Frequency Stability Assessment of Future Power Systems

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Challenges and Opportunities

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Date: 03 June 2023

Acknowledgement of Country

KPMG acknowledges Aboriginal and Torres Strait Islander peoples as the First Peoples of Australia. We pay our respects to Elders past, present, and future as the Traditional Custodians of the land, water and skies of where we work.

At KPMG, our future is one where all Australians are united by a shared, honest, and complete understanding Of our past, present, and future. We are committed to making this future a reality. Our story celebrates and acknowledges that the cultures, histories, rights, and voices of Aboriginal and Torres Strait Islander People are heard, understood, respected, and celebrated.

Australia's First Peoples continue to hold distinctive cultural, spiritual, physical and economical relationships with their land, water and skies. We take our obligations to the land and environments in which we operate seriously.

We look forward to making our contribution towards a new future for Aboriginal and Torres Strait Islander peoples so that they can chart a strong future for themselves, their families and communities. We believe we can achieve much more together than we can apart.

*This acknowledgement of country has been developed within KPMG Indigenous Network (KIN) should you wish to modify the wording please reach out for consultation of the KIN. The KIN is a culturally safe and supportive space for Aboriginal and Torres Strait Islander colleagues from all geographies, divisions, and levels of the firm and you can get in touch by emailing smoates@kpmg.com.au

Outline

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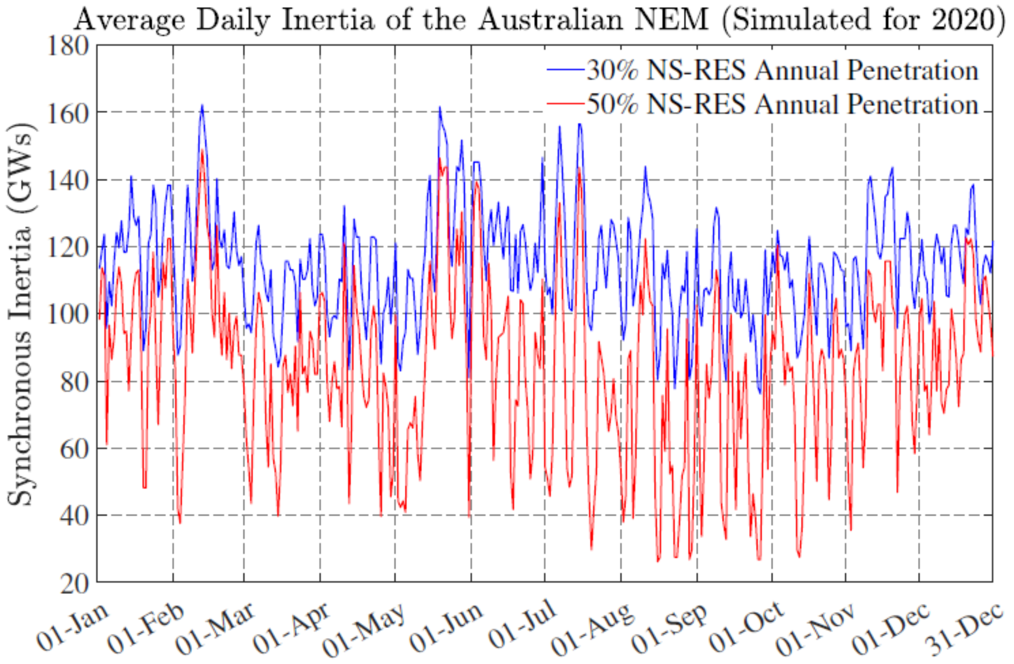
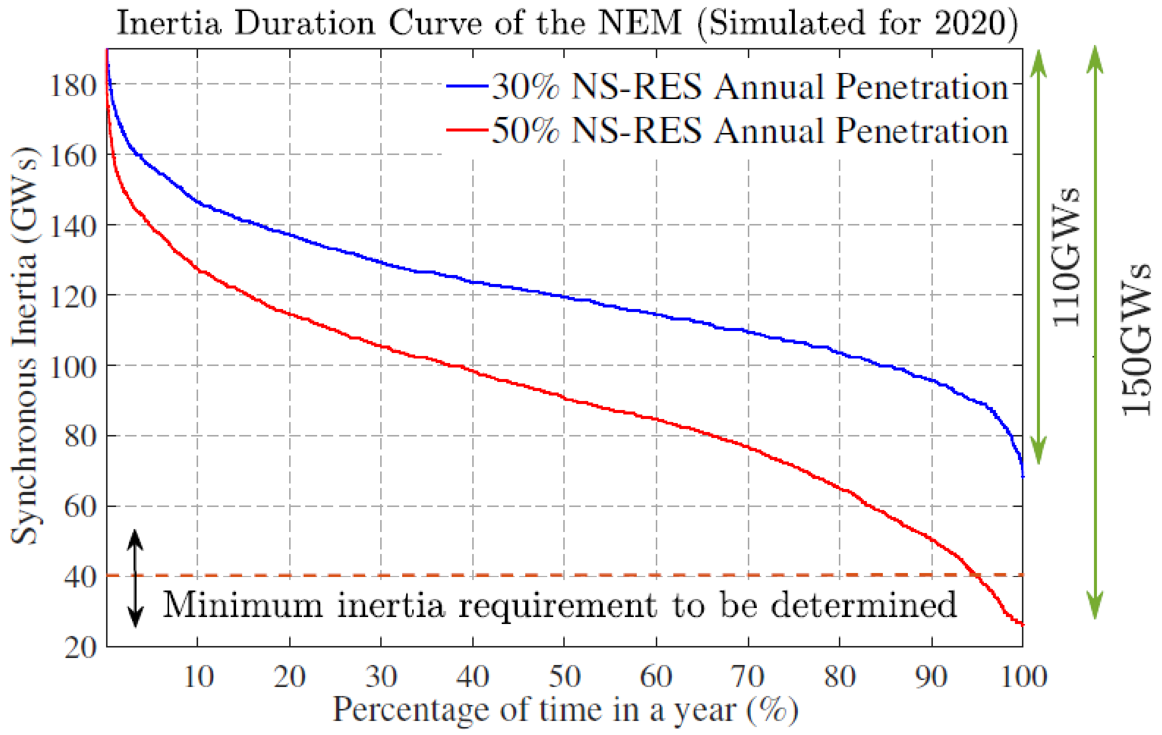
01

Motivation

System Inertia

- With the increasing penetration of NS-RES, not only the synchronous system inertia reduces, but it also becomes more time variant.
- As the inertia reduces, the rate of change of frequency increases
- Minimum inertia requirement of a system should be determined.
- New indices might be required to better represent the system's inertia requirement.





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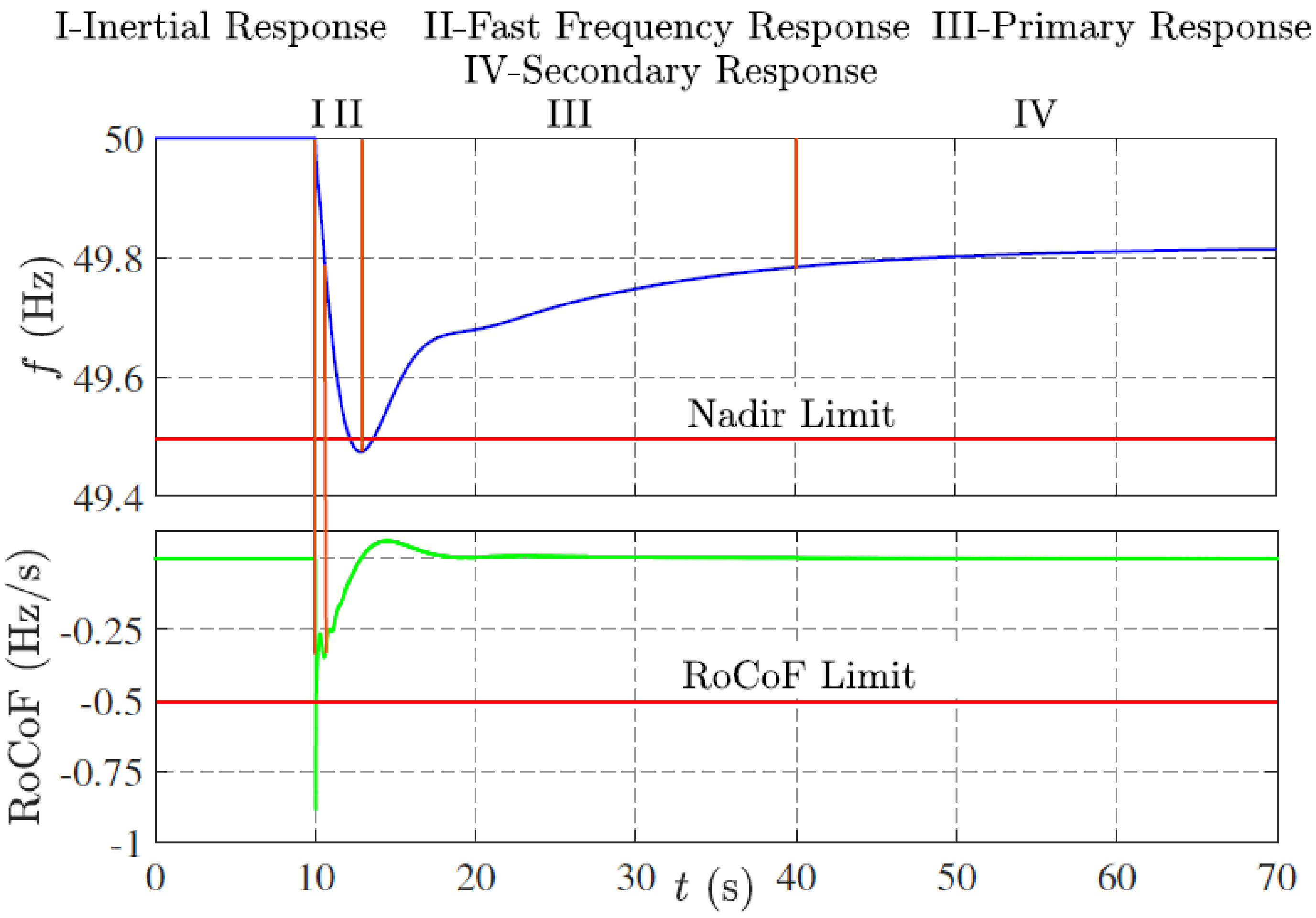
A Typical System Frequency Response



➢ Frequency behaviours of the NEM with low inertia after a contingency

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02

Background

Rate of Change of Frequency (RoCoF)

Aggregated Swing Equation:

$$\downarrow H = \frac{\text{stored energy at rated speed (MWs)}}{\text{MVA rating}}. \qquad (1)$$

$$\uparrow \left|\frac{df}{dt}\right| = \frac{f_0}{2HS_B D_{\text{load}}}\Delta f + \frac{f_0}{2HS_B}(\Delta P_g - \Delta P_{\text{load}}), \qquad (2)$$

Some of the Consequences:

- Higher rate of change of frequency, which might result in activation of RoCoF relays.
- Higher turbines' rotational acceleration/deceleration, which might result in mechanical degradation of turbines' shaft.
- Negative impacts on combustion turbines because of potential turbine combustor lean blowout.

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Other Studies on Frequency Stability

EirGrid Study in Ireland:

- At least 30% of the power should be supplied by synchronous generators, or the ratio of system synchronous inertia over the largest in-feed generator should be larger than 20 s.
- The main issue is high RoCoF.

NREL Study of WECC:

- Based on maximum of 53% non-synchronous penetration.
- Both RoCoF and Frequency nadir increased, but the UFLS scheme was not activated.

AEMO 100% Renewable Study in Australia:

- A minimum of 15% synchronous generation was considered for maintaining system stability.

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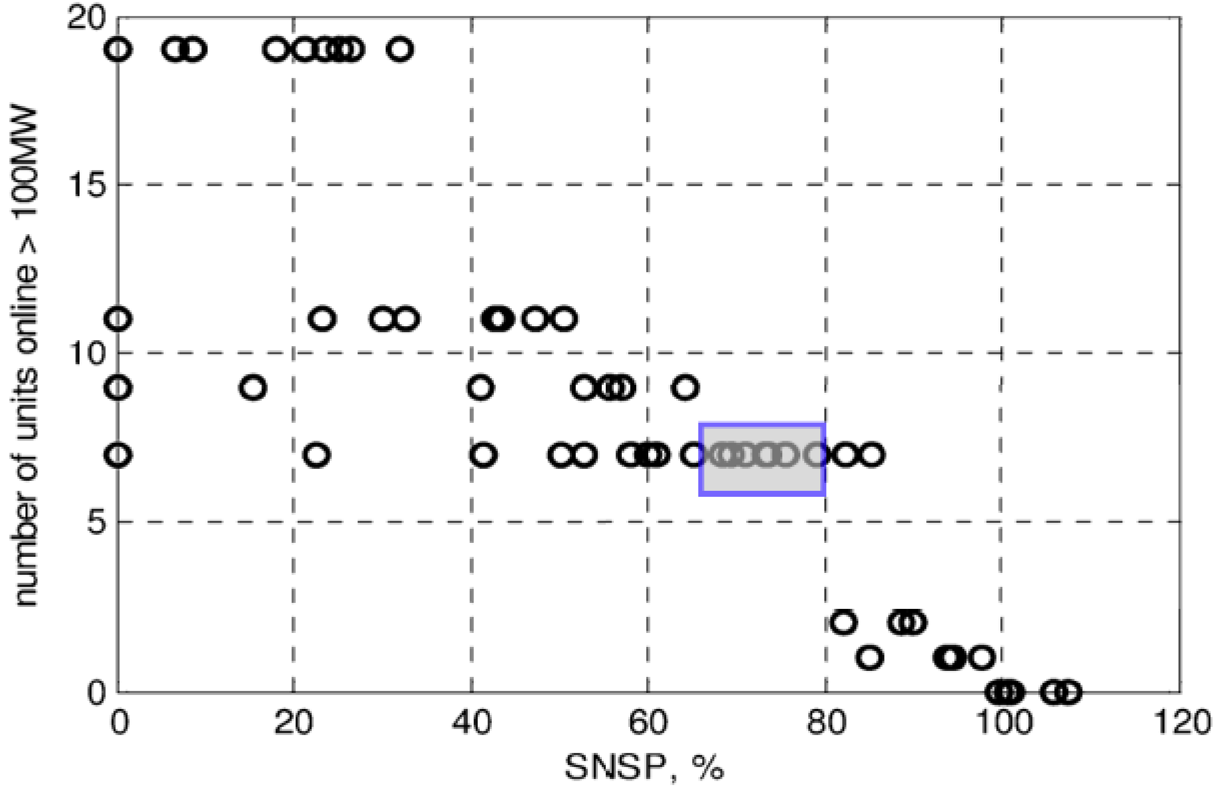
Synchronous Generation or Inertia?

