Different Types of Fast Frequency Response from Inverter-based Resources

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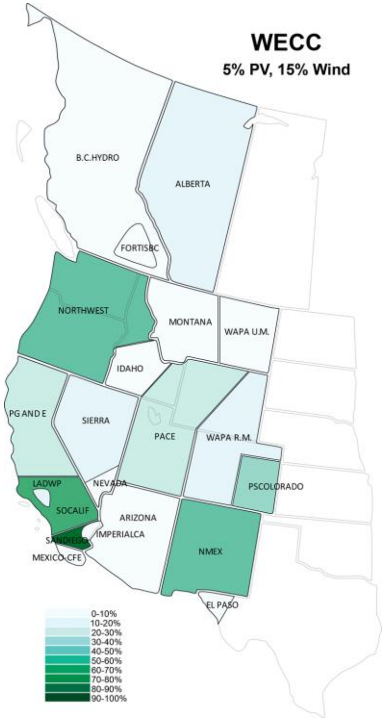
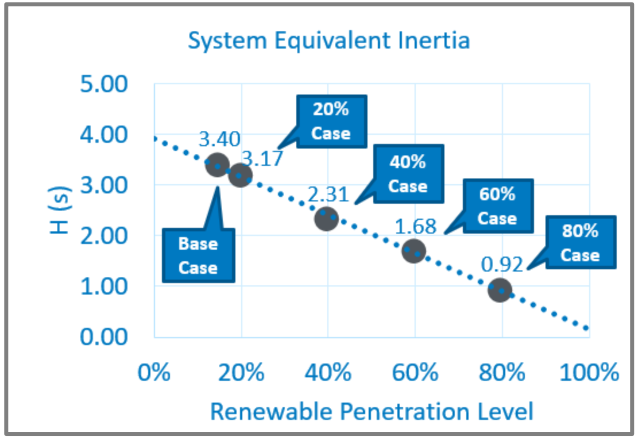
Agenda

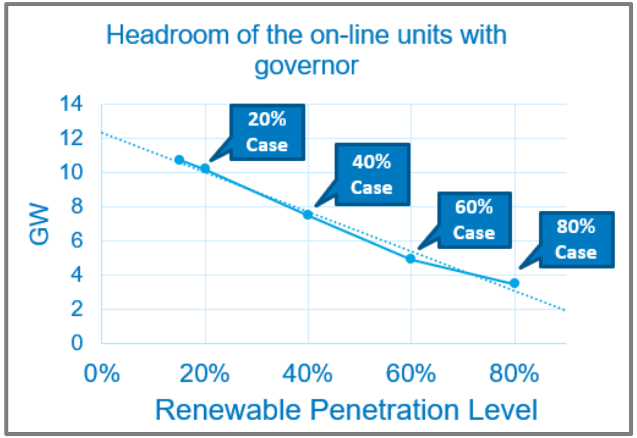
1. Background
2. What is Fast Frequency Response?
3. Characteristics of FFR and Their Impact
4. Analytical Prediction of Frequency Nadir
5. Fast Frequency Nadir Prediction for Real-time Operation
6. Develop Stability Constraints in Scheduling with Various FFRs
7. Conclusion

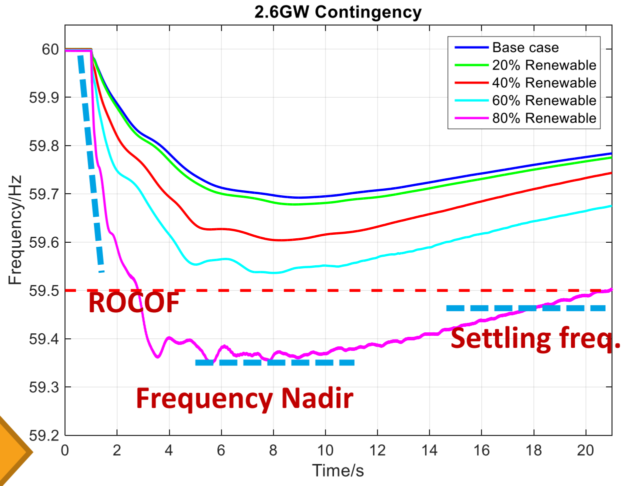
High Renewable Penetrated Grid Requires Fast Frequency Response



