Eastern Interconnection Frequency Response in System Low Inertia Condition

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***Abstract*—As the bulk power system (BPS) continues to transition towards higher instantaneous penetrations of renewable energy, system synchronous inertia will decrease. Lower inertia impacts system frequency response. It is essential for interconnections to take prudent steps to ensure that frequency does not reach under-frequency load shedding (UFLS) levels for large unplanned losses of generation. This paper presents a frequency response study to demonstrate that the Eastern Interconnection (EI) will have sufficient system inertia over the next 5 years with the generation resource mix, load, and interchange levels and governor participation anticipated. In addition, this paper discusses the impact of system inertia reduction and governor participation on system frequency response. Study results, findings, discussions and conclusions are presented in the paper.**

***Index Terms*—Eastern Interconnection (EI), Frequency Response, Governor Participation, Inertia Response, Under-Frequency Load Shedding (UFLS)**

I. Introduction

The Eastern Interconnection Planning Collaborative (EIPC) represents an effort that draws Planning Coordinators (PC) in the Eastern Interconnection (EI) together in a collaborative effort to perform the technical analysis of transmission planning and related matters, and to model the impact on various energy policy options for the grid determined to be of interest by state, provincial, and federal policy makers and other stakeholders. As part of the EIPC's ongoing work to perform technical analyses of transmission planning issues and for the NERC Long Term Reliability Assessment, the EIPC Technical Committee (TC) established the Frequency Response Task Force (FRTF) on July 20, 2017 (later changed to the Frequency Response Working Group (FRWG) in March 2019) to take a leadership role in providing on a biannual basis the EI Frequency Response Measures 1, 2, and 4 as specified by NERC Essential Reliability Services Working Group (ERSWG) Measures Framework Report [1].

The quickly evolving resource mix for the EI continues to place importance on ensuring the EI frequency response to loss of generation events will not lead to activation of Under Frequency Load Shedding (UFLS). This paper presents, discusses and summarizes an EI frequency response study including technical analyses, model modifications, and simulations performed by members of the EIPC-FRWG to assess the NERC-ERSWG frequency measures for the EI.

The study consists of several tasks including benchmarking historical frequency events with Spring Light Load (SLL) cases to determine how the existing generator governor models perform in response to the frequency events in the EI, followed by developing the low inertia 5-year out system model, and simulating frequency response under generation resource contingency events and computing NERC-ERSWG frequency measures using the model. Improvements to future modeling of governors is expected to supersede the need for limiting generator governor responses. The FRWG also created a list of recommended changes to improve the frequency responsiveness of the planning models for use by the EI Reliability Assessment Group (ERAG) Multiregional Modeling Working Group (MMWG) in future model development cycles.

The FRWG tested two different historical frequency events, the Most Severe Single Contingency (MSSC) for the EI, and the benchmark 10,000 MW test event from the 2018 study [2]. The two historical frequency events included the loss of 4,307 MW event from 2007, and the largest EI frequency event of the last 10 years of 3,852 MW. The EI MSSC selected for this study is the loss of 2,299 MW. The benchmarking analysis for this study resulted in choosing MMWG Frequency Response Case (Base Case #2 in Table III) as the starting case, and removing 17% of governor models from this case in addition to the non-responsive governors in the original MMWG Case (Base Case # 1 in Table III), resulting in approximately total 65% of governors modeled as responsive.

Building on the benchmark analysis, generation resource mix and dispatch changes were applied to model forecasted changes in system inertia over the next 5 years. With these changes applied to the MMWG 2018 Series 2023 case, the simulated resource contingency events under the selected MSSC exhibited satisfactory frequency response with a minimum frequency of 59.80 Hz. The study results are above the UFLS triggering set-point of 59.6 Hz.

The rest of this paper is organized as follows: Section II discusses the frequency measure process. Section III discusses the study base cases. Section IV benchmarks the two historical frequency events. Development of the low inertia 5-years out case is discussed in Section V. Simulations of resource

The 2020 EIPC report provides information on the technical analysis, model modifications, and simulations performed by members of the Eastern Interconnection Planning Collaborative (EIPC) Frequency Response Working Group (FRWG) to assess the North American Electric Reliability Corporation (NERC) Essential Reliability Services Working Group (ERSWG) forward looking frequency Measures 1, 2, and 4 for the Eastern Interconnection (EI) for inclusion in the 2021 NERC Long-Term Reliability Assessment (LTRA). EIPC FRTF 2020 Final Report 2020-10-21.

