ESIG TECHNICAL WORKSHOP, PHILADELPHIA, 29 OCTOBER 2025

Dynamic Properties and Frequency Response of IBR-dominating Power Systems

Numerical study

Slava Maslennikov

TECHNICAL MANAGER, ADVANCED TECHNOLOGY SOLUTIONS

Objective for Study

1. How system dynamic property change with large IBR penetration?
   a. Is there a risk that large deployment of GFM IBRs of VSM type will replicate traditional structure of system oscillations and particularly inter-area oscillations?

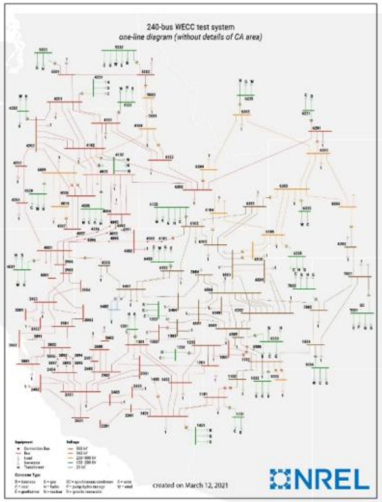
2. How the frequency nadir is impacted by large penetration of IBRs?
   a. What GFL and GFM shares are acceptable?
   b. How much total MW head room of GFM in the system is necessary to control frequency nadir?
   c. Does a certain allocation of IBRs across the system affect frequency nadir and stability?

3. What is a reasonable metric to monitor acceptable system behavior at large IBR penetration

240-bus WECC system

- Positive sequence phasor model
- Synchronous generator
  - Detailed model of each generator + AVR + PSS + Governor
- Grid Forming IBRs (GFM)
  - REGFM_A1: Droop-controlled Inverter; Mp=0.015 Mq=0.05
  - REGFM_B1 : Virtual synchronous machine(VSM), droop-controlled invertor; Mp=0.015 Mq=0.05 H=0.5s, D=0.1
- Grid Following IBRs (GFL)
  - REGC_A (REGCA1 + REECA1 + REPCA1)
  - REGC_C
- Load: MVA - 30%, Current -30%, Impedance - 40%
- Vary randomly:
  - Number of generators replaced by IBRs from 0% to 100%
  - Share of GFL and GFM in IBRs from 0% to 100%
  - Location of GFL and GFM replacing synchronous generators
  - MW headroom of GFM for frequency and voltage control from 0% to 10% of Pmax

Results of phasor-type modeling are limited as they do not reflect details (sub-synchronous oscillations) to be captured by EMT-type simulation



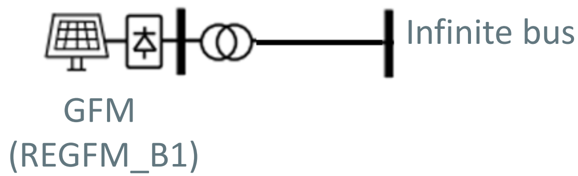
Oscillations structure

Real	Frequency(Hz)	Damping(%)
-0.3084	0.3721	13.08
-0.2186	0.5264	6.59
-0.1764	0.6082	4.61
-0.2196	0.701	4.98
-0.1565	0.7343	3.39
-0.2016	0.7706	4.16
-0.2964	0.8778	5.37
-0.32	0.9006	5.65
-0.2771	0.972	4.53
-0.2605	0.9875	4.19
-0.3949	1.0612	5.91
-0.8871	1.1746	11.93
-0.3962	1.1783	5.34
-0.3313	1.1908	4.42
-0.8968	1.2143	11.67
-0.4462	1.2186	5.82
-0.5173	1.2426	6.61
-0.5184	1.2511	6.58
-0.3386	1.2718	4.23
-0.4388	1.3	5.36

Dynamic properties of power system at large GFM IBR penetration
(Eigenvalue analysis)

Does VSM model REGFM_B1 create oscillations?