Renewable Penetration (20%, 40%, 60%, 80%)







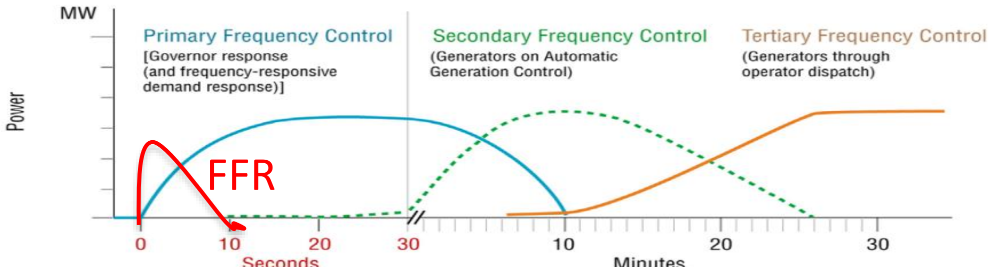
- ☹ High rate of change of frequency (ROCOF)
- ☹ Low frequency nadir
- ☹ Low settling frequency

What is Fast Frequency Response?

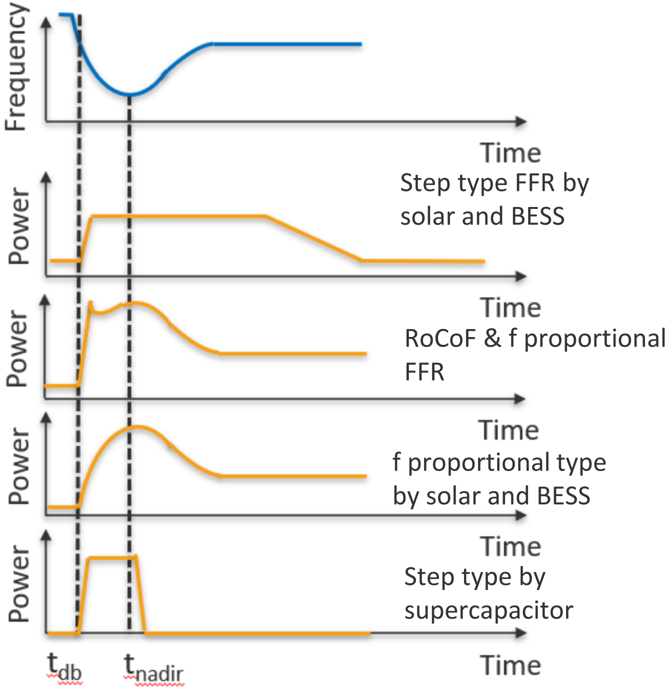
- **Different technologies can have different forms of Fast frequency response (FFR)**
  - Response type; Trigger; trajectory

Action	Response Type	Trigger Condition
Active Power Injection Or Load Reduction	Step	frequency threshold
		RoCoF threshold
		contingency event
	Proportional	to frequency error
		to RoCoF

How to quantify various types of FFR capability from IBRs during the planning and operation?



Eto, Joseph H. "Use of frequency response metrics to assess the planning and operating requirements for reliable integration of variable renewable generation." (2011).