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contingency events are presented in Section VI. Section VII discusses mitigation solutions. Conclusions are drawn in Section VIII.

II. Frequency Measures

The NERC-ERSWG specifies measures for system frequency responses [1]. Fig. 1 illustrates a representative plot of frequency deviation in the EI due to a loss of generation resource. The event starts at time t_0. Value A is the average frequency from t-16 to t-2 seconds. Point C is the lowest frequency point observed in the first 12 seconds and value B is the average from t+20 to t+52 seconds. Point C' occurs when the frequency after 52 seconds falls below either the point C (12 seconds) or average value B (20 – 52 seconds.

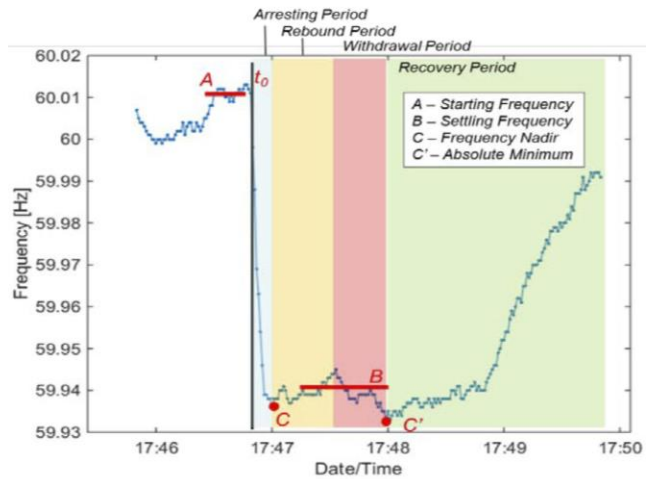

Fig. 1. Frequency Response Example for a Disturbance [1].

The frequency response components and measures specified by the NERC-ERSWG are shown in Table I.

TABLE I: FREQUENCY RESPONSE COMPONENTS

A to B frequency response captures the effectiveness of primary frequency response in stabilizing frequency following a large frequency excursion.   *Frequency Response (Current)* = $\frac{Generation\ Lost\ (MW)}{Frequency\ (A) - Frequency\ (B)}$
A to C frequency response captures the impacts of inertial response, load response (load damping) and initial governor response (governor response is triggered immediately after frequency falls outside of a pre-set dead band; however, depending on generator technology, full governor response may require up to 30 seconds to be fully deployed).   *Frequency Response (Nadir)* = $\frac{Generation\ Lost\ (MW)}{Frequency\ (A) - Frequency\ (C)}$
C to B ratio captures the difference between maximum frequency deviation and settling frequency. The C to B ratio is related to governor responsiveness with respect to frequency deviation reading, and their capability to arrest and stabilize system frequency.   *C:B Ratio* = $\frac{Frequency\ (C) - Frequency\ (A)}{Frequency\ (B) - Frequency\ (A)}$
C' to C ratio is the ratio between the absolute frequency minimum (Point C') caused by governor withdrawal and the initial frequency nadir (Point C).   *C':C Ratio* = $\frac{Frequency\ (C') - Frequency\ (A)}{Frequency\ (C) - Frequency\ (A)}$

Time-based Measures are used to capture the speed in which inertial and primary frequency response as well as governor withdrawal are occurring. These Measures can be trended year to year to identify trends in the rate of change of frequency decline and whether the governor withdrawal phenomena are trending toward improvement or further degradation. These Measures are shown in Table II.

TABLE II: TIME-BASED MEASURES

$t_C - t_0$ Measure is the difference in time between the frequency nadir and initial event. It captures the time in which system inertia and governor response arrest declining frequency to its minimum level.
$t_{C'} - t_C$ Measure is the difference in time between the governor withdrawal minimum and the initial frequency nadir, which captures the time in which governor stabilization and withdrawal occur prior to secondary controls and load responsiveness beginning to return frequency to its initial value.
$t_{C'} - t_0$ Measure is the difference in time between the governor withdrawal minimum and the initial event. This provides a comprehensive picture of the overall time in which frequency declines and continues to fall due to the initiating event. While C' should be mitigated and eliminated entirely, the time between the initial event and absolute minimum should also be minimized. In the EI, it is observed that the minimum frequency level (C' value) due to governor response withdrawal generally occurs 59–78 seconds after an event.