- Simple Model:



- Yes, oscillation exist, as expected
  - Damping is well controlled by the values Mp and Tp
  - Frequency is well controlled by parameter H

Parameters of REGFM_B1						
Mp	Tp	H	D1	D2	Frequency(Hz)	Damping(%)
0.01	0.02	3	100	0.001	2.1694	37.29
0.03	0.02	3	100	0.001	2.1628	4.81
0.01	**0.06**	3	100	0.001	2.6582	14.87
0.01	0.02	**6**	100	0.001	1.6418	26.23
0.01	0.02	3	**0.1**	0.001	2.6839	37.64
0.01	0.02	3	100	**0.0005**	2.1694	37.29
0.04	**0.04**	3	100	0.001	2.1944	**-0.72**

Increase of Mp and Tp can creates instability

Does VSM replicate creation of inter-area modes in bulk system?

Inter-area modes at wide penetration of GFM (VSM type)

- Replacing 25,50,75,100% of synchronous generators by REGFM_B1 model
  - Mp=0.04, Tp=0.04.
  - The same parameters for all IBRs

Eigenvalues

0% IBR		25% IBR		50% IBR		75% IBR		100% IBR	
Freq., Hz	Damp., %	Freq., Hz	Damp., %	Freq., Hz	Damp., %	Freq., Hz	Damp., %	Freq., Hz	Damp., %
0.2385	67.19	0.2465	72.2	0.2243	97.78	0.2373	97.71	0.2137	97.95
0.3722	**13.07**	**0.3862**	**28.55**	0.3146	86.57	**0.3081**	**92.59**	1.0078	68.02
0.5266	6.59	0.5802	16.76	**0.3787**	**95.44**	0.9225	43.78		
0.6083	4.61	0.6658	23.17	0.4856	40.16	1.0005	68.13		
0.7011	4.98	0.7882	21.81	0.8076	47.06				
0.7344	3.39	0.8092	12.7	0.8104	20.19				
0.7707	4.16	0.836	13	0.9079	10.25				
0.8778	5.37	0.9177	11.23	0.9314	72.49				
0.9006	5.65	1.0064	68.21	0.9574	45.59				
0.9721	4.53			1.0067	67.84				
0.9875	4.2								
1.0068	68.19								

- Inter-area modes transformation
  - Still exist with increase of IBR penetration, but the damping drastically increases
  - Practically disappear with IBR penetration close to 100%

Inter-area modes for Droop-control and VSM GFMs

No IBRs

Frequency(Hz)	Damping(%)
0.372	13.1
0.527	6.6
0.608	4.6
0.701	5.0
0.734	3.4
0.771	4.2
0.878	5.4
0.901	5.7
0.972	4.5
0.988	4.2

GFM IBRs replacing synchronous generators

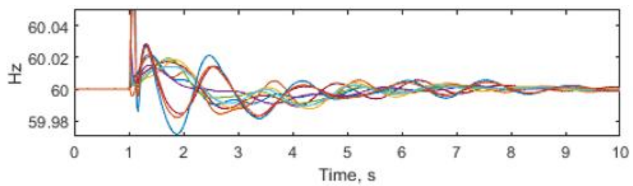
IBR share	Model REGFM_A1		Model REGFM_B1	
	Frequency(Hz)	Damping(%)	Frequency(Hz)	Damping(%)
25%	0.523	27.6	0.522	28.5
	0.805	28.0	0.801	27.8
	0.851	22.7	0.852	22.3
	0.871	22.0	0.872	21.5
	0.913	12.8	0.914	12.8
50%	0.679	30.2	0.677	30.9
	0.911	11.2	0.911	11.1
75%	1.002	68.1	0.295	96.0
100%	1.002	68.1	0.335	94.3

1. Tables include all oscillatory modes with frequency below 1Hz and damping < 50%
2. For 75% and 100% IBR share, the table include the modes with minimal damping