- For non-synchronous generation ranging from 65% to 80% same amount of synchronous inertia and governor response:



[1] J. O'Sullivan, A. Rogers, D. Flynn, S. Member, P. Smith, A. Mullane, and M. O'Malley, "Studying the Maximum Instantaneous Non-Synchronous Generation in an Island System - Frequency Stability Challenges in Ireland," IEEE Transactions on Power Systems, vol. 29, no. 6, pp. 2943-2951, 2014

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Inertia Constraints?

- **SgN30:** The available capacity of synchronous generators is 30% of total demand.

$$\sum_{g \in \mathcal{G}_{\text{synch}}} s_{g,t} \overline{S}_g \geq 0.3 S_t^{\text{load}} \quad \forall t. \qquad (3)$$

- **Isynch30:** We consider a minimum synchronous kinetic energy of 30% (Hsys = 4 s).

$$\sum_{g \in \mathcal{G}_{\text{synch}}} s_{g,t} H_g \overline{S}_g \geq 0.3 H_{sys} S_t^{\text{load}} \quad \forall t. \qquad (4)$$

- **SgP30:** Synchronous generators should supply at least 30% of total demand.

$$\sum_{g \in \mathcal{G}_{\text{synch}}} p_{g,t} \geq 0.3 p_t^{\text{load}} \quad \forall t. \qquad (5)$$

[2] A.S. Ahmadyar, S. Riaz, G. Verbiˇc, J. Riesz, A. Chapman ″Assessment of Minimum Inertia Requirement for System Frequency Stability,″ in Power System Technology (POWERCON), 2016 IEEE International Conference, 28 Sept. - 1 Oct. 2016.

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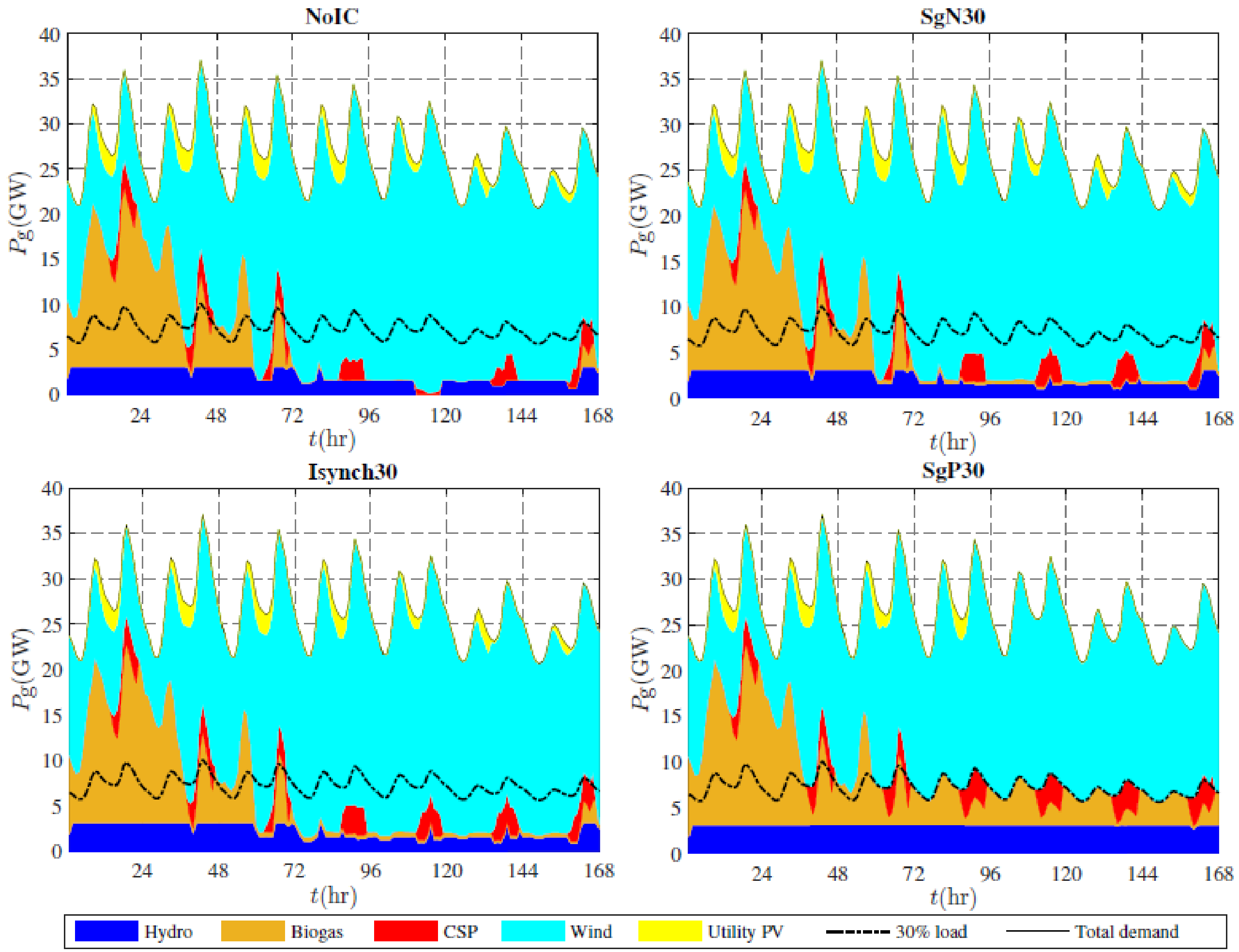
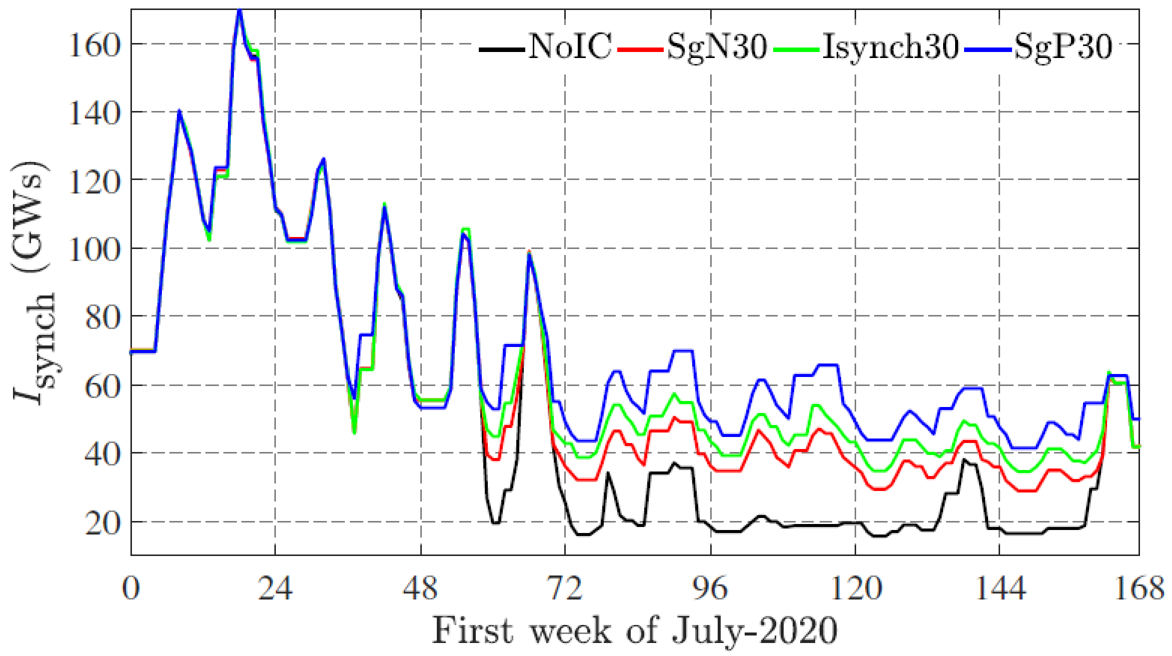
Dispatch Results & Synchronous Inertia of the System





- System kinetic energy during the first week of July-2020 considering different inertia constraints

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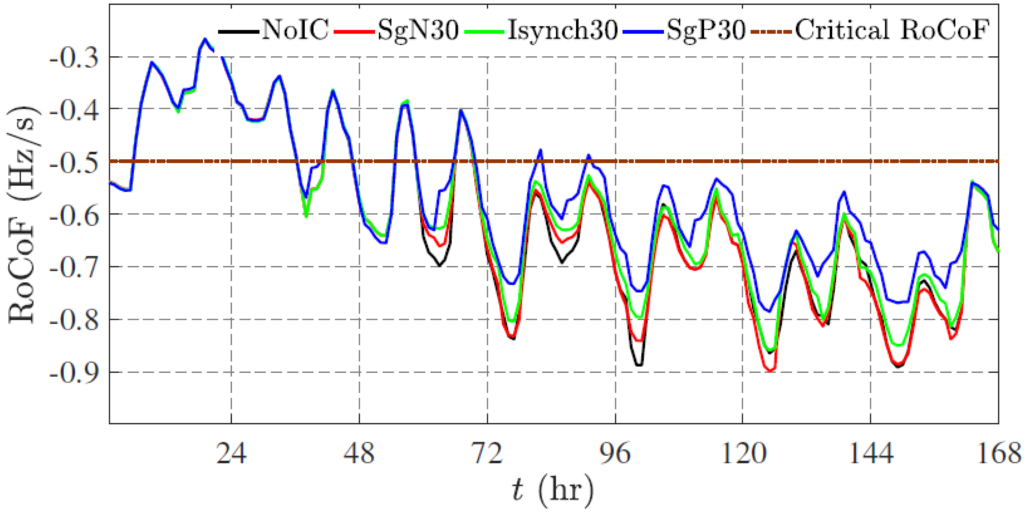
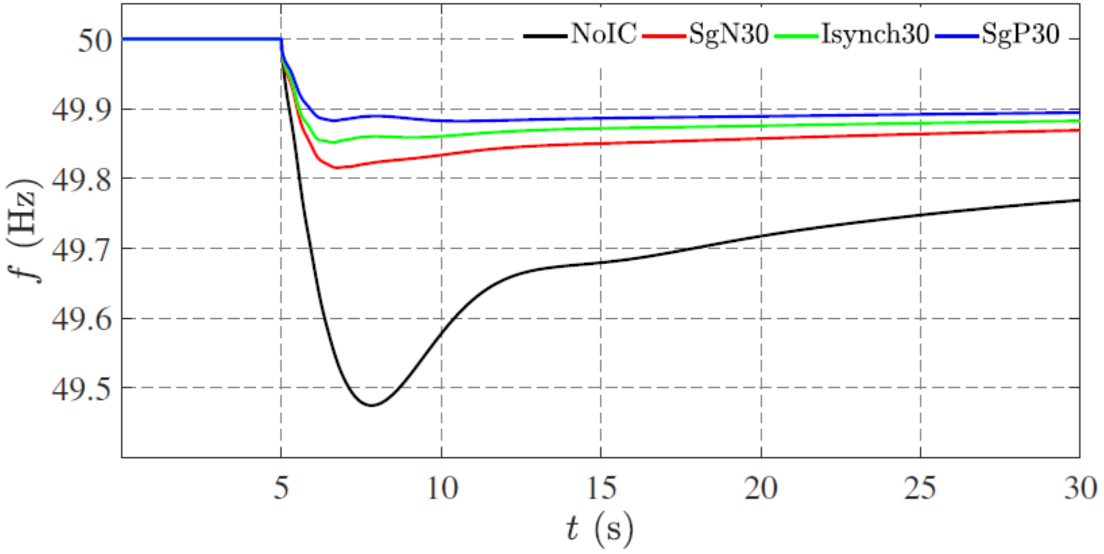
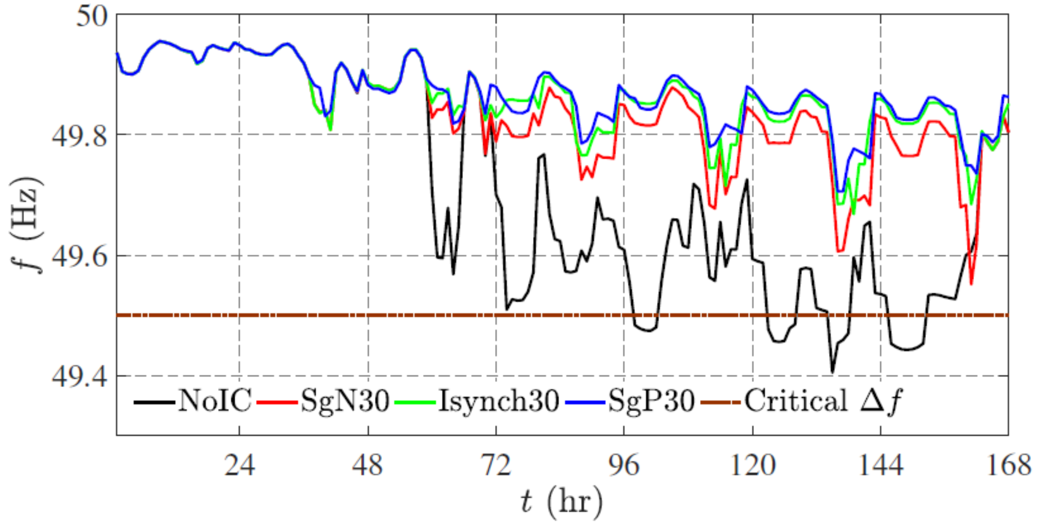
System Frequency Response

- System frequency behaviour after the loss of the largest in-feed for a typical hour in July-2020
- Minimum rate of change of frequency after the loss of the largest in-feed for the first week of July-2020
- System frequency nadir after the loss of the largest in-feed for the first week of July-2020.