System frequency response immediately after generation tripping can be measured by the rate of change of frequency at the first 0.5 second of the disturbance, i.e., $ROCOF_{0.5}$ and is considerably driven by the system's generators kinetic energy or inertia, as follows:

$$ROCOF_{0.5} = \frac{f(t0 + 0.5) - f(t0)}{0.5} \left[\frac{Hz}{s}\right]$$

III. Study Base Cases

MMWG 2018 Series dynamics base cases representing system SLL conditions for 2019 and 2023 were used in this study, as shown in Table III.

TABLE III: 2019 AND 2023 SLL DYNAMICS BASE CASES

Case	Base Case Name
#1	MMWG_2019SLL_2018Series_Final_ds
#2	MMWG_2019SLL_2018Series_Final_ds (Freq Response)
#3	MMWG_2023SLL_2018Series_Final_ds(Freq Response)

It is noted that the difference between the two 2019 base cases is that in the system stability model, one case has more governor models in-service than the other case. In Base Case #2, modifications were applied to disable several generation governor models, identified as either non-responsive or squelched. As shown in Fig. 2, in Base Case #1, approximately 39% of generation dispatch was modeled as non-responsive, while in Base Case #2, this number is approximately 53%. Fig. 3 demonstrates the governor types and the total generation dispatch associated with each governor type in Base Case #2. It should be noted that the governor models with low percentage are not shown in this figure.

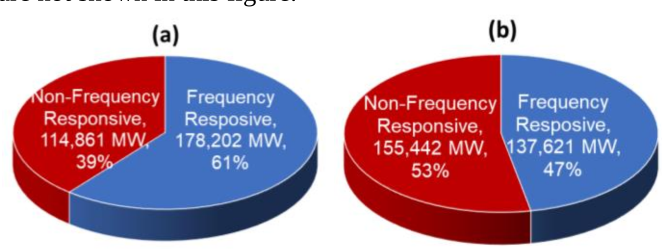

Fig. 2. Generation Dispatch by Governor Responsiveness in Base Case #1 and Base Case #2.

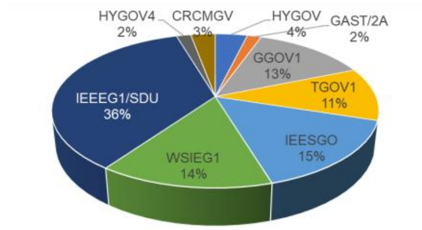

Fig. 3. Generation Dispatch by Governor Model Type in Base Case #2.

IV. BENCHMARK HISTORICAL FREQUENCY EVENTS

A. Base Case Analysis

To benchmark the selected EI minimum low inertia model, two historical frequency response events based on NERC Frequency Monitoring Network (FNET) raw data were selected which are shown in Table IV.

TABLE IV: HISTORICAL FREQUENCY EVENTS

Event ID	Local Time
Frequency Event I	03/10/2019 01:01:45
Frequency Event II	03/15/2019 20:39:02

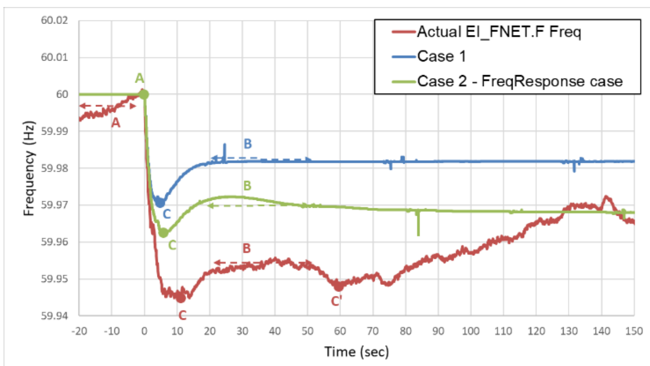

Fig. 4. Frequency Event I FNET Raw Data Plot and Simulated Frequency Responses for Both Base Case #1 and Base Case #2.