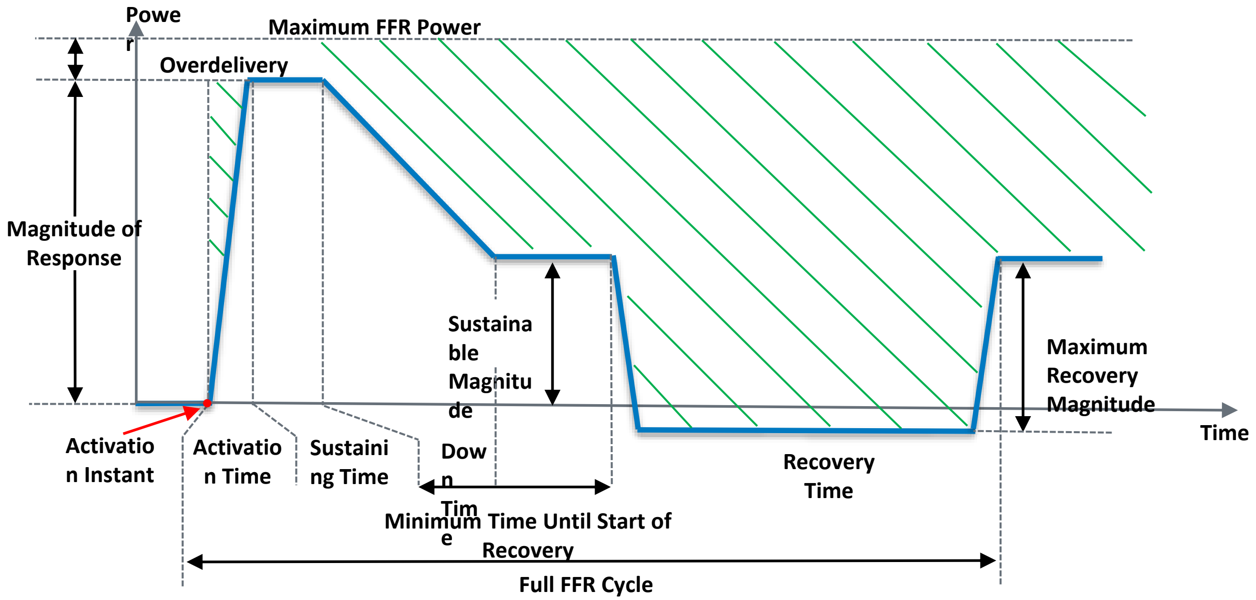


NERC. "Fast frequency response concepts and bulk power system reliability needs“. 2020.

Characteristics of Fast Frequency Response

- **3H - H**ow fast, **H**ow much and **H**ow long?

Key features of the fast frequency response (FFR) trajectory

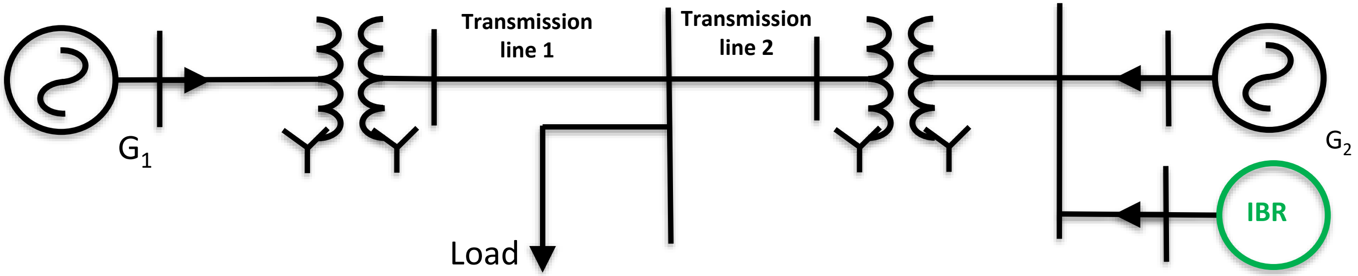


Four factors

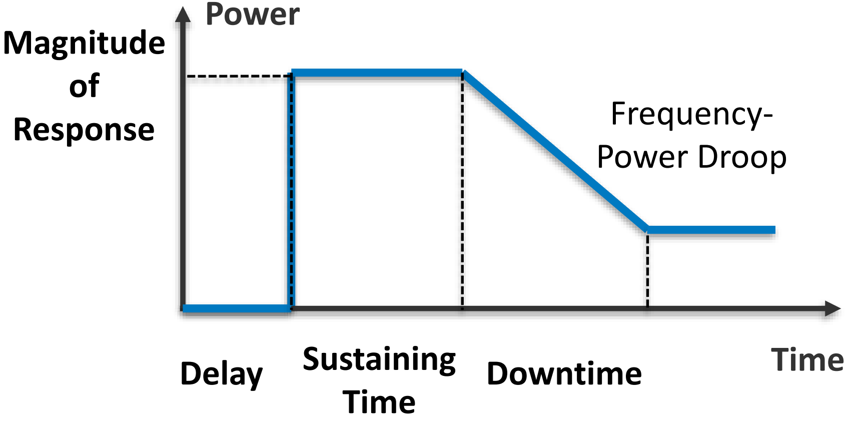
- Speed of response (i.e., response time)
- Magnitude of response
- Sustaining time
- Downtime

ENTSOE. Technical Requirements for Fast Frequency Reserve Provision in the Nordic Synchronous Area – External document. 2021.