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03

Frequency Stability Assessment Framework

The Framework

Algorithm 1 FPS Frequency Stability Assessment Framework

Inputs: Network data, generation data, ancillary service requirements (e.g. spinning reserve), wind, solar and demand traces for each scenario $s \in \mathscr{S}$ in the studied year.

for $s \leftarrow 1, |\mathscr{S}|$ **do**
  for $t \leftarrow 1, |\mathscr{T}|$ **do**
    Market simulation (generation dispatch);
    Identify credible contingencies;
    Load-flow analysis;
  end for
  for $c \leftarrow 1, |\mathscr{C}|$ **do**
    for $t \leftarrow 1, |\mathscr{T}|$ **do**
      Frequency stability assessment by;
      Considering all the credible contingencies;
    end for
  end for
end for

Outputs: Frequency stability indices (i.e. minimum RoCoF and frequency nadir) for each time slot $t \in \mathscr{T}$, for each sensitivity case $c \in \mathscr{C}$, and for each scenario $s \in \mathscr{S}$.

[3] A.S. Ahmadyar, S. Riaz, G. Verbi˘c, A. Chapman, D. J. Hill ”A Framework for Frequency Stability Assessment of Future Power Systems: An Australian Case Study,” Submitted to IEEE Transactions on Power Systems June 2017

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The Market Model

UC problem that aims to fulfil the demand requirement by:

- Fixed, start-up, shut-down and fuel cost of all generators.
- Minimum stable limits, ramp rates, up/down time of SGs.
- Renewable energy availability.
- Thermal and stability limits of transmission lines.

$$\text{minimise} \quad \sum_{h=1}^{\mathcal{H}} \sum_{g=1}^{\mathcal{G}} \left(c_g^{\text{fix}} s_{g,h} + c_g^{\text{su}} u_{g,h} + c_g^{\text{sd}} d_{g,h} + c_g^{\text{var}} p_{g,h} \right). \quad (6)$$

Scanning tool for identifying credible contingency:

- A minimum of 15% synchronous generation was considered for maintaining system stability.

$$p_t^{\text{cc}} = \max\left(p_{g,h}\right) \quad g \in \mathcal{G}_{\text{synch}}. \quad (7)$$

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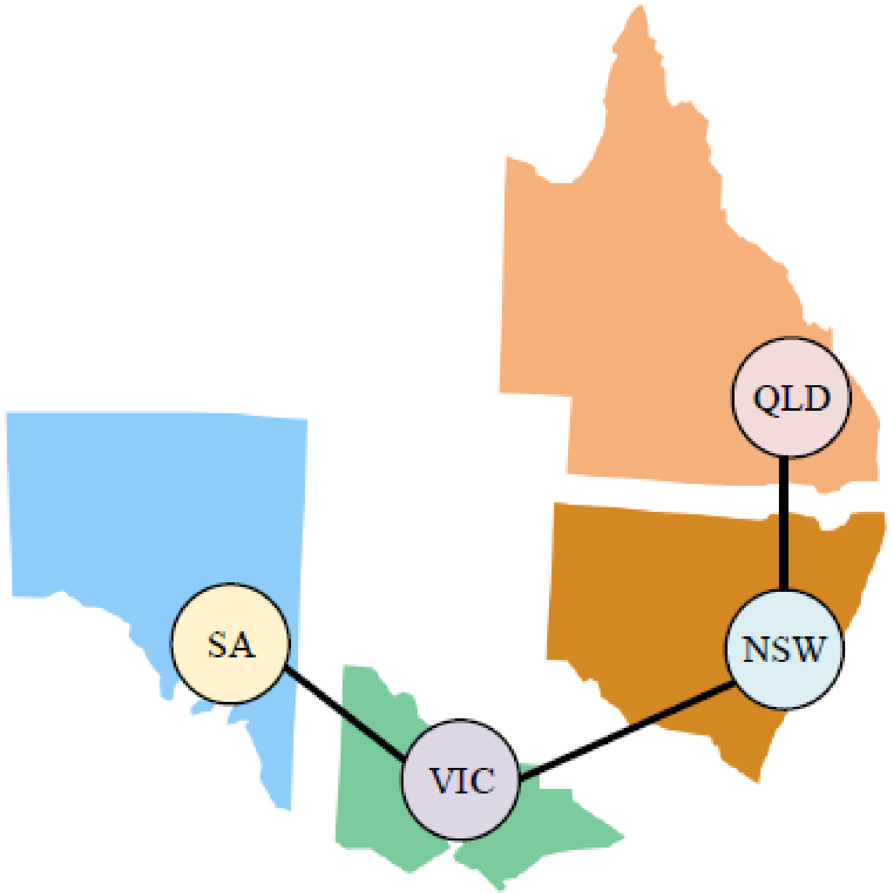
The Australian NEM

- The longest transmission network (i.e. More than 5000 km from port Douglas in QLD to Augusta in SA).
- Australian Energy Market Operator (AEMO):
  - Energy market.
  - Ancillary service market; including 8 Frequency control markets.
- Retirement of coal fired plants.
- Percentage of homes with rooftop-PV, 15 %in 2015 (i.e. Highest in the world).



Simplified SLD of the NEM

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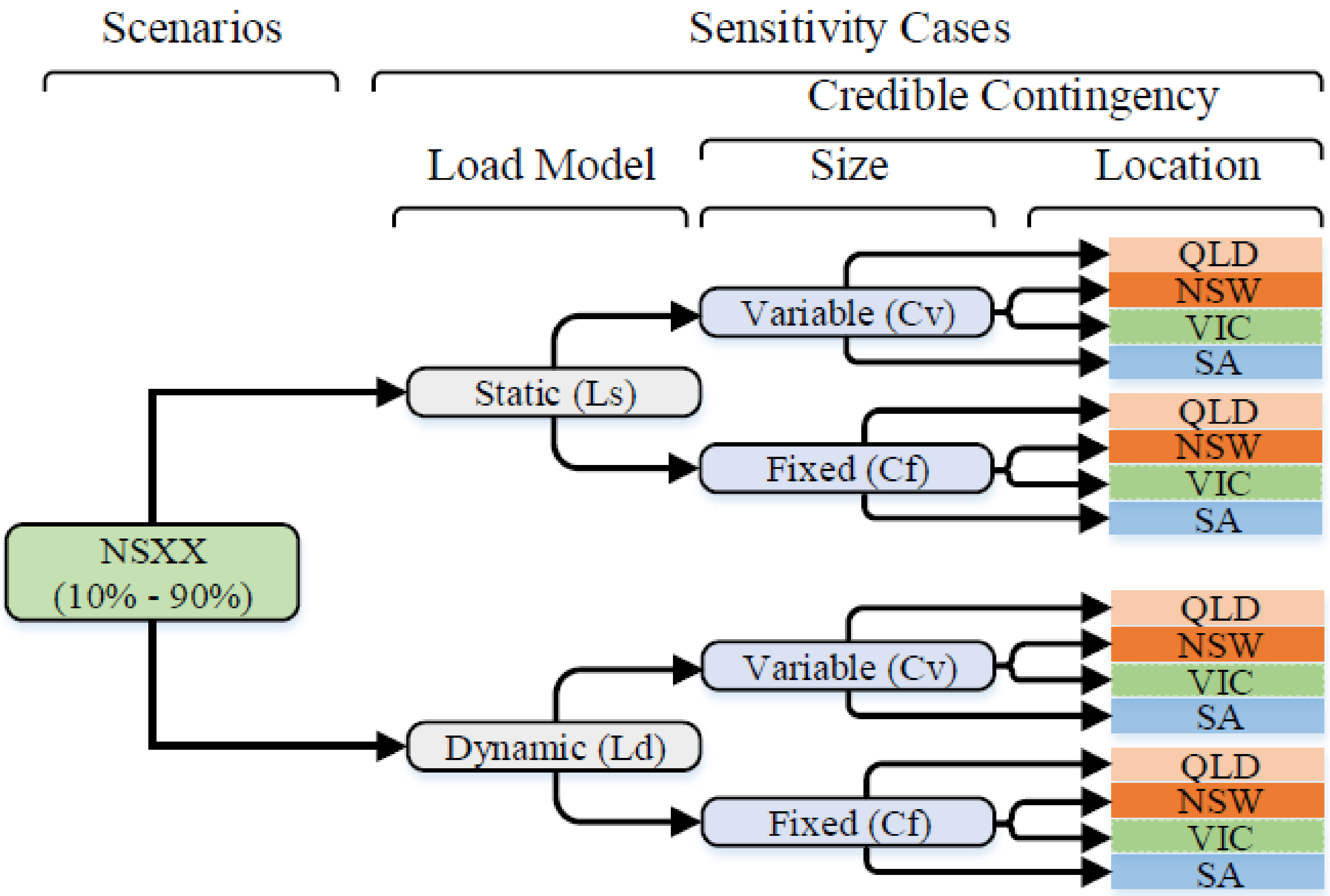
Sensitivity Cases



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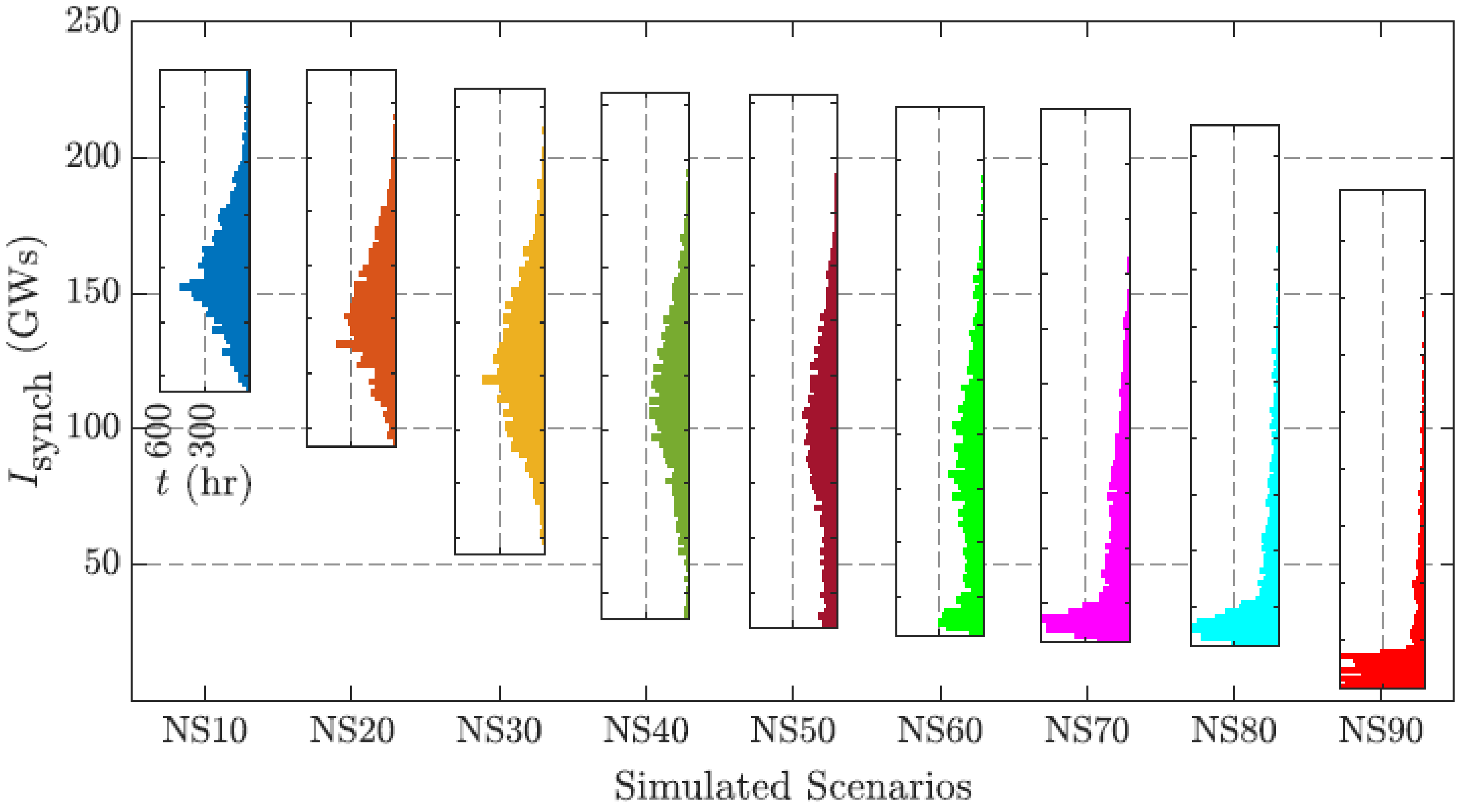
System Inertia