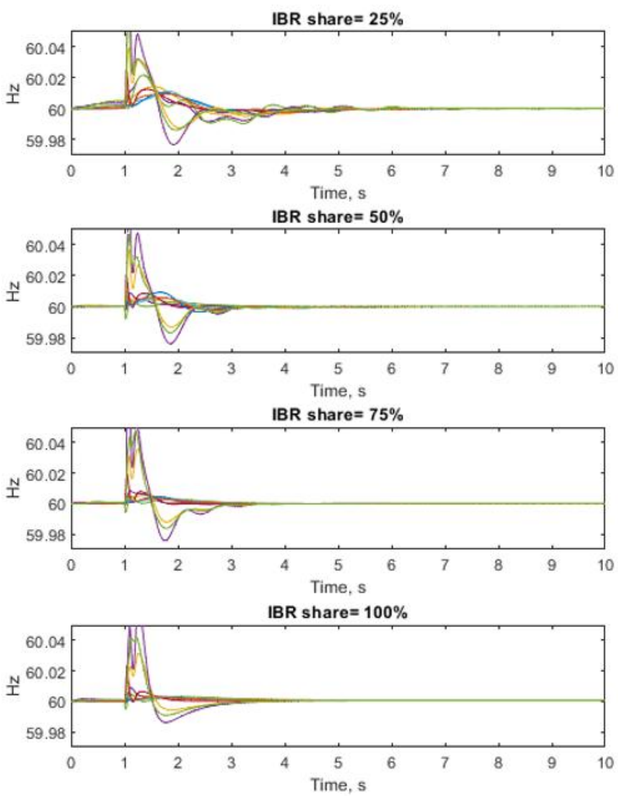
- Oscillation structure is practically the same for both GFM models

Verification by time domain simulation

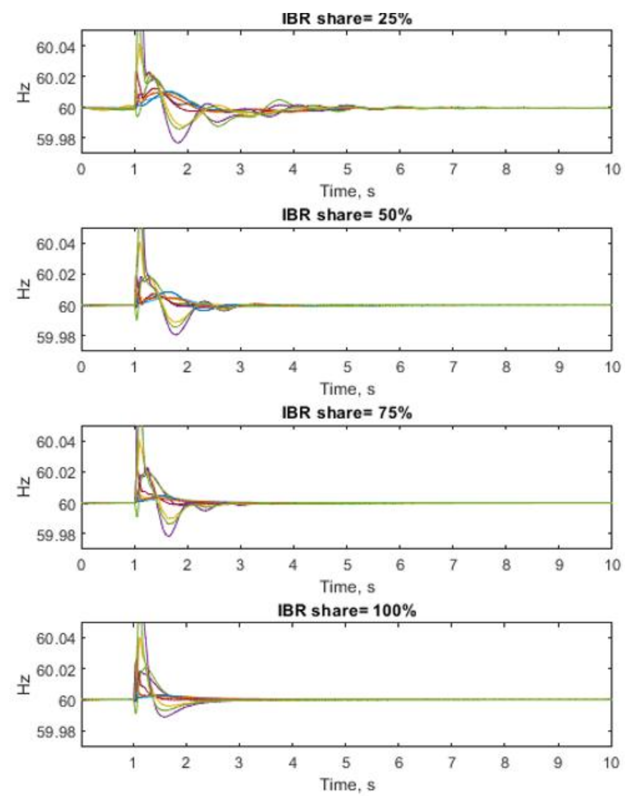
No IBRs



Model REGFM_A1



Model REGFM_B1



- Disturbance: four simultaneous 3-phase short circuits equally distributes across entire system to excite all oscillatory modes
- Monitoring: Bus frequency at 11 500 kV buses equally distributed in the system

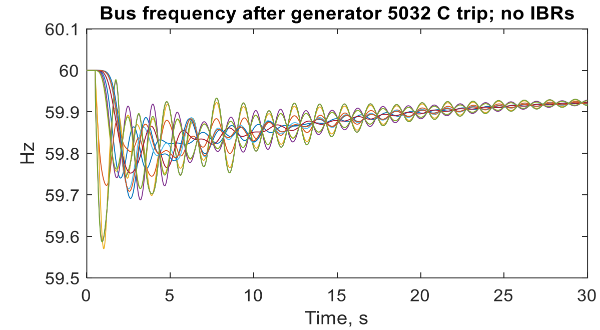
Oscillation structure is practically the same for both GFM models