Start with a Simple Test System and a Generalized form of FFR



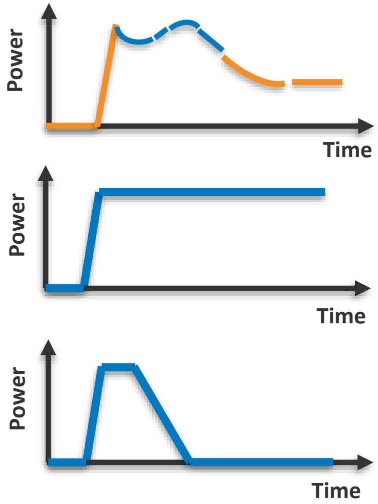
A generalized form of FFR



Frequency-dependent magnitude of response

Very long sustaining time

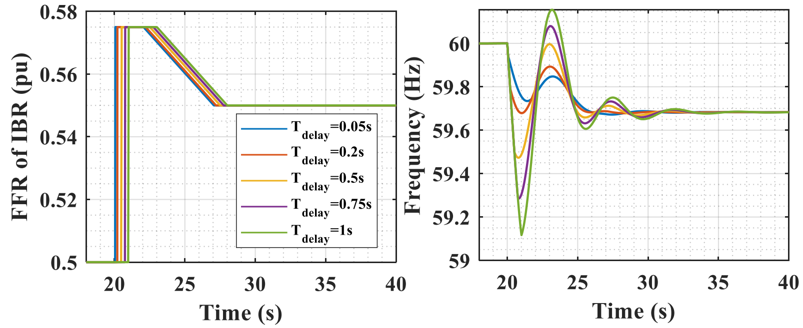
Short sustaining time, no frequency-power droop



X. Cui, S. Dong, A. Hoke and J. Tan, "A Unified Metric for Fast Frequency Response in Low-Inertia Power Systems," *2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2023, pp. 1-5, doi: 10.1109/ISGT51731.2023.10066382.

Impact of Key Fast Frequency Response Factors (Con’t)

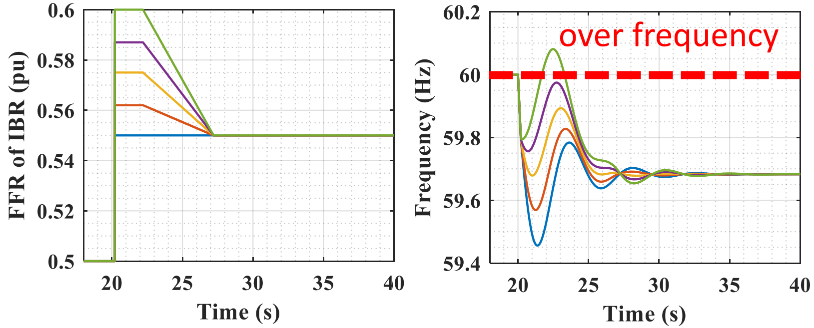
Impact of Speed of Response



Findings

- Fast response always significantly increases the nadir.
- If T_{delay} < 0.2s, the nadir is not sensitive to the response speed anymore.
- The faster, the better.
- No need to be super fast.

Impact of Magnitude of Response

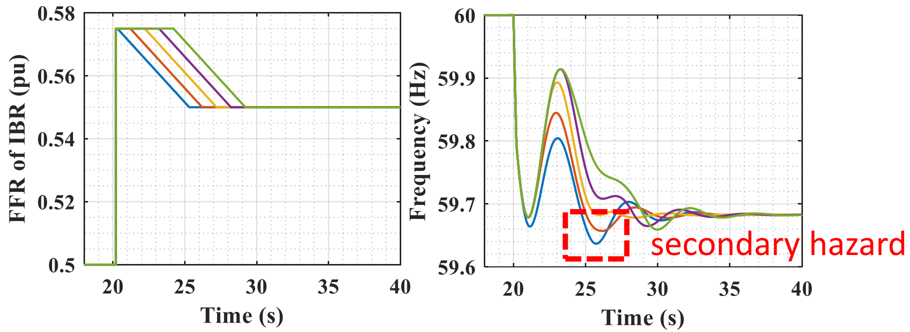


Findings

- High response magnitude decreases the RoCoF and increases the nadir.
- Excessively high response magnitude can even cause over frequency and exacerbate the “secondary hazard”.
- Not always the larger, the better→ over frequency issues