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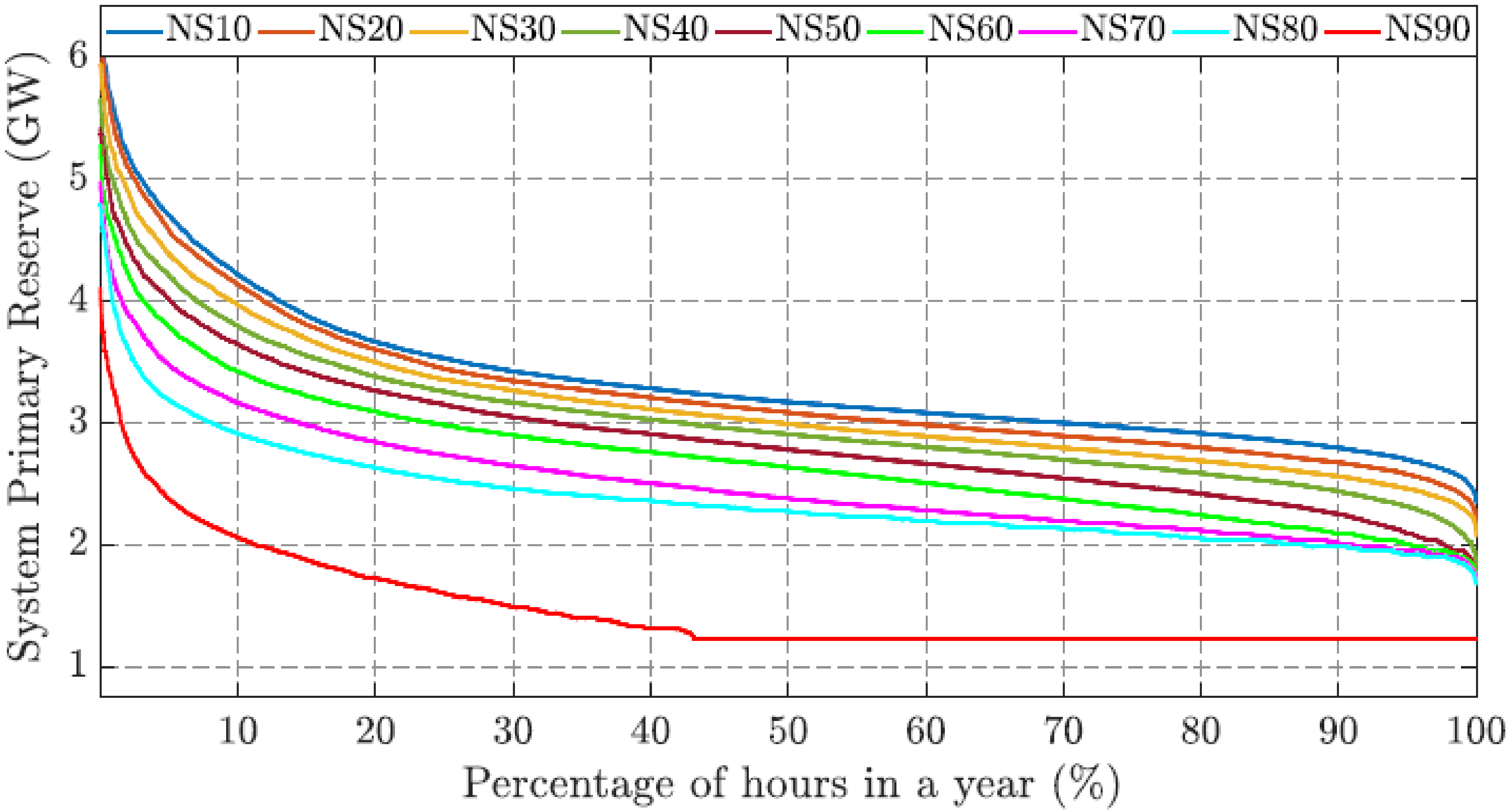
System Headroom



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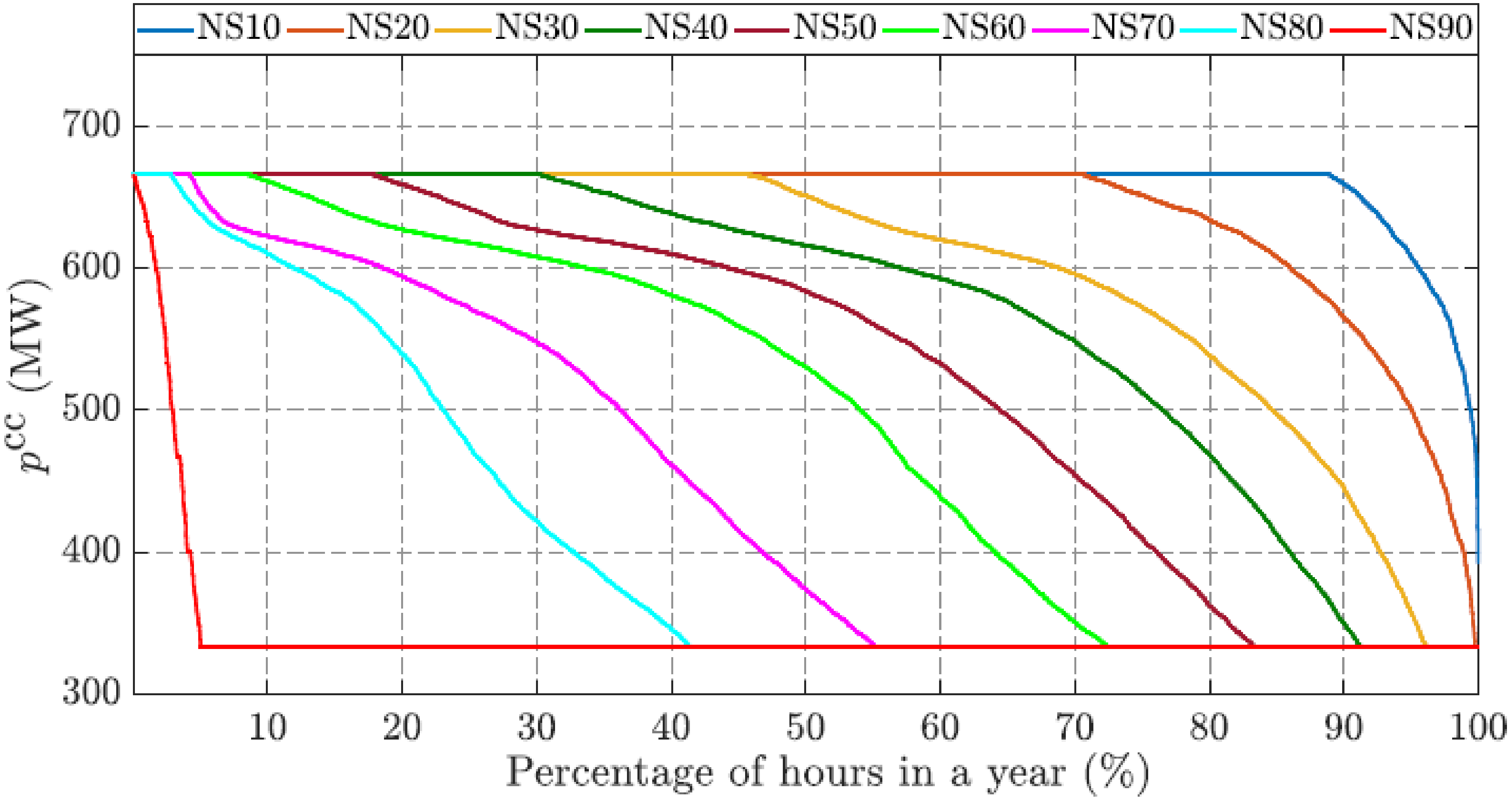
System Credible Contingency



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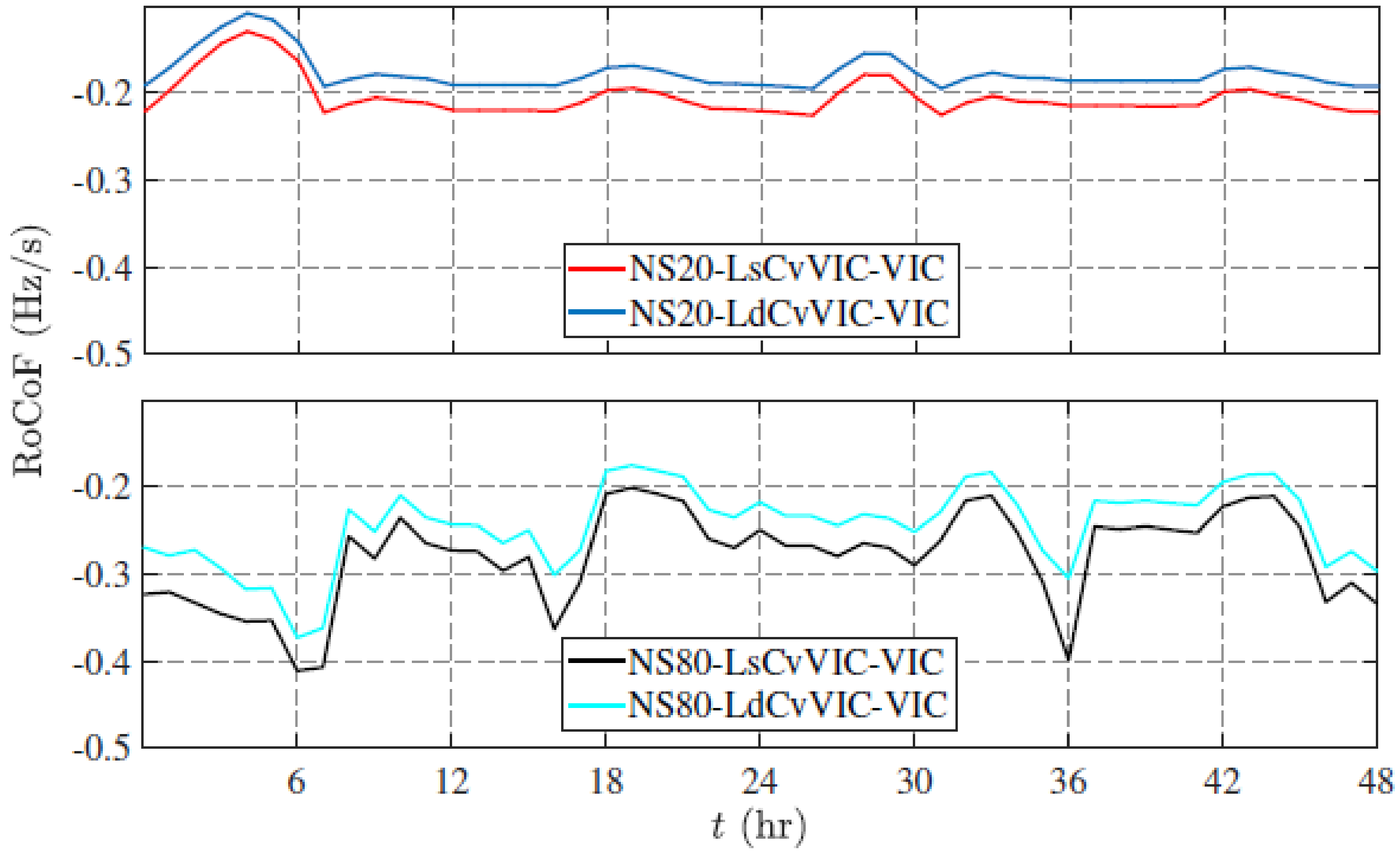
Impact of Load Model on RoCoF



- More evident with a high non-synchronous instantaneous penetration (NSIP) and high load level,
  - E.g. Scenario NS80, $t = 6$ h and $t = 36$ h.

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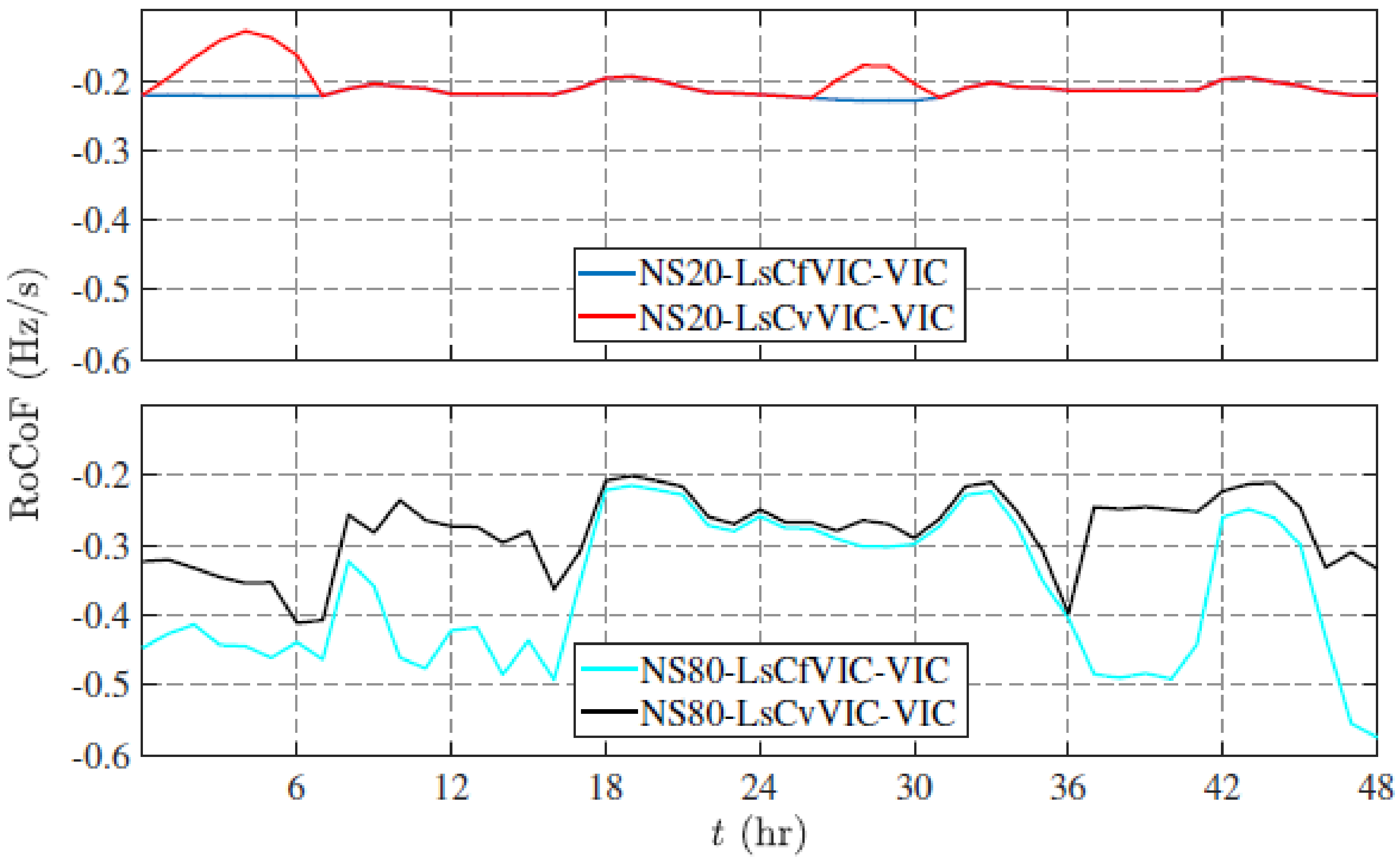
Impact of Contingency Size on RoCoF



- ➢ With a high NSIP, the impact of contingency size more significant.