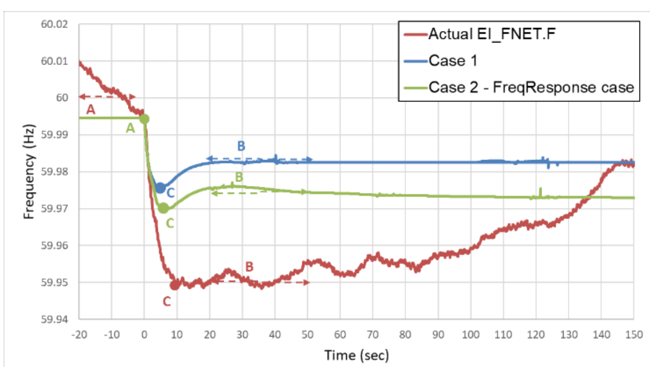

Fig. 5. Frequency Event II FNET Raw Data Plot and Simulated Frequency Responses for Both Base Case #1 and Base Case #2.

Preliminary simulations were performed on the two 2019 base cases listed in Table III for the two actual frequency events described in Table IV. Fig. 4 and Fig. 5 show the simulated system frequency responses of the two 2019 base cases versus the responses for the two actual frequency events. The simulations plots and frequency parameters indicate that Base Case #2 (named "FreqResponse" case) produces a closer matching to the actual frequency event than Base Case #1. Hence, Base Case #2, was used for benchmarking the two historic frequency events in this study.

B. Impact of System Inertia on Frequency Response

In order to investigate the impact of system inertia on frequency response during the arresting period, in specific $ROCOF_{0.5}$ and frequency nadir, the system inertia in the Base Case #1 was reduced in four stages to 91% of the original system inertia. The process was achieved by switching off generating units with high inertia, balanced with switching on or scaling up renewable or low inertia units. In reducing system inertia, these aspects were considered:

- System load was not changed,
- Generation balance was performed on a transmission area basis,
- Pumping units were excluded from the headroom calculations.

In each stage, the results were plotted while frequency nadir and $ROCOF_{0.5}$ were recorded. Based on the plots, there were no major differences in the simulation results throughout the four stages. Each simulation appeared to provide similar frequency responses during the times recorded. The frequency nadir remained unchanged for both frequency events and $ROCOF_{0.5}$ only varied slightly in each stage. As an Example, Fig. 6 shows the plots for all 4 stages for Frequency Event I.

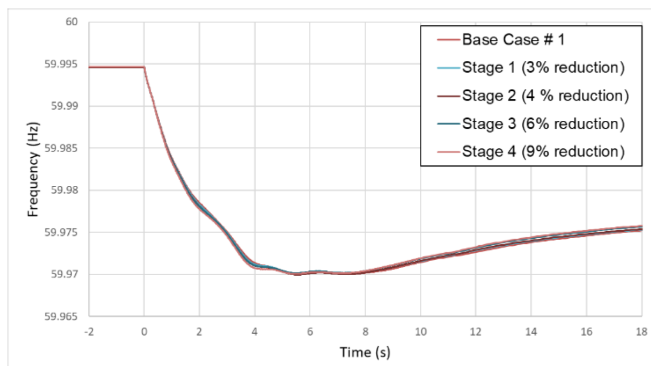

Fig. 6. Impact of System Inertia Reduction on Frequency Response in Base Case #1 (Frequency Event I).

C. Impact of Governor Participation on Frequency Response

The impact of governor participation on the frequency response was evaluated by varying the number of online governors. Preliminary simulations and comparison of the two 2019 base cases in the previous section indicated that reducing the frequency response capability of online generators, by disabling governors, would reduce the frequency nadir and change the nadir occurring time. The amount of governor participation was determined by a trial and error approach as well as engineering judgments (e.g., selecting governors with higher Beta values). The resulting frequency nadir was then compared to the nadir of each actual frequency event. For Frequency Event I, through simulations, it was determined that removing 9% of governors from Base Case #2 would provide the closest matching plot. For Frequency Event II, it was determined that removing 17% of governors from Base Case # 2 provided the closest matching plot. These percentages are in addition to the governors already modeled as non-responsive. This brings the total number of non-responsive governors with respect to the Base Case #1 governors for Event I to 29% and for Frequency Event II to 35%.