Impact of Key Fast Frequency Response Factors

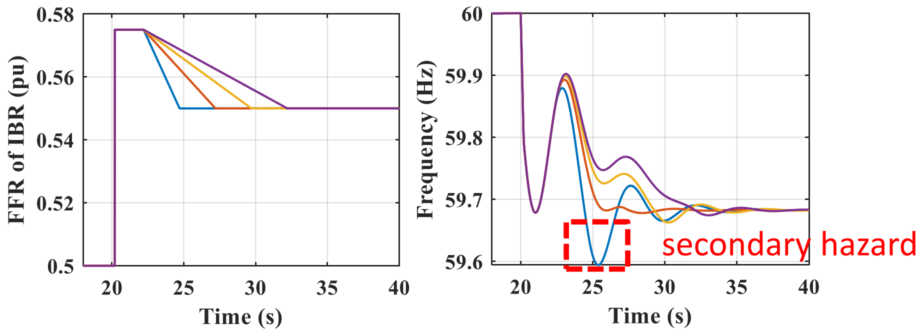
Impact of Sustaining Time



Findings

- Sustaining time doesn’t affect the RoCoF.
- $T_{sus} < 1s$, T_{sus} ↓, nadir ↓
- $T_{sus} > 1s$, T_{sus} ↑, nadir →
- **Secondary hazard:** the frequency drop caused by the ending of FFR.
- Needs to be long enough.
- No need to be super long.

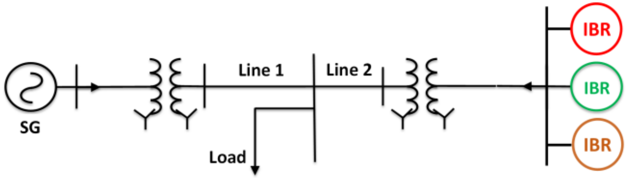
Impact of Downtime



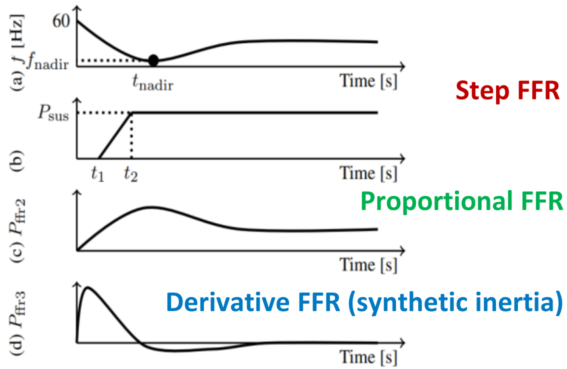
Findings

- Down time doesn’t affect the RoCoF.
- Given sustaining time = 2s, fast downtime doesn’t affect the Nadir.
- **The fast downtime can cause the “secondary hazard”.**
- The slower, the better.
- Too fast might cause a secondary hazard
- Too slow can cause a long settling time.

Analytical Prediction of Frequency Nadir



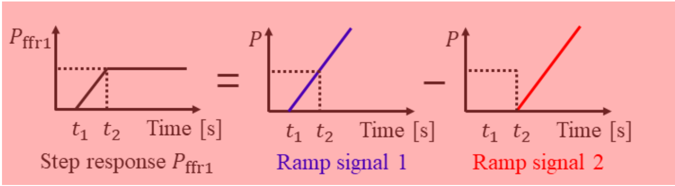
Step FFR
Proportional FFR
Derivative FFR (synthetic inertia)



Model power system frequency dynamics

$$2H_g \frac{df}{dt} = P_m - P_{\mathrm{load}} - D_g(f - f_n) + (P_{\mathrm{ffr1}} + P_{\mathrm{ffr2}} + P_{\mathrm{ffr3}}),$$

$$T_m \frac{dP_m}{dt} = P_m + \frac{1}{R_g}(f - f_n),$$



$$P_{\mathrm{ffr2}} = -\frac{1}{R_{\mathrm{ibr}}}(f - f_n), P_{\mathrm{ffr3}} = -H_{\mathrm{ibr}} \frac{df}{dt}.$$