Frequency response at large IBR GFM penetration

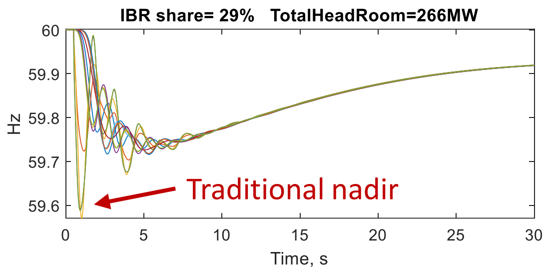
Estimation of frequency nadir

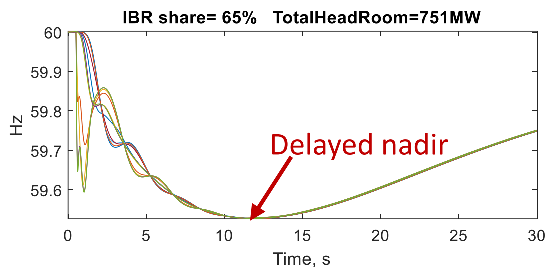
- Modeling
  - Time domain simulation for tripping generator 5032 C, 4052 MW (2.8% of total MW generation)
  - All IBRs are GFM model REGFM_A1 with droop control for frequency (Mp=0.02) and voltage (Mq=0.05)
- Monitoring
  - The difference of frequency nadir: $dNADIR = NADIR_{GEN} - NADIR_{IBR}$ (dNADIR > 0 means IBRs deteriorate frequency nadir)

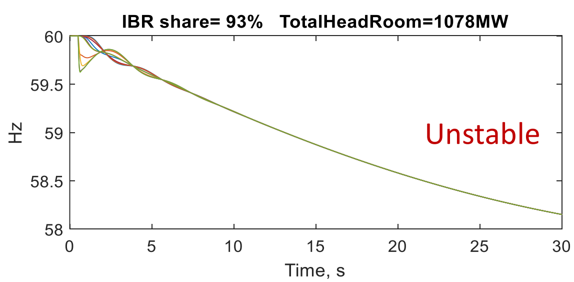
Examples of transient



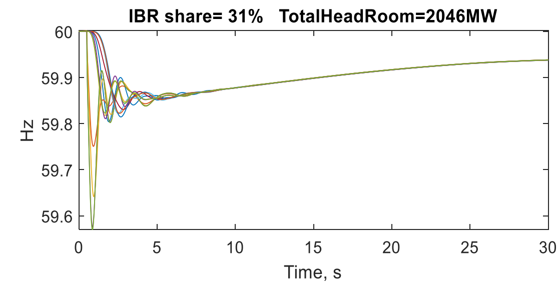
Low “total MW head room”

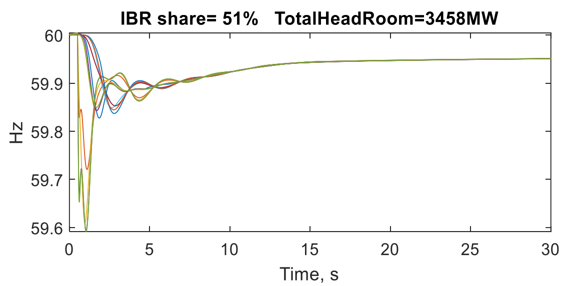


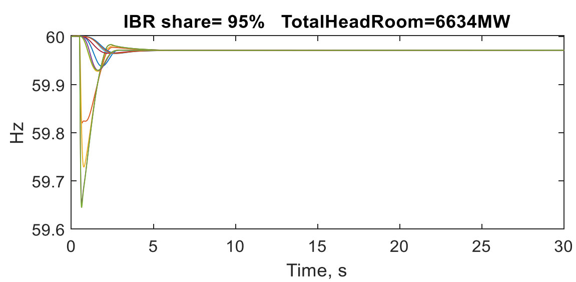




High “total MW head room”