Fig. 7 and Fig. 8 show the system response of governor reduction case (9% and 17% of governors non-responsive) for both Frequency Event I and Frequency Event II. The simulation results indicate that the simulated frequency events are consistent with the actual frequency events and provide the best fit, especially during the arresting, rebounding and stabilizing periods which are mainly driven by the primary frequency control. On the other hand, as seen from these figures, the system in the actual frequency events experience a primary frequency response withdrawal and then start recovering to the nominal frequency. These frequency behaviors were not simulated due to lack of modeling functions such as governor response squelching and Automatic Generation Control (AGC).

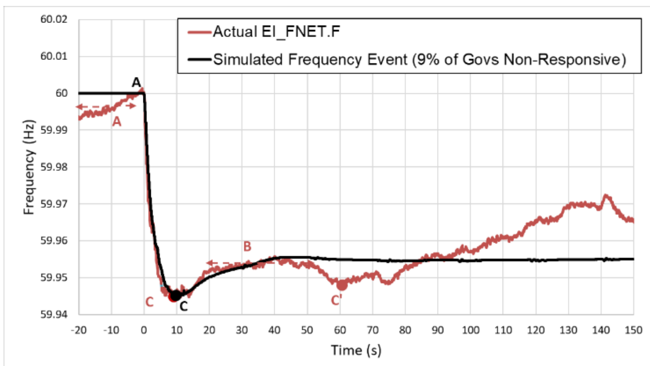

Fig. 7. Benchmarking Simulation of Frequency Event I.

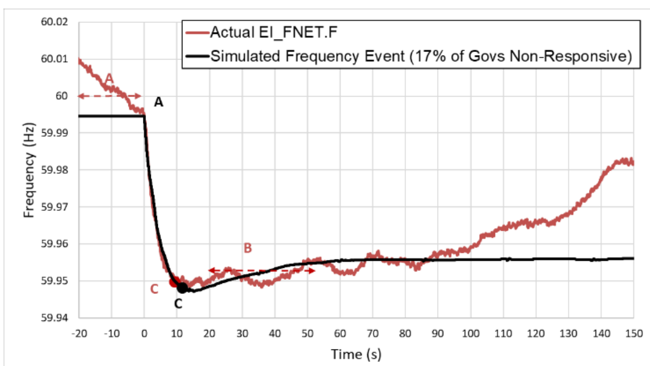

Fig. 8. Benchmarking Simulation of Frequency Event II.

V. Development of Low Inertia 5-Year Out Case

In developing the low inertia 5-year out dynamics case, modeling changes representing the generation resource mix, load and interchange levels for an expected future system low inertia condition projected to occur by 2023, as provided by all FRWG members, were merged, concurrently applied to the 2023 Base Case #3, tested and verified to ensure that the case could be successfully solved and initialized. Then 17% of the governor models were removed from the case based on benchmarking results for Frequency Event II. The case with 17% governor reduction was initialized and tested with faults which showed stable response. This case was used as the low inertia 5-year out dynamics case for simulating resource contingency events which will be discussed in the next section. A summary of Statistics of the 5-year out case are shown in Table V and Fig. 9.

Table V: Comparison of the Low Inertia 5-Year Out Case with 17% of Governors Non-Responsive and the 2023 Base Case (Base Case #3)

Parameter	2023 Spring Light Load Base Case (Base Case #3)	Low Inertia 5-Year Out Study Case	Change in Study Case (%)
Sum of PMax (MW)	383,443.88	337,158.74	-12.07%
Sum of PGen (MW)	295,867.96	250,371.27	-15.38%
Equivalent H (s)	3.59	3.59	0.00%
Equivalent R (pu)	0.19	0.20	5.26%
Spinning Reserve (%)	29.60	34.70	17.23%
Sum of MBase (MVA)	471,648.61	411,158.49	-12.83%
System Inertia (MVA-s)	1,694,098.28	1,476,165.65	-12.86%
Beta in pu of MBase	5.28	5.04	-4.55%

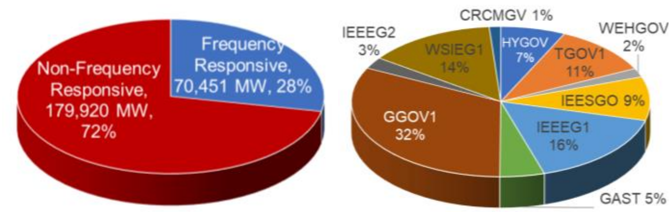

Fig. 9. Generation Dispatch by Frequency Responsiveness and Governor Model Type.