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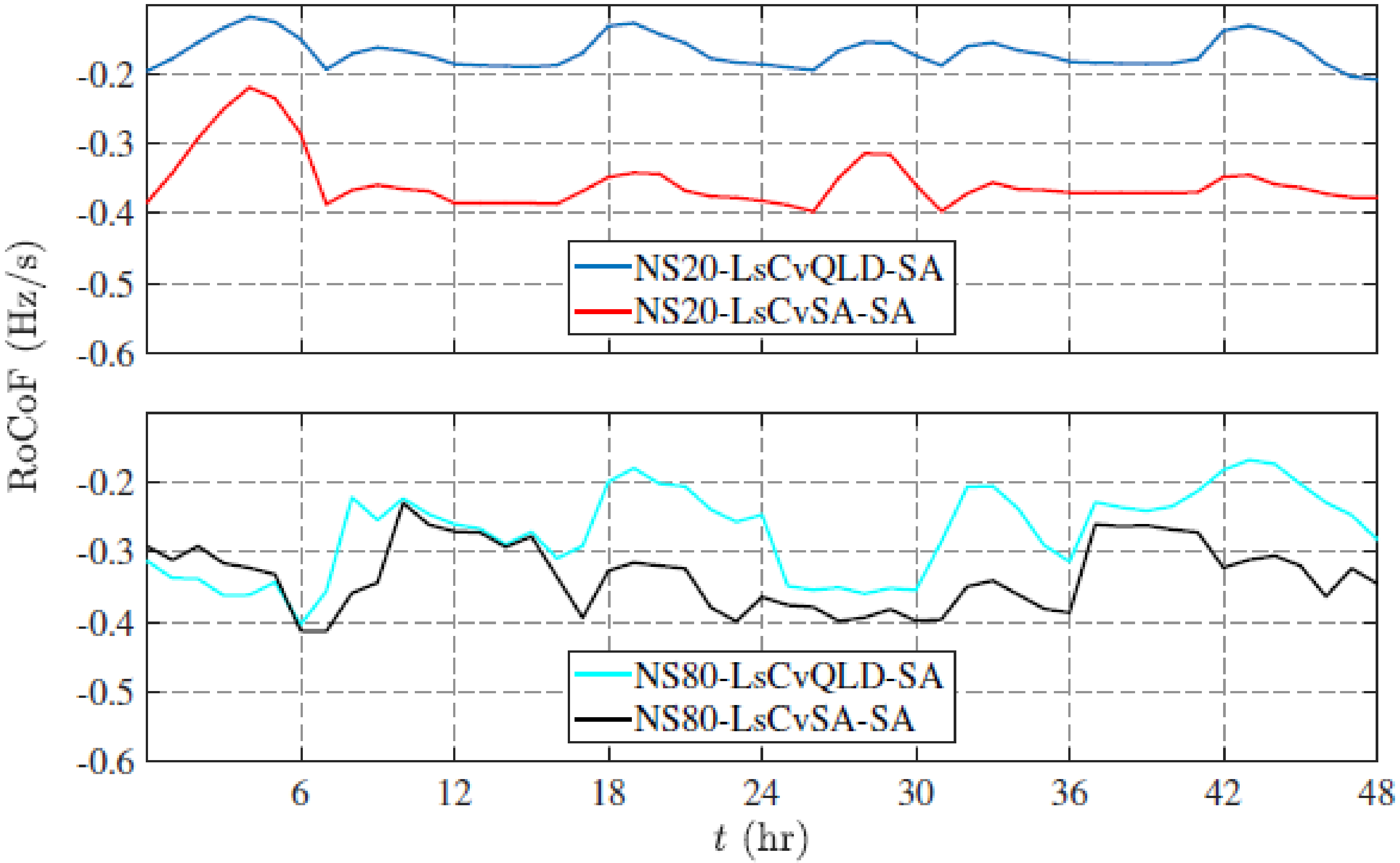
Impact of Contingency Location on RoCoF



- With a high NSIP, both inertia location as well as network strength becomes more significant on the frequency stability performance.

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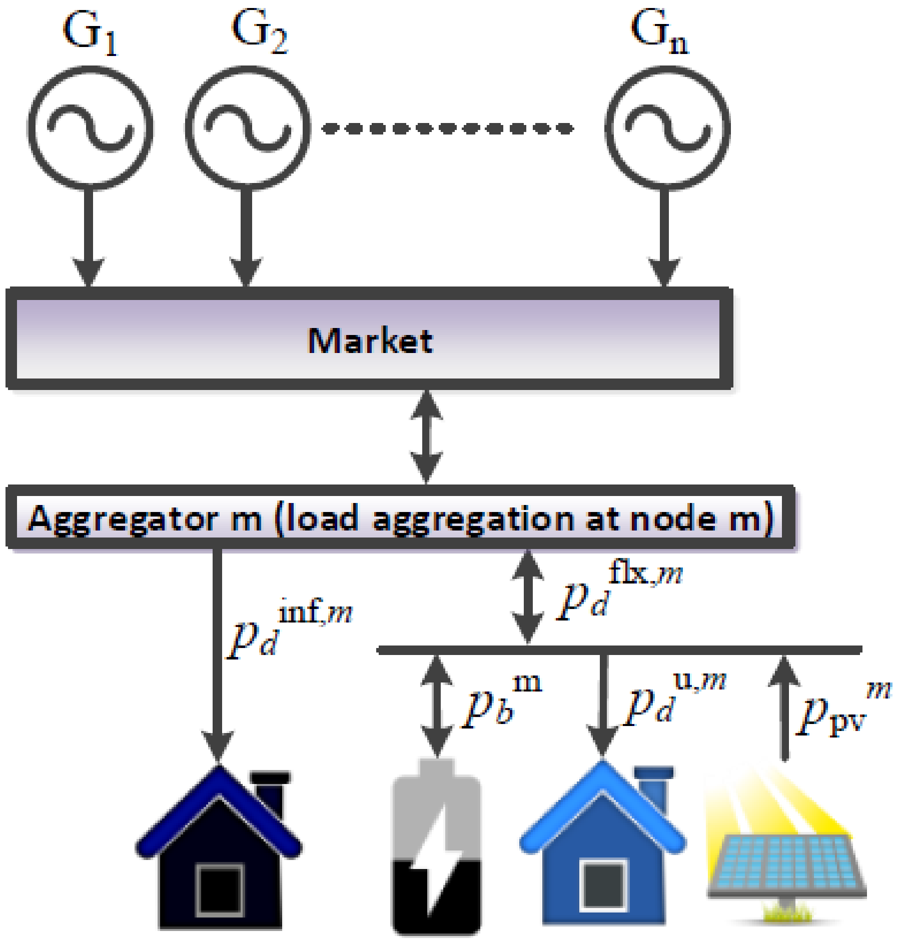
04

Frequency Stability Assessment Framework

Demand Modelling Considering Prosumers



[4] H. Marzooghi, G. Verbiˇc, D. J. Hill, "Aggregated demand response modelling for future grid scenarios," Sustainable Energy, Grids and Networks, vol. 5, pp. 94-104, 2016

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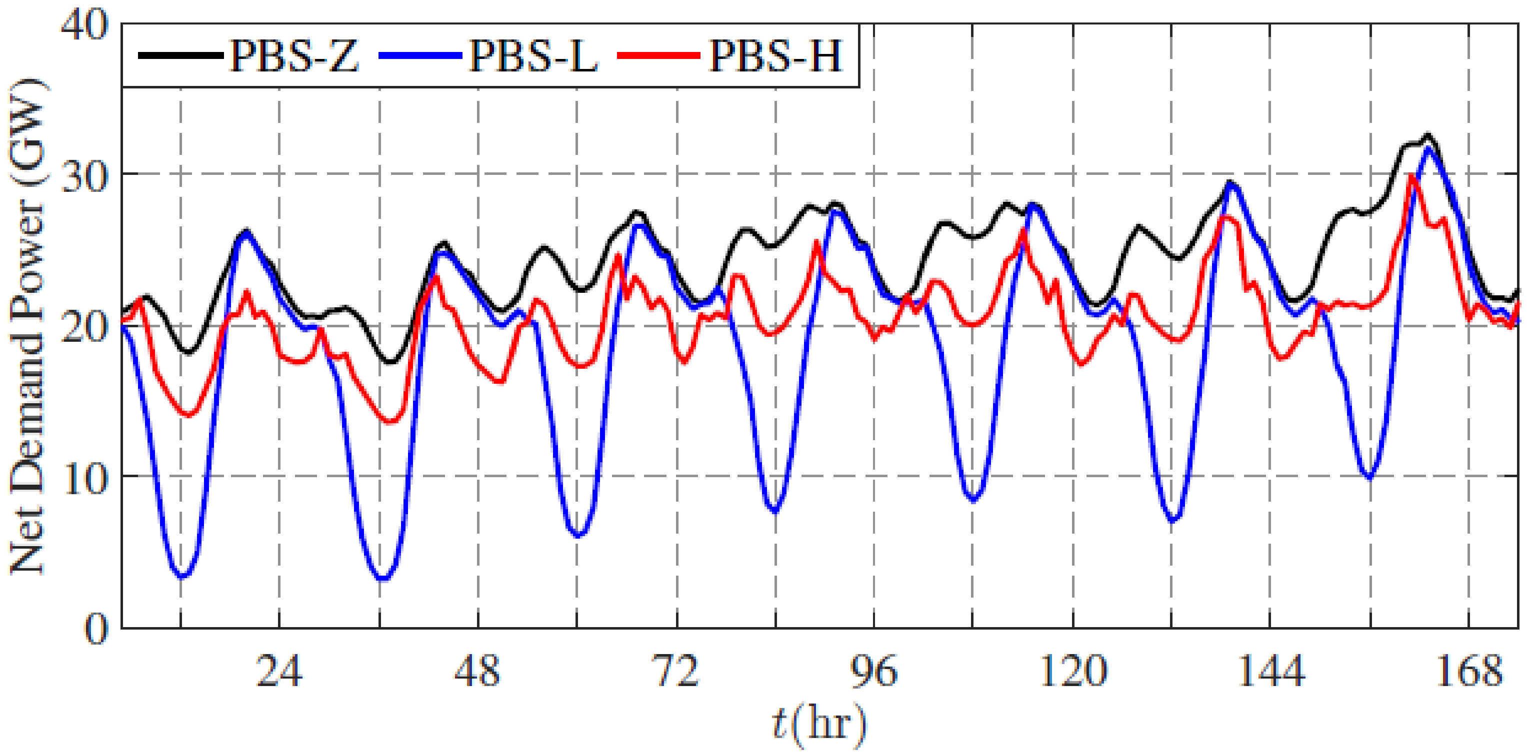
Prosumers' Impact on System Performance



- **PBS-Z**: Conventional demand model is considered.
- **PBS-L**: BS capacity of 1.8 kWh per 1 kW of rooftop-PV.
- **PBS-H**: BS Capacity of 3 kWh per 1 kW of rooftop-PV.

[5] A.S. Ahmadyar, H. Marzooghi, G. Verbi˘c, D. J. Hill "Impact of Prosumers on Frequency Stability of the Australian Future Grid," in 2017 IEEE Power and Energy Society General Meeting, 16 - 20 July. 2017.

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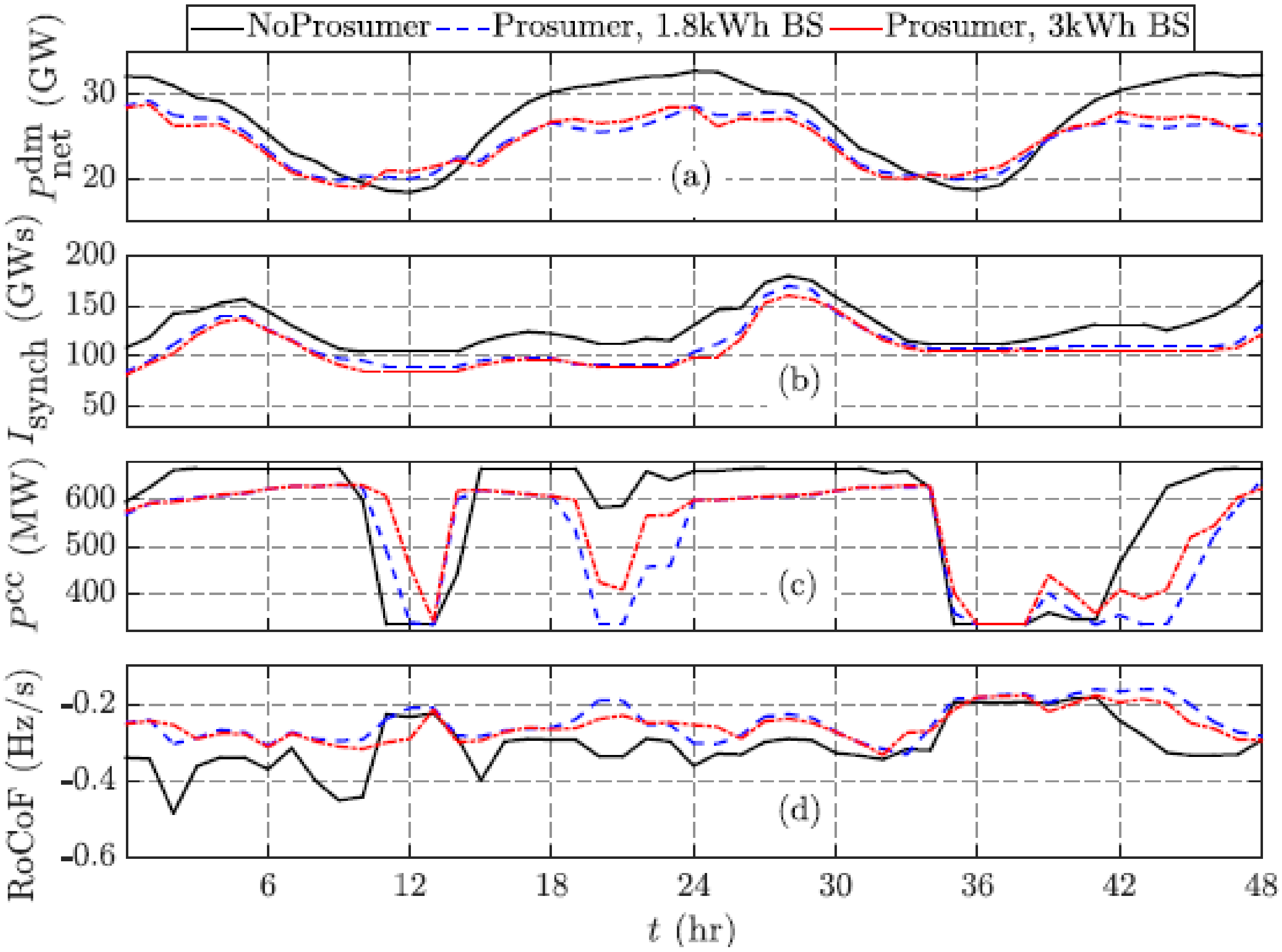
Sensitivity of BS Capacity