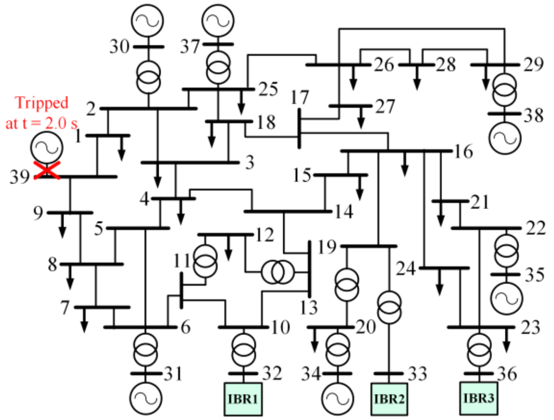
Proposed **analytically predict the frequency nadir** $\Delta f_{\mathrm{nadir}}$ as follows

$$\Delta f_{\mathrm{nadir}} = \frac{P_{\mathrm{sus}} - \Delta P_{\mathrm{load}}}{D_\Sigma + R_g^{-1}} + \frac{T_g R_g^{-1} M e^{(\alpha - \phi - \pi)} \cos\phi}{(t_2 - t_1)\left(D_\Sigma + R_g^{-1}\right)^{3/2}},$$

where P_{sus}, ΔP_{load}, D_Σ, R_g, T_g, M, α, t_1, t_2, and ϕ depend on system parameters.

Shuan Dong, Xin Fang, Jin Tan, Ningchao Gao, Xiaofan Cui, and Anderson Hoke, "A Unified Analytical Method to Quantify Three Types of Fast Frequency Response from Inverter-based Resources," in Proc. of 22nd Wind & Solar Integration Workshop 2023, Copenhagen, Denmark, Sep. 2023.

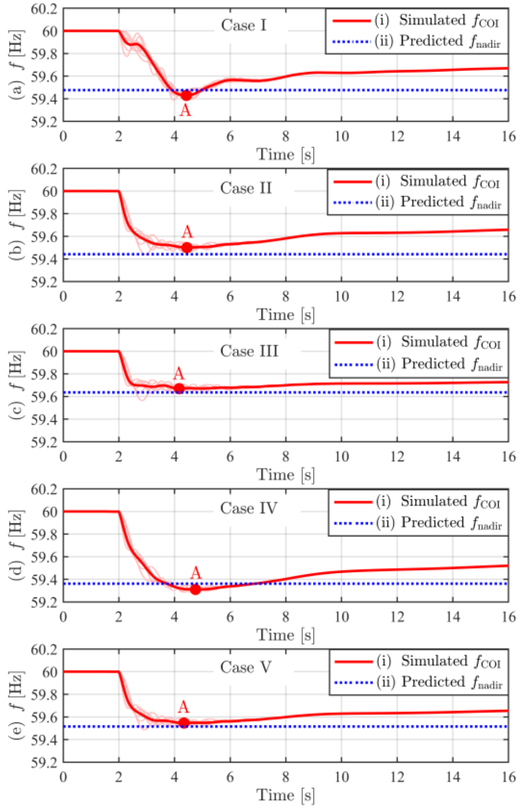
Application I:
Fast Frequency Nadir Prediction for Real-time Operation



Modified 39-bus system with three types of FFR from IBRs

Case	Bus32	Bus33	Bus36
I	SG	SG	SG
II	P_{ffr1}	P_{ffr1}	P_{ffr1}
III	P_{ffr2}	P_{ffr2}	P_{ffr2}
IV	P_{ffr3}	P_{ffr3}	P_{ffr3}
V	P_{ffr2}	P_{ffr3}	P_{ffr1}

Case I-V: IBR1-3 provides different combination of FFRs



- **High accuracy:** The predicted frequency nadirs (blue dotted line) in cases I-V are close to the simulated ones (point A) with error smaller than **0.06 Hz**.
- **High efficiency:** Our frequency nadir prediction method takes **0.15 ms** while the EMT simulation requires **~1000 s (10^6 times acceleration)**.