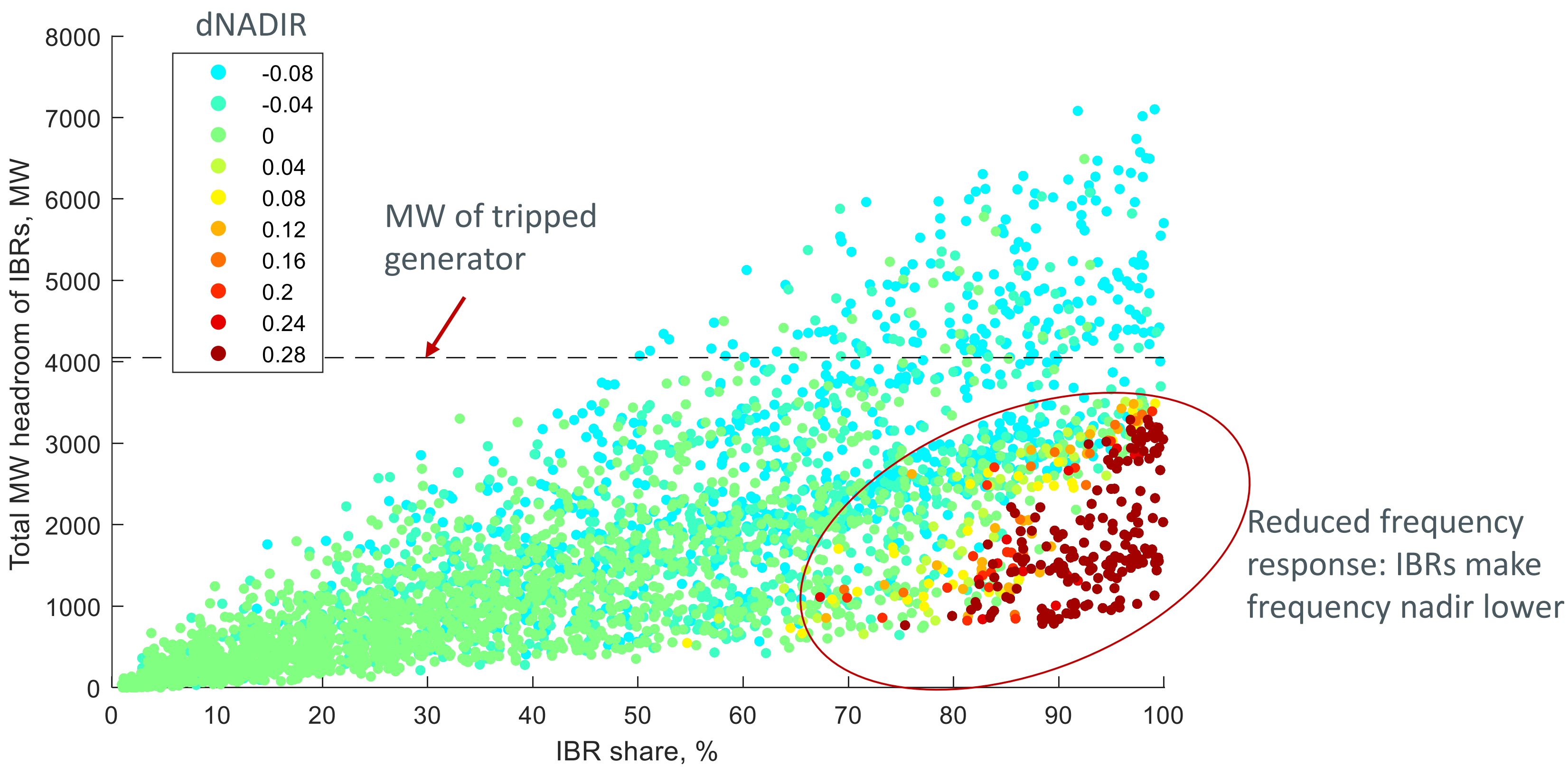


High “total MW head room” and particularly with high IBR share:

