interest to run simulations for analysing the location dependence of inertia's impacts on inter-area oscillations. We will report those works in future.

VI. Acknowledgment

This work was supported by the U.S. Department of Energy Consortium for Electric Reliability Technology Solutions (CERTS).

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