Shuan Dong, Xin Fang, Jin Tan, Ningchao Gao, Xiaofan Cui, and Anderson Hoke, "A Unified Analytical Method to Quantify Three Types of Fast Frequency Response from Inverter-based Resources," in Proc. of 22nd Wind & Solar Integration Workshop 2023, Copenhagen, Denmark, Sep. 2023.

Application II: Develop Stability Constraints in Scheduling

Question: How to utilize fast frequency response capabilities from IBRs?

- Fast Frequency Reserve
- **Frequency-nadir Stability Constraints**

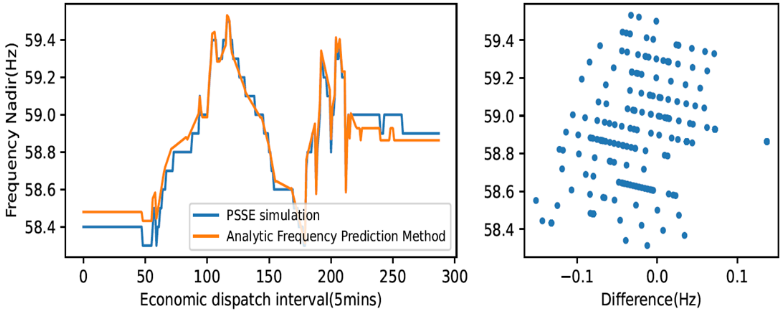
Challenges:

- How to apply the analytical method to a real large-scale system? How accurate it is?
  - Different types of SG governors (TGOV1, and GGOV1)
  - The response time of IBRs
  - A linearized constraint between key parameters needs to be discovered.

Step 1: Develop low-order frequency response model for TGOV1, GGOV1 and IBRs

Step 2: Improve the aggregated system frequency response model (ASFR)

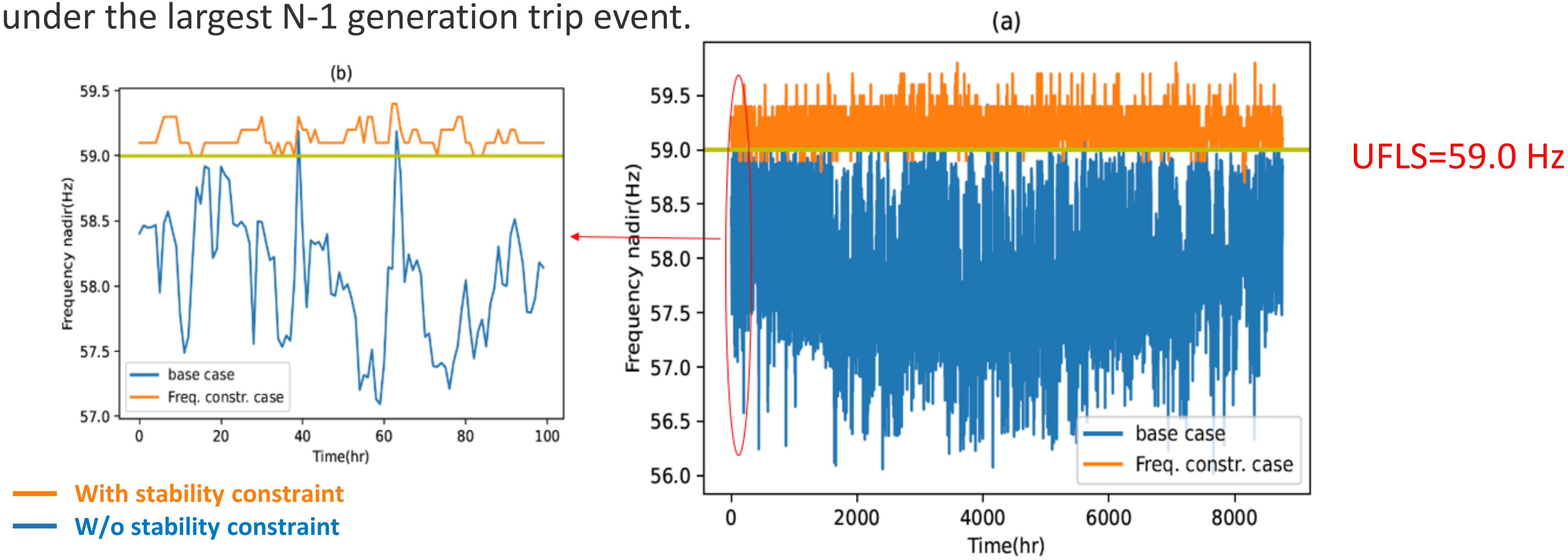
Step 3: Comparison of f_{nadir} in simulation and analytical method for a real Island Grid



Application II:
Verification of Proposed Constraint in Island Power Systems

Test system: A real island power system with a 70% renewable energy penetration level.