- Ensure high nadir and fast stabilization of frequency
- Provide much better damping of oscillations
- Practically eliminate inter-area oscillations

Increment of nadir: dNADIR = $NADIR_{GEN} - NADIR_{IBR}$

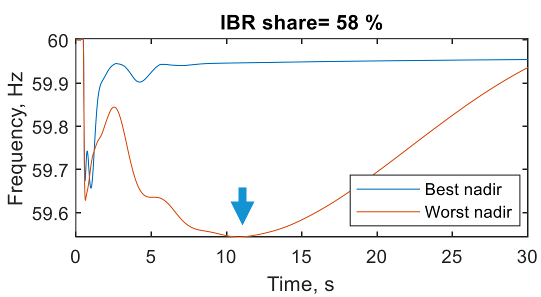
- Statistical results of 3600 transient runs

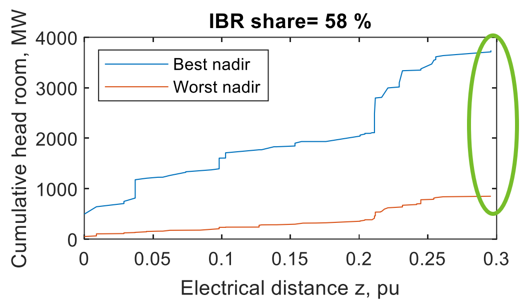


dNADIR > 0 means IBRs deteriorate frequency nadir

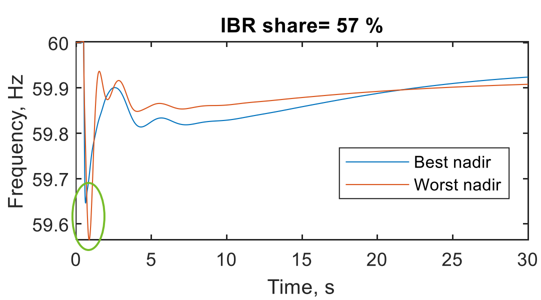
Observations from statistical analysis

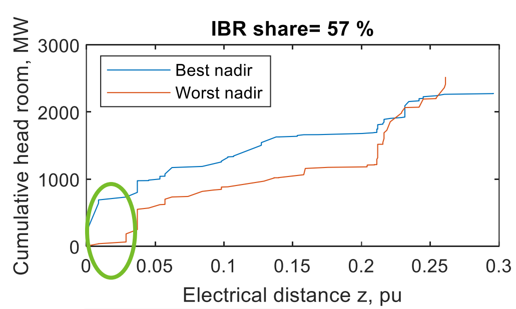
- At the same IBR share, deterioration of NADIR happens if:
  - Insufficient total, cumulative “MW head room” for control from all GFMs
  - Even for sufficient total “MW head room” for control , GFMs with MW headroom are located far away from tripped generator
  - Sufficient allocation of total “MW head room” in close proximity to tripped generator is necssary to keep high frequency nadir





Example: lack of total “MW head room”