VI. Simulation of Resource Contingency Events

Four resource contingency events were simulated using the low inertia 5-year out dynamics case developed in the previous section. For illustrative purposes, system frequency responses following two resource contingency events are discussed below.

A. *Most Severe Single Contingency Event*

The simulated frequency response following the MSSC event is shown in Fig. 10. It is noted from the figure that the frequency nadir of the event is approximately 59.89 Hz occurring at about 8 sec after the initiation of the event, $ROCOF_{0.5}$ is -42.6 mHz/s, and primary frequency response is about 59.91 Hz. The frequency nadir is well above the UFLS triggering threshold which was set to 59.6 Hz in the study.

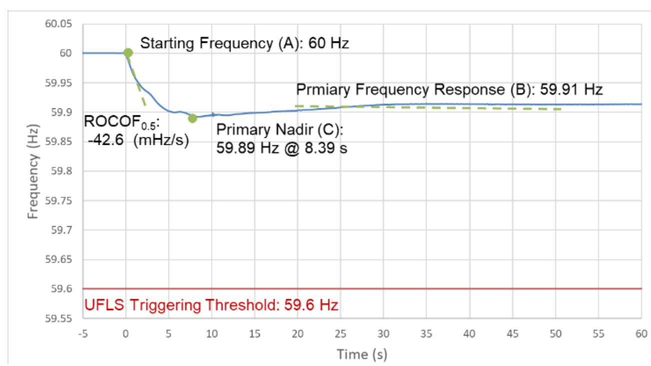

Fig. 10. Frequency Response Following MSSC.

B. *Benchmark 10,000 MW Test*

The simulated frequency response following this benchmark 10,000 test event is shown in Fig. 11. It is noted that the frequency nadir for the simulation is approximately 59.52 Hz occurring at about 9.5 sec after the initiation of the generation tripping, $ROCOF_{0.5}$ is -169.3 mHz/s, and Primary Frequency Response is about 59.63 Hz. The frequency nadir is below the UFLS triggering threshold 59.6 Hz.

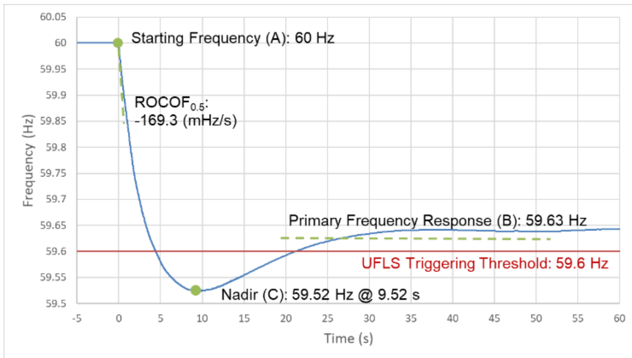

Fig. 11. Frequency Response for the Benchmark 10,000 MW Test Event.

VII. Mitigation Solution

The frequency nadir following the Benchmark 10,000 MW Test Event is approximately 59.52 Hz which is below the UFLS triggering threshold 59.6 Hz. To mitigate this condition, two options were tested and discussed below.

A. Governor Participation Reduction

One mitigation option was to reduce non-responsive governor participation in the low inertia 5-year out case. The test indicates that changing non-responsive governor participation from 17% to 7% in the low inertia 5-year out case would raise the frequency nadir above 59.6 Hz following the Benchmark 10,000 MW Test, as shown in Fig. 12.