Scenarios: One-year test with and without stability constraints in the optimal scheduling model under the largest N-1 generation trip event.



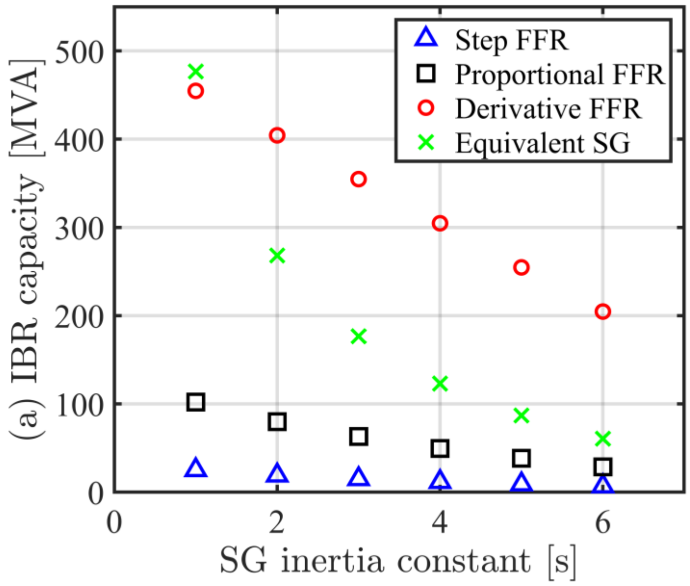
With the proposed frequency stability constraint, 98% of the system's frequency nadir is above 59.0 Hz.

Ningchao Gao, Shuan Dong, Xin Fang, Andy Hoke, David Wenzhong Gao, and Jin Tan, “Developing Frequency Stability Constraint for Unit Commitment Problem Considering High Penetration of Renewables” presented at 2023 IEEE 50th Photovoltaic Specialists Conference (PVSC).

FFR quantifications: IBR v.s. SGs

Increase SG inertia from 1 s to 6 s and plot the required FFR1, FFR2, and FFR3 IBR as well as SG capacity of achieving 59.5 Hz nadir.

- Step FFR (FFR1): reaction time 0.02 s and ramp-up time 0.05 s.
- Proportional FFR (FFR2): IBR P/f droop is 3%.
- Derivative FFR (FFR3): IBR inertia is 6 s.



When the renewable penetration level is high (H=1s)

- 1 FFR1=19 SGs
- 1 FFR2 =5 SGs
- 1 FFR3 =1 SG

When the renewable penetration level is medium/low (H=3s)

- 1 FFR1=12 SGs
- 1 FFR2 =3 SGs
- 1 FFR3 =0.5 SG

- Step FFR1 is the most effective type of FFR.
- We recommend combining FFR2 and FFR3 for the FFR service.

Concluding Remarks

- Needs for Fast Frequency Response have been growing along with the high renewable integration. Various types of FFR bring challenges for FFR quantification.
- We developed a **fast** and **accurate** method to analytically predict post-disturbance frequency nadir in power systems with both SGs and IBRs. All **three major types of FFR from IBRs** are fully considered in our improved system frequency response (SFR) model.
- The proposed FFR quantification method can be used for
  - **Prediction of frequency nadir** in real-time operation or planning study.
  - **Developing stability constraints in the scheduling model** to ensure sufficient FFR resources online.

Compelling future directions:

- More types of FFR will be added further, such as grid-forming inverters' responses (Droop-based, virtual synchronous machine, etc.).
- Evaluation of FFR capacity adequacy from IBRs in planning study.
- Application of frequency nadir prediction method in real-time power system security monitoring.

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Team

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Sponsor

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Thank you!

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