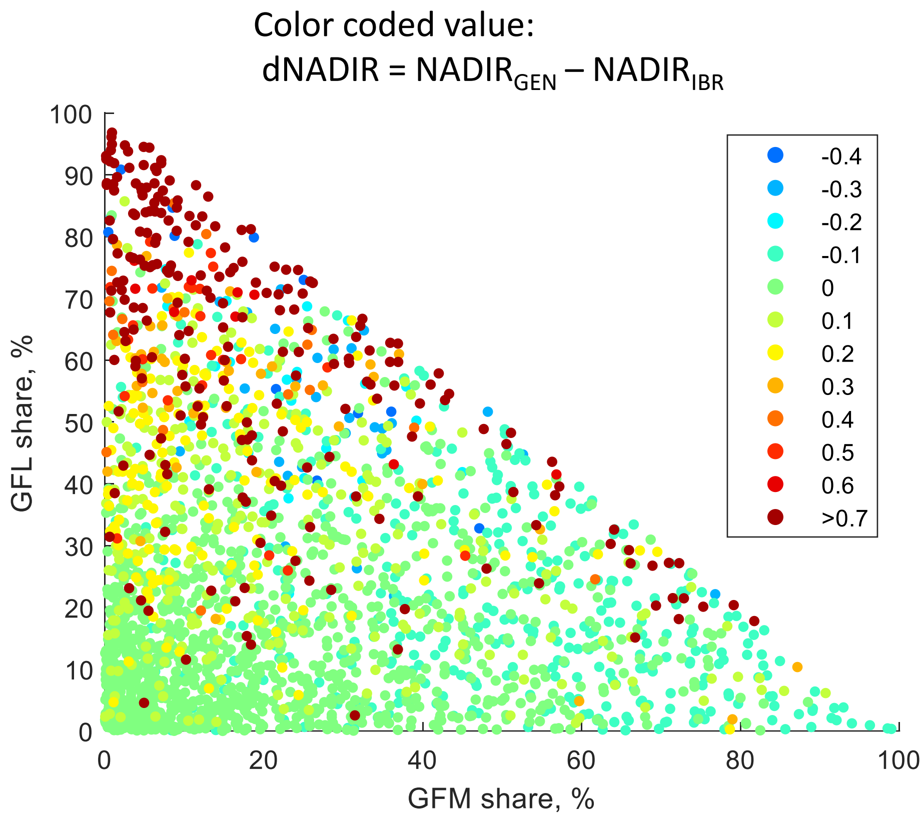




Example: lack of “MW head room” in proximity of tripped generator

Frequency response at large GFL and GFM IBR penetration

Impact of IBRs on frequency nadir

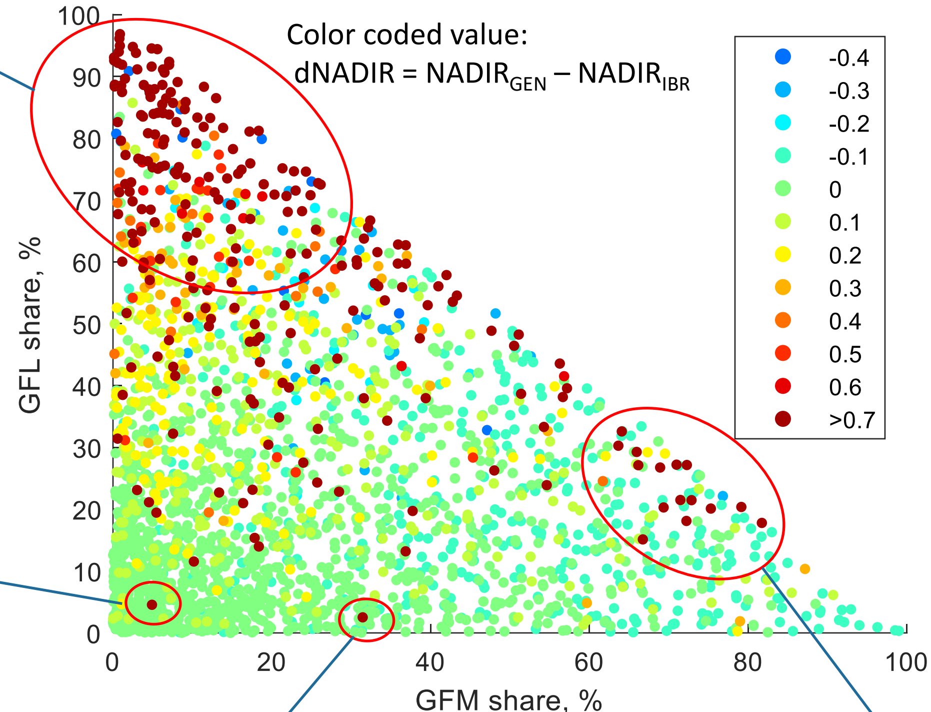


- The picture combines impact of several factors:
  - ✓ GFL share
  - ✓ GFM share
  - ✓ Total MW head room of GFM
  - ✓ Location of GFLs relative to tripped generator
  - ✓ Location of GFMs relative to tripped generator