[3] A.S. Ahmadyar, S. Riaz, G. Verbi˘c, A. Chapman, D. J. Hill ”A Framework for Frequency Stability Assessment of Future Power Systems: An Australian Case Study,” Submitted to IEEE Transactions on Power Systems June 2017

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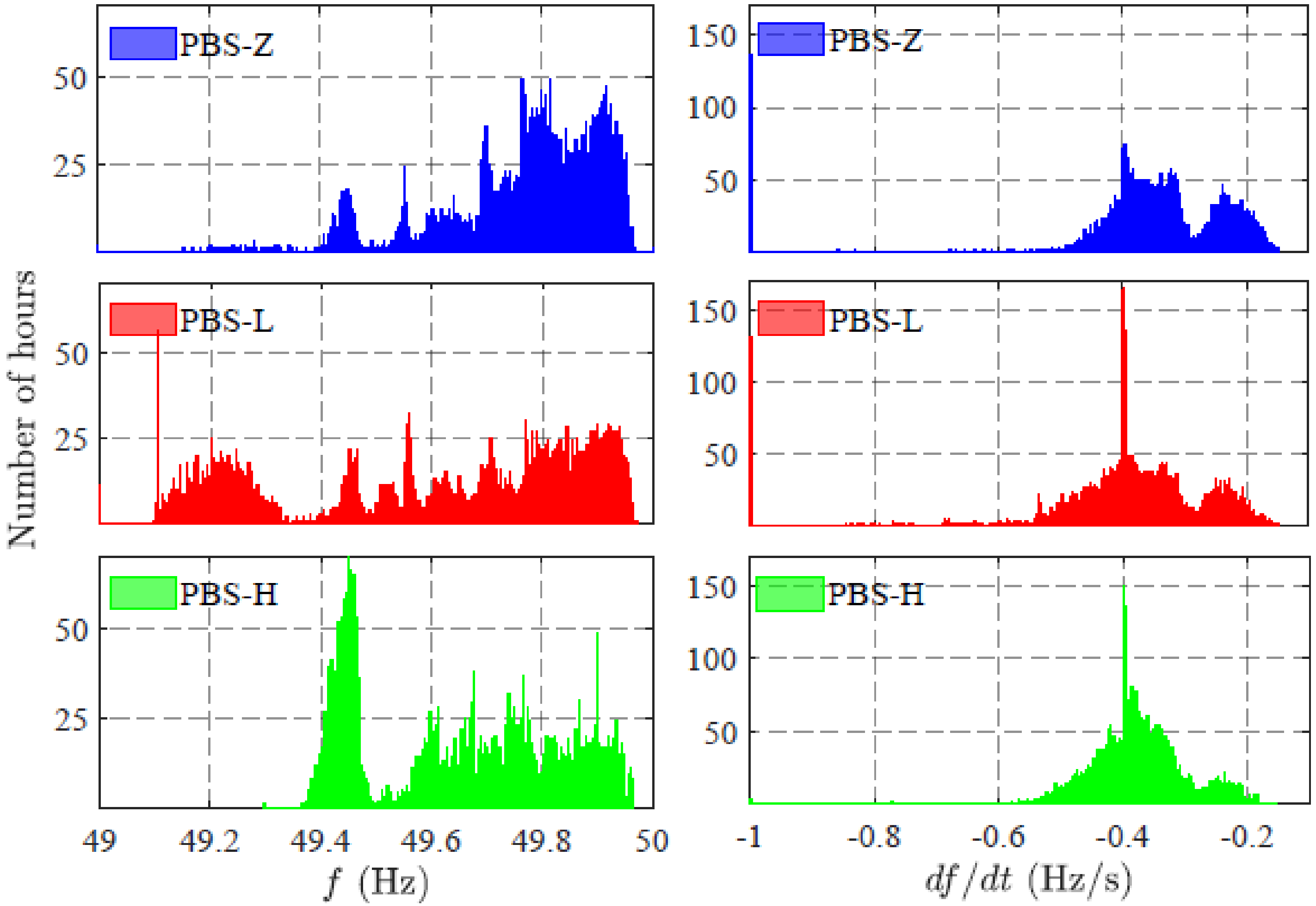
Prosumers' Impact on System Frequency



[5] A.S. Ahmadyar, H. Marzooghi, G. Verbi˘c, D. J. Hill "Impact of Prosumers on Frequency Stability of the Australian Future Grid," in 2017 IEEE Power and Energy Society General Meeting, 16 - 20 July. 2017.

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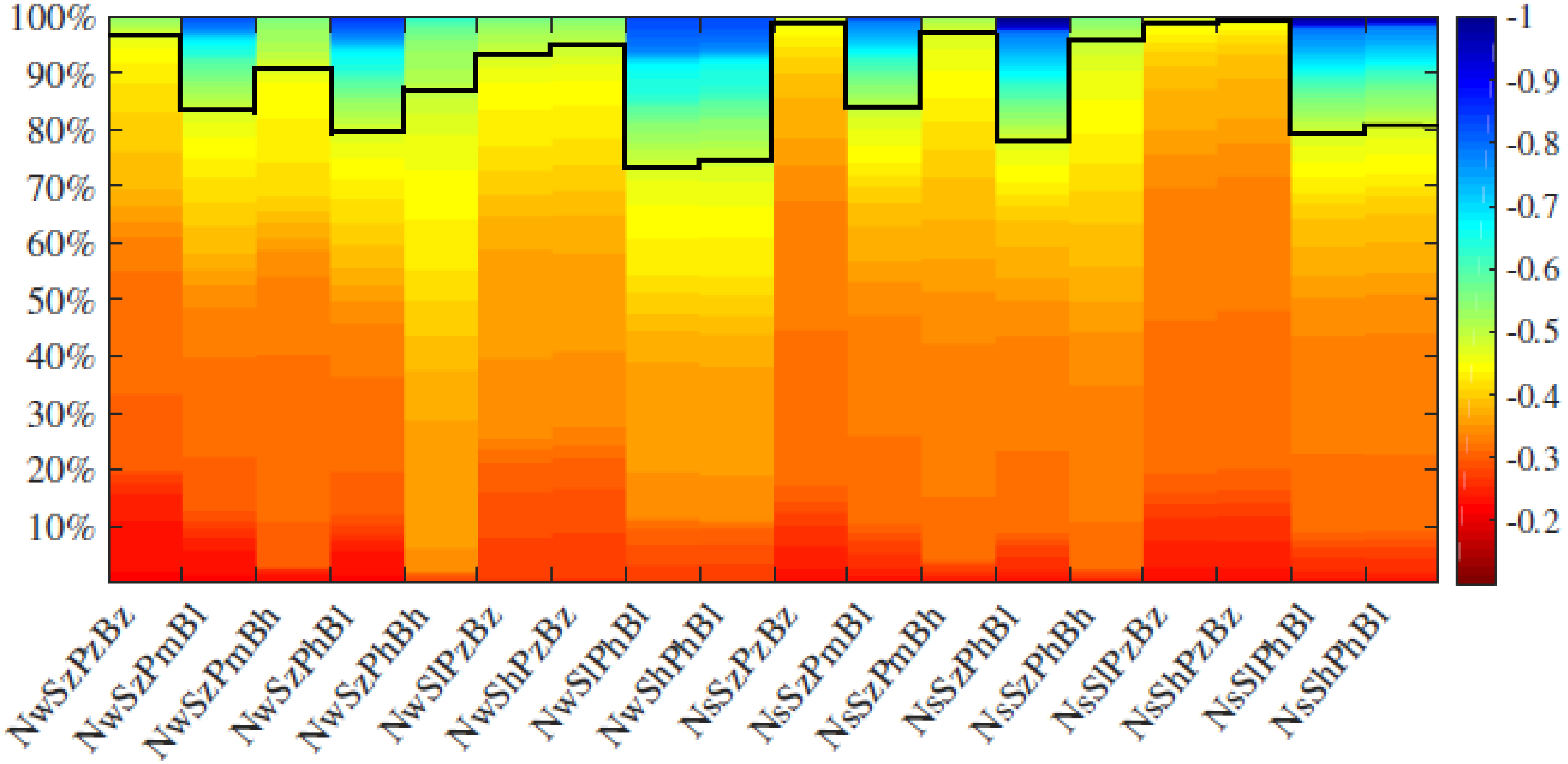
Impact of Other Parameters on RoCoF



- Network strength, utility storage, rooftop-PV and Prosumers, Battery storage

[6] H. Marzooghi, M. Gramroodi, A.S. Ahmadyar, R. Liu, G. Verbi˘c, D. J. Hill ”Scenario and Sensitivity Based Stability Analysis of the Australian Future Grid,” Submitted to IEEE Transactions on Power Systems, July 2017.

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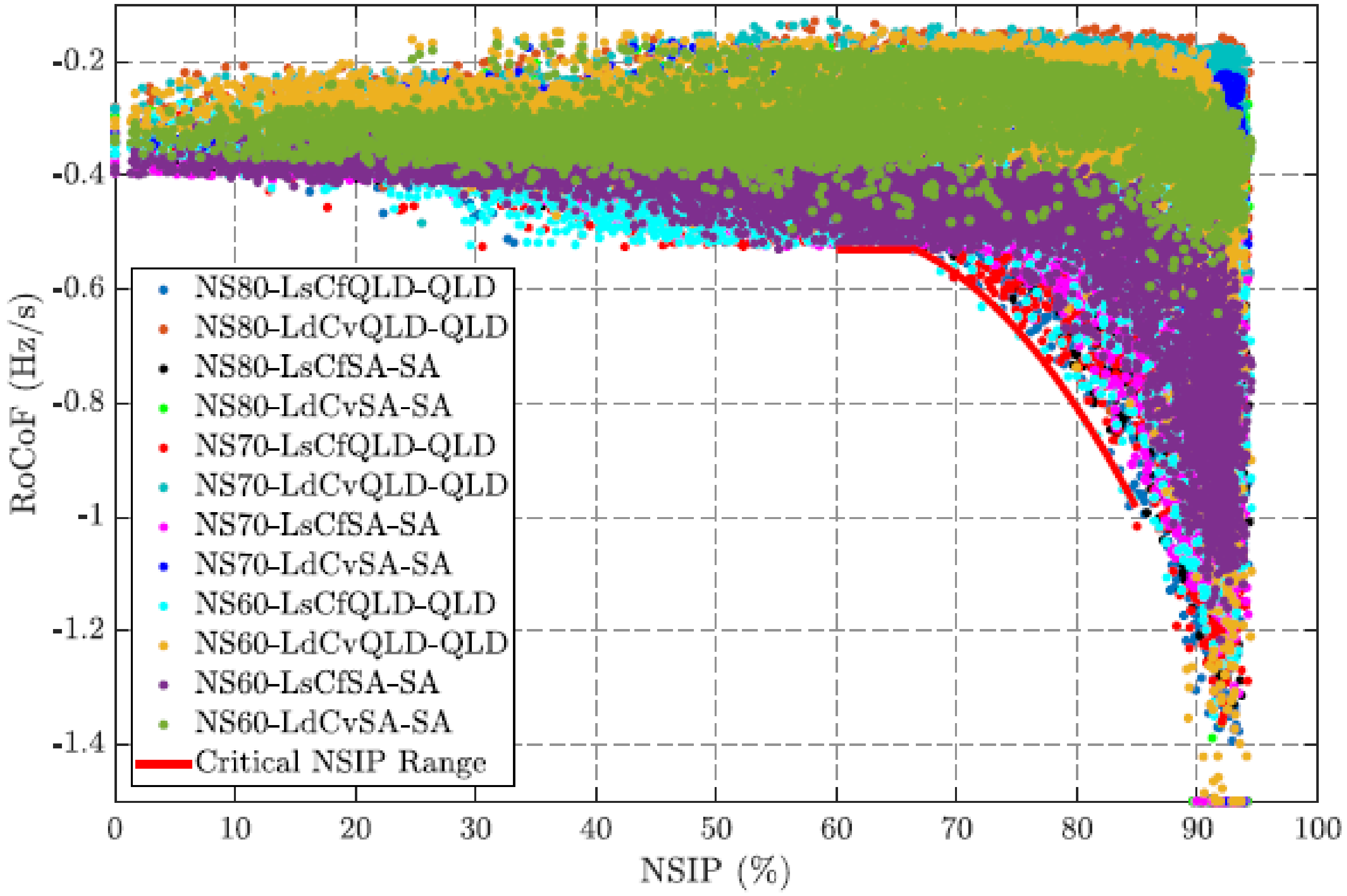
Frequency Response Summary



- Considering the impact of: load model, contingency size and location, prosumers and network strength.