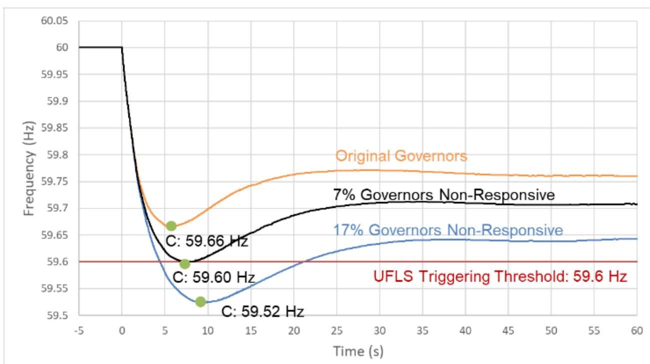

Fig. 12. Mitigation Option 1: Reducing the Number of Non-Responsive Governors for the Benchmark 10,000 MW Test Event.

B. Generation MW Loss Reduction

The second mitigation option was to reduce the amount of generation MW loss in the 5-year out case. The test indicates that reducing generation MW loss from 10,001 MW to 8,597 MW would raise the frequency nadir above 59.6 Hz following the Benchmark 10,000 MW Test Event. This is shown in Fig. 13.

Table VI: Comparison of the 5-Year Out Cases: 2022 vs 2023

Study Case	5-Year Out 2018 Study	5-Year Out 2020 Study	% Change from 2022 to 2023
Case Year	**2022**	**2023**	
Total Non-synchronous Generation Dispatched	8.70%	9.40%	8.0%
Total Synchronous Generation Dispatched	91.30%	90.60%	-0.8%
Total Synchronous Inertia (MVA-s)	1,628,796	1,476,166	-9.4%
Total DC Tie-Line Imports (MW)	3,393	3,123	-8.0%
Total System Load (MW)	288,143	247,574	-14.1%

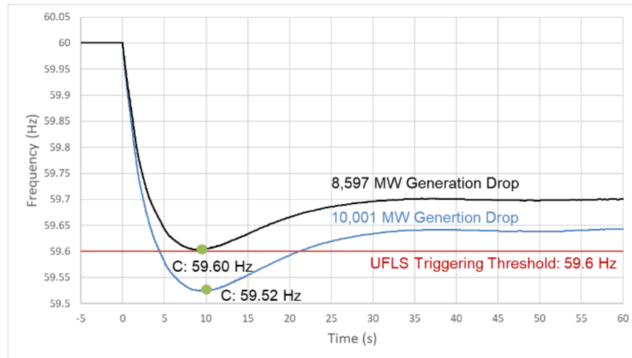

Fig. 13. Mitigation Option 2: Reducing the Amount of Generation MW Loss for the Benchmark 10,000 MW Test Event.

Table VII: Comparison with 2018 Frequency Response Study Findings

Event	Study Year	Gen Loss (MW)	Point C Nadir (Hz)	Point B (Hz)	ROCOF$_{0.5}$ (mHz/sec)
MSSC	2018	2,513	59.91	59.92	-28.00
	2020	2,299	59.89	59.91	-42.59
	Change (%)	-8.52%	-0.03%	-0.02%	51.79%
Benchmark 10,000 MW Test	2018	10,000	59.64	59.69	-155.0
	2020	10,001	59.52	59.63	-169.3
	Change (%)	-0.01%	-0.2%	-0.1%	91.55%

Table VI and Table VII show the comparison of the 2020 and 2018 frequency response study results. In Table VI, the 5-year out cases from 2018 and 2020 studies are compared. It can be seen that, from 2018 to 2020, non synchronous generator increased around 8% and synchronous generator reduced by 0.8% which can cause the change in system inertia which has been reduced around 9.4%.

VIII. Conclusions

This study has demonstrated that the EI would have sufficient system inertia over the next 5 years with the generation resource mix, load, and interchange levels and governor participation anticipated. However, with the addition of non-synchronous generation and planned resource retirements, maintaining frequency in the EI is a concern which warrants continued frequency response studies. The EIPC TC has been tasked with identifying and understanding how future generation contingencies could lead to UFLS events due to the reduction of frequency support from the changing generation resource mix.

While improvements to future modeling of governors is expected to supersede the need for limiting generator governor responses, this study has shown that continued improvement is still needed in this modeling area. The benchmarking analysis performed for this study demonstrated that the frequency response sensitivity to changes in governor modeling is greater than changes in total system inertia at the current resource mix levels.

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IX. References

[1] NERC Essential Reliability Services Task Force, Measures Framework Report, November 2015
[2] EIPC Technical Committee, FRTF 2018 Final Report, February 27, 2019.