Factors of instability

Lack of GFMs and too many of GFLs

GFLs with low SCR or located close to tripped generator and lack of GFMs

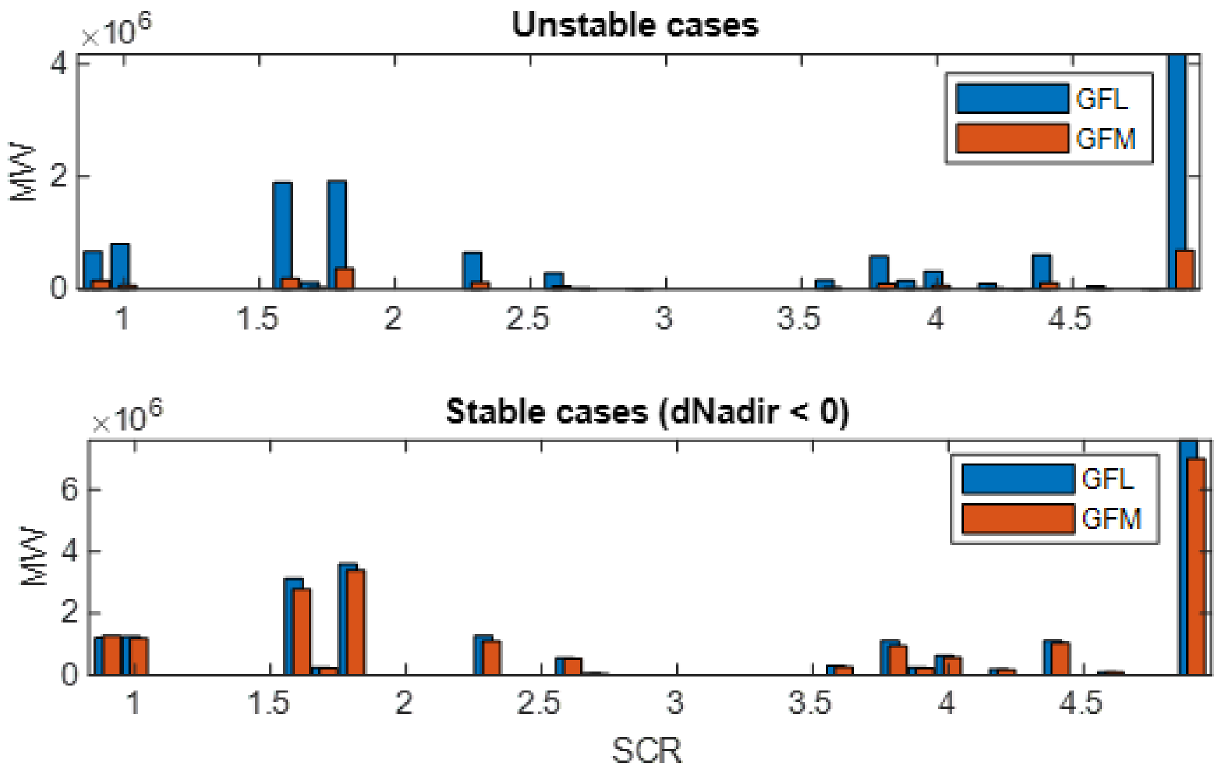


Low total MW head room of GFMs

- Low total MW head room of GFMs
- Lack of GFM located close to tripped generator

Impact of IBRs location: SCR metric