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Dynamic Frequency Control Constraint

- Identify contingencies of each region, in the market simulation:

$$p^{\mathrm{cc}}_{r,h} = \max\left(p_{\mathrm{g},h}\right) \quad g \in \{\mathcal{G}_{\mathrm{synch}} \cap \mathcal{G}_r\}, \tag{8}$$

- Calculate total inertia of each region, considering; MVA rating, on/off status, and H of each SG.

$$I_{\mathrm{synch},r} = \sum_{i=1}^{N_r} H_{\mathrm{g},i} S_{\mathrm{B},i}. \tag{9}$$

- Enforce the inertia based constraint to limit initial RoCoF.

$$I_{\mathrm{synch},r} \geq \frac{f_0 p^{\mathrm{cc}}_{r,t}}{2\left|\frac{df_{\mathrm{crt}}}{dt}\right|}, \tag{10}$$

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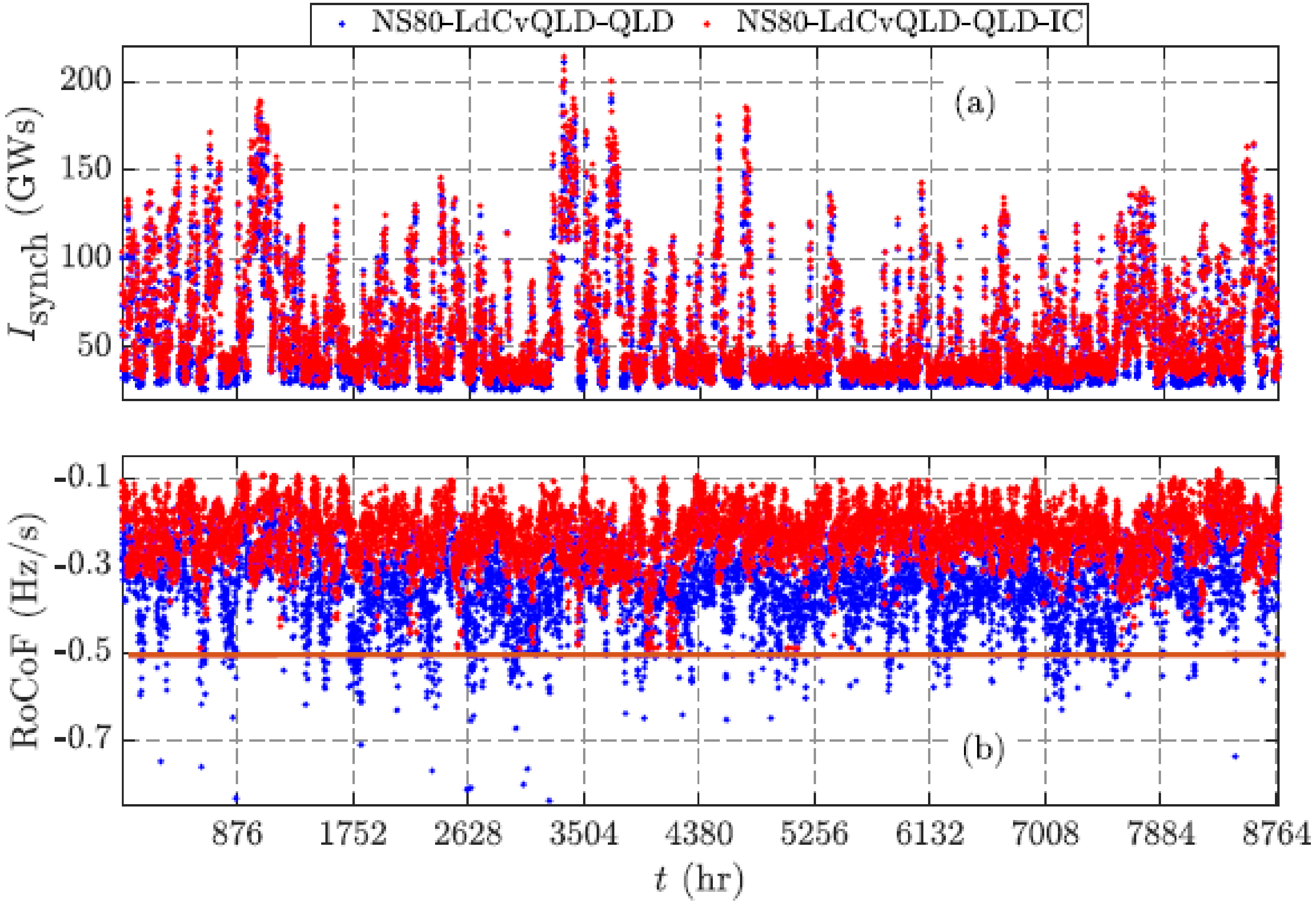
RoCoF with Dynamic Constraint



- However, implementation of frequency control results in curtailment of renewable generations.

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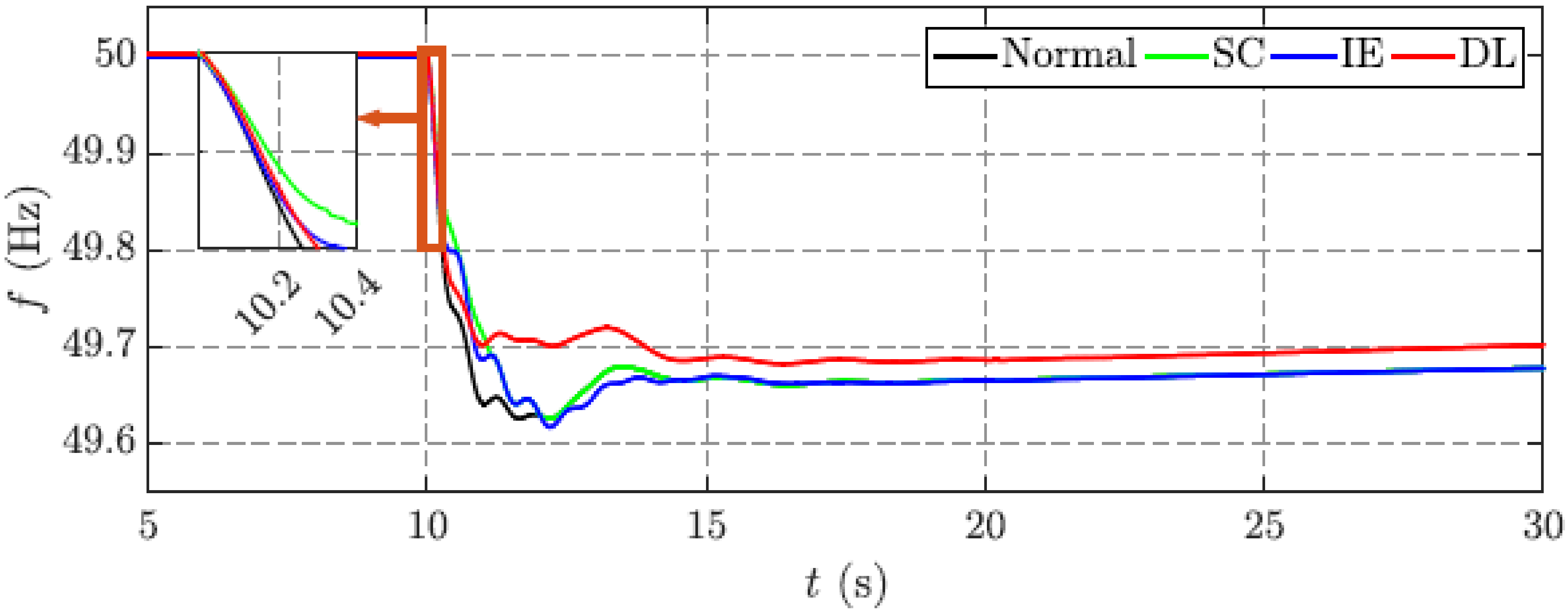
Utilisation of Other Resources



- **SC:** In every region, a synchronous condenser (SC), with (S = 400MVA) and (H = 6 s).
- **IE**: A WFs with, $t = 600\ MW$ capacity provides synthetic inertia.
- **DL:** De-loading the WF by combined optimisation of pitching angle and rotor speed to obtain a governor like response.

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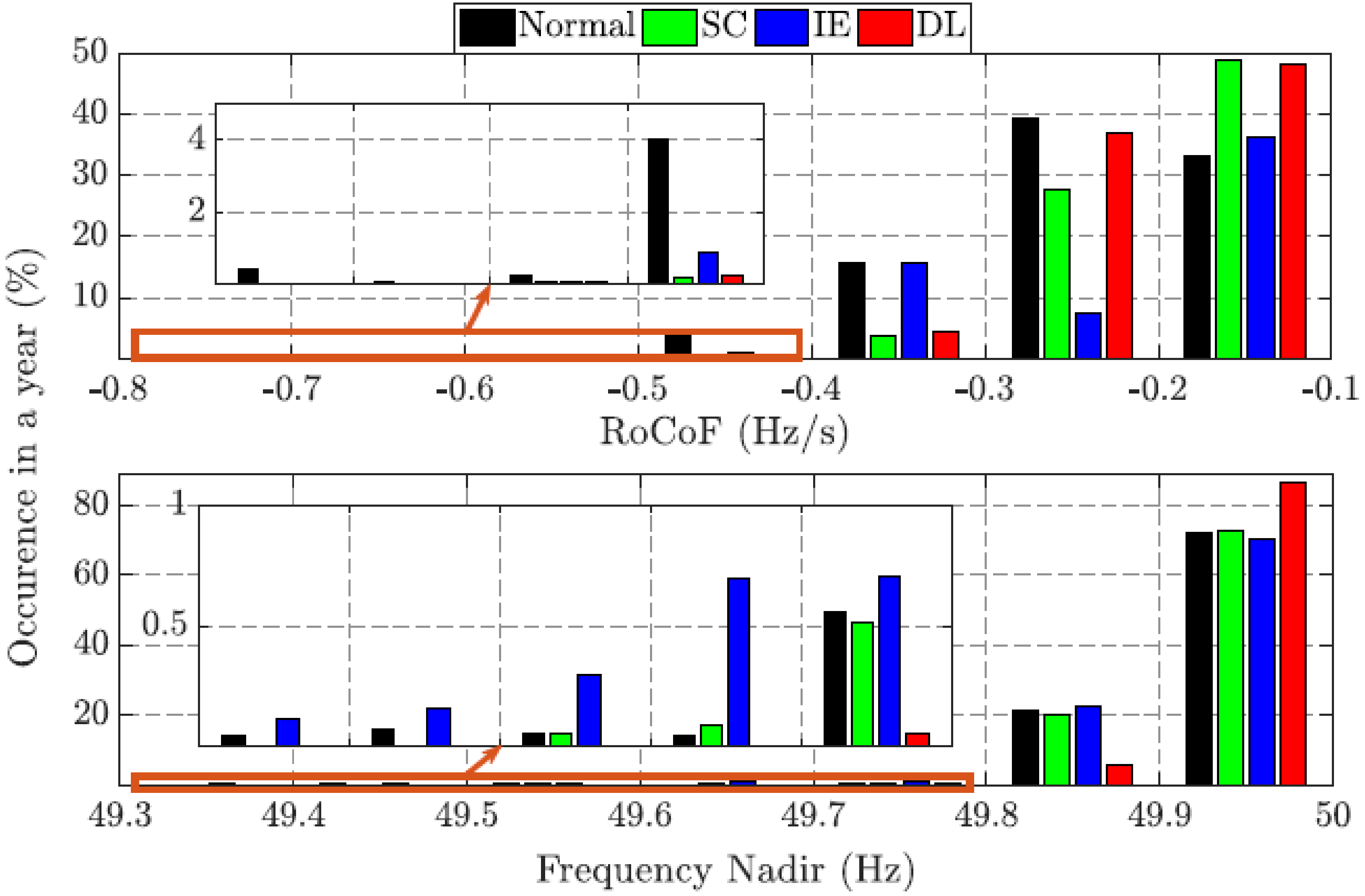
Summary: Contribution of Other Resources



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05

Coordinated Operation of Wind Farms

Operation of Wind Farms

- **Current Practice:**
  - **MaxPwt**: Every individual WT within the WF operates in the optimal operation mode to locally maximise the energy capture.

- **Proposed Operation Strategies:**
  - **MaxEk:** To maximise kinetic energy of the wind farm, E, for frequency control services.
  - **MaxEkX:** T Maximise kinetic energy of the wind farm and consider a X% de-loading margin for the WF.
  - **MaxPwf:** To Maximise power capture of the wind farm,.

[7] A.S. Ahmadyar, G. Verbiˇc "Exploring Wake Interaction for Frequency Control in Wind Farms, in the 13th Wind Integration Workshop Berlin, 11 - 13 Nov. 2014."
[8] A.S. Ahmadyar, G. Verbiˇc "Control Strategy for Optimal Participation of Wind Farms in Primary Frequency Control, PowerTech, 2015 IEEE Eindhoven, 29 June. - 2 July. 2015."

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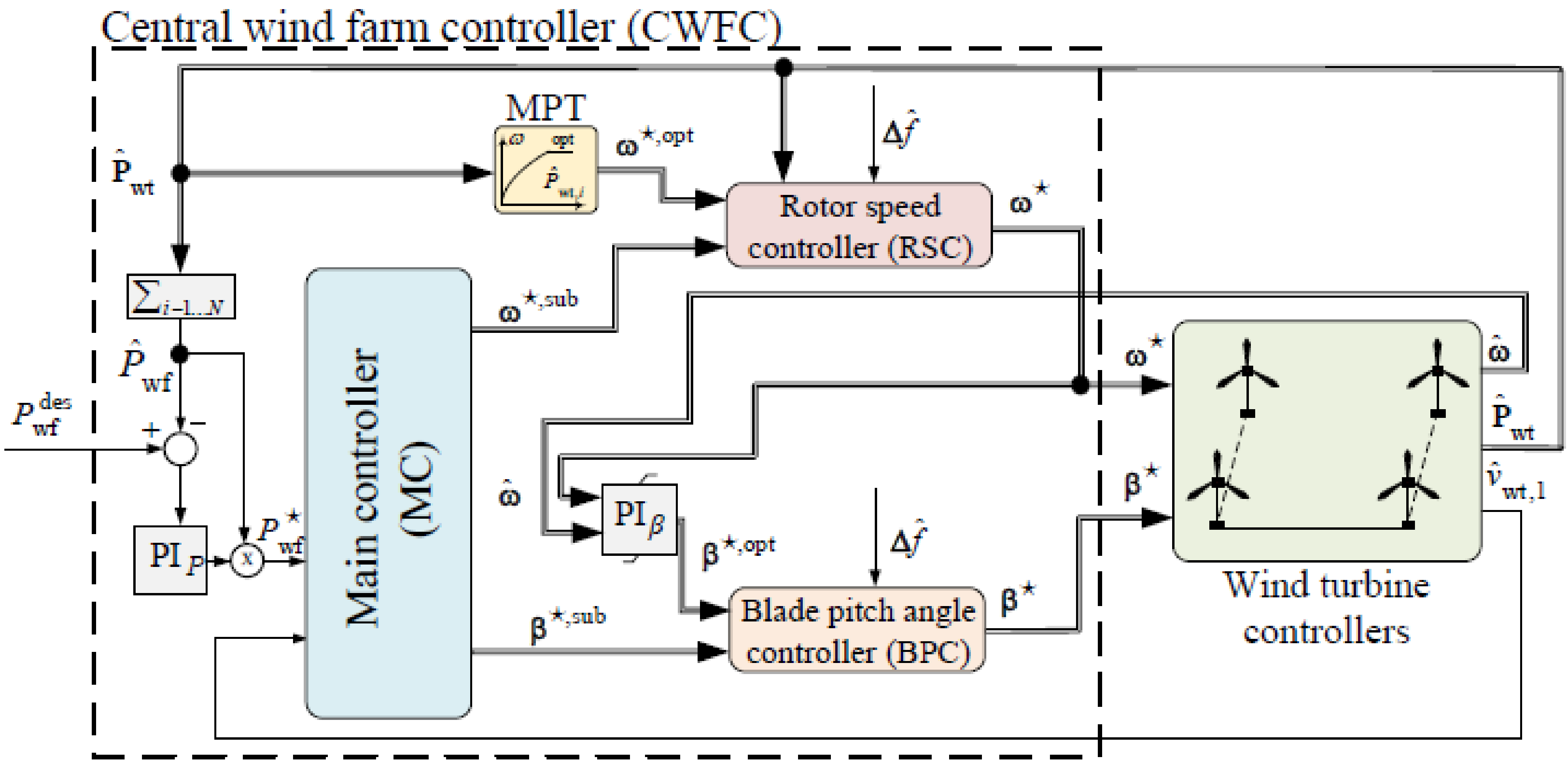
Proposed Central Wind Farm Controller



[9] A.S. Ahmadyar, G. Verbiˇc "Coordinated Operation Strategy of Wind Farms for Frequency Control by Exploring Wake Interaction IEEE Transactions on Sustainable Energy, vol. 8 no. 1, pp. 230-238, Jan. 2017."

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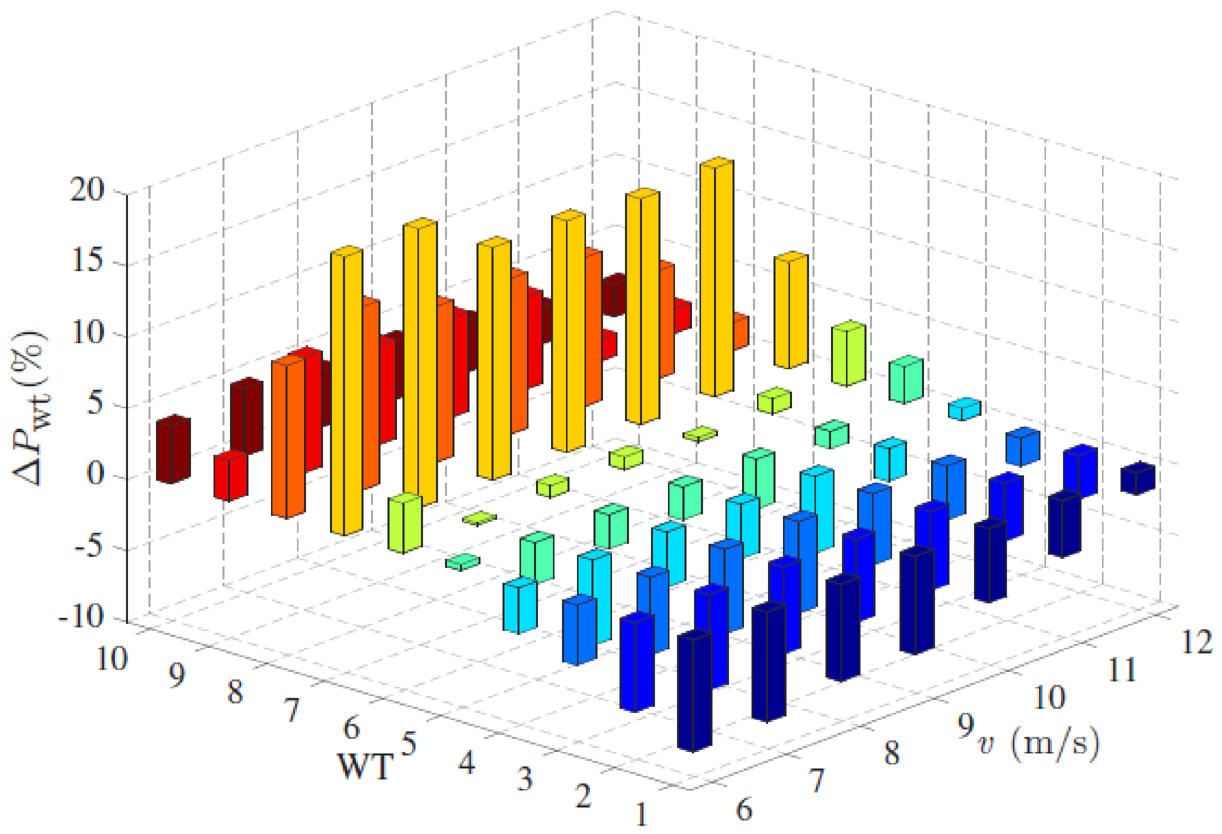
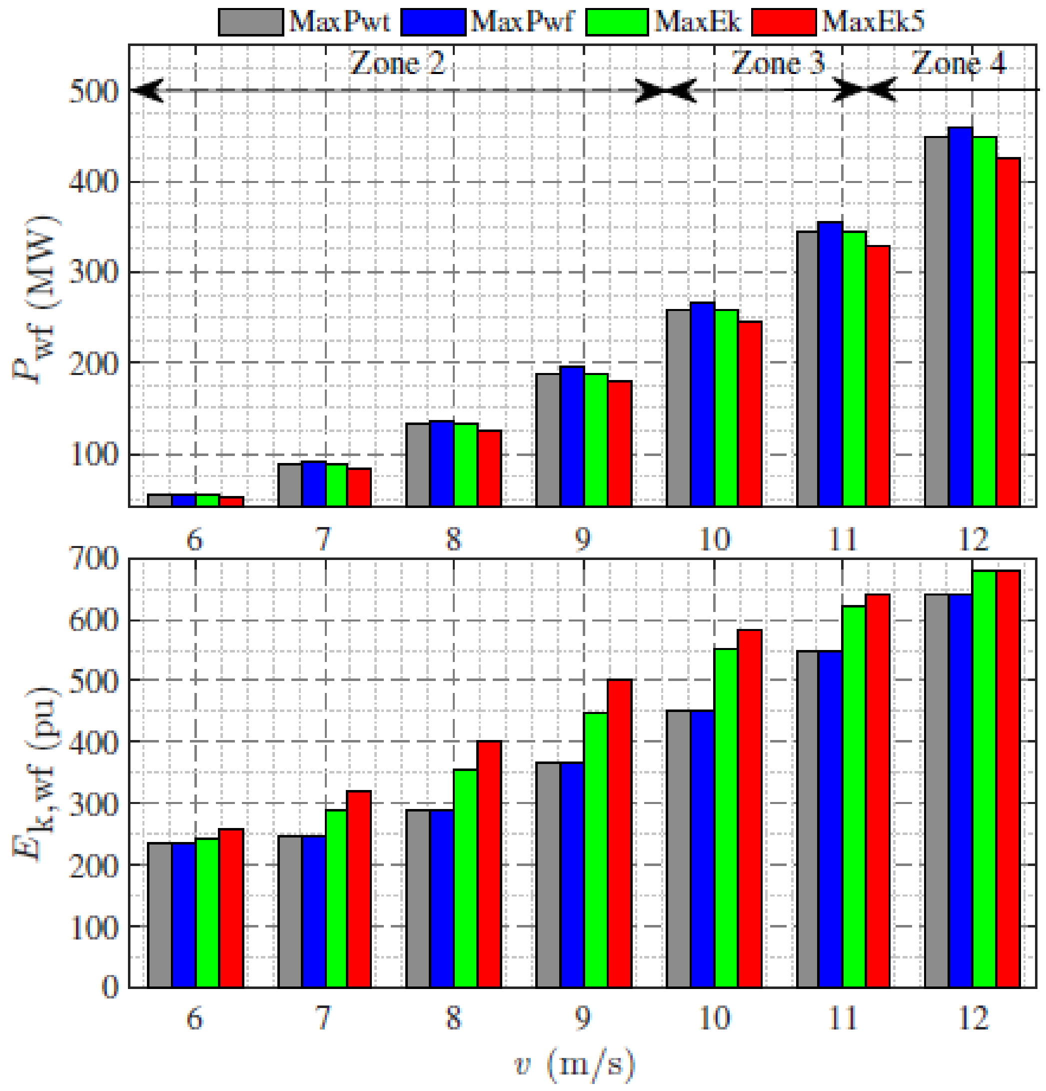
Changes in the Output Power of WTs & Improvement in Power and KE of WF





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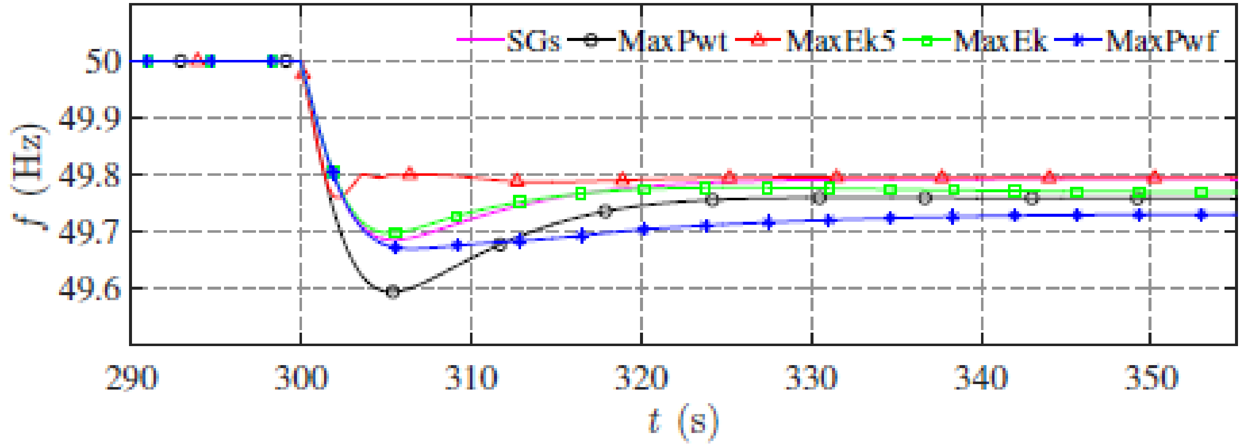
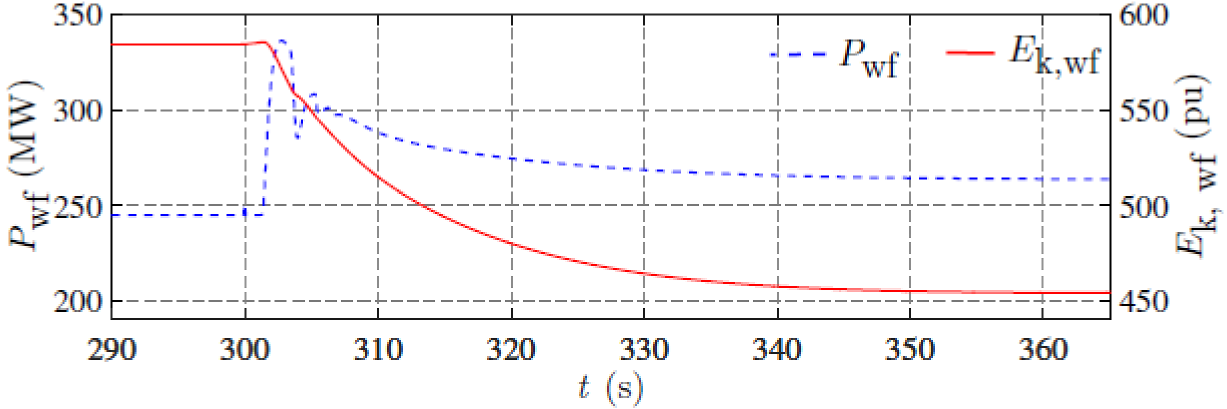
Contribution of WF on Frequency Control

- System frequency behaviour for simulated cases.



- Power and kinetic energy of the wind farm in case MaxEk5.



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06

Summary

Contribution of WF on Frequency Control

Conclusions:

- A framework based on time-series analysis to assess the frequency stability of future power systems.
- Minimum level of synchronous inertia for the NEM to limit RoCoF.
- Technically, wind technologies can provide value-frequency service; the value of energy vs ancillary services needs to be justified.

Future works:

- Identification of the least-cost technical options (i.e. Technologies) as frequency control service providers.
- Proposing a market or regulatory framework (e.g. Inertia market) for managing the issue efficiently.
- Quantifying the synthetic inertia provided by grid-forming technology connected to BESS or Solar and Wind Farms, where the letters operate with headroom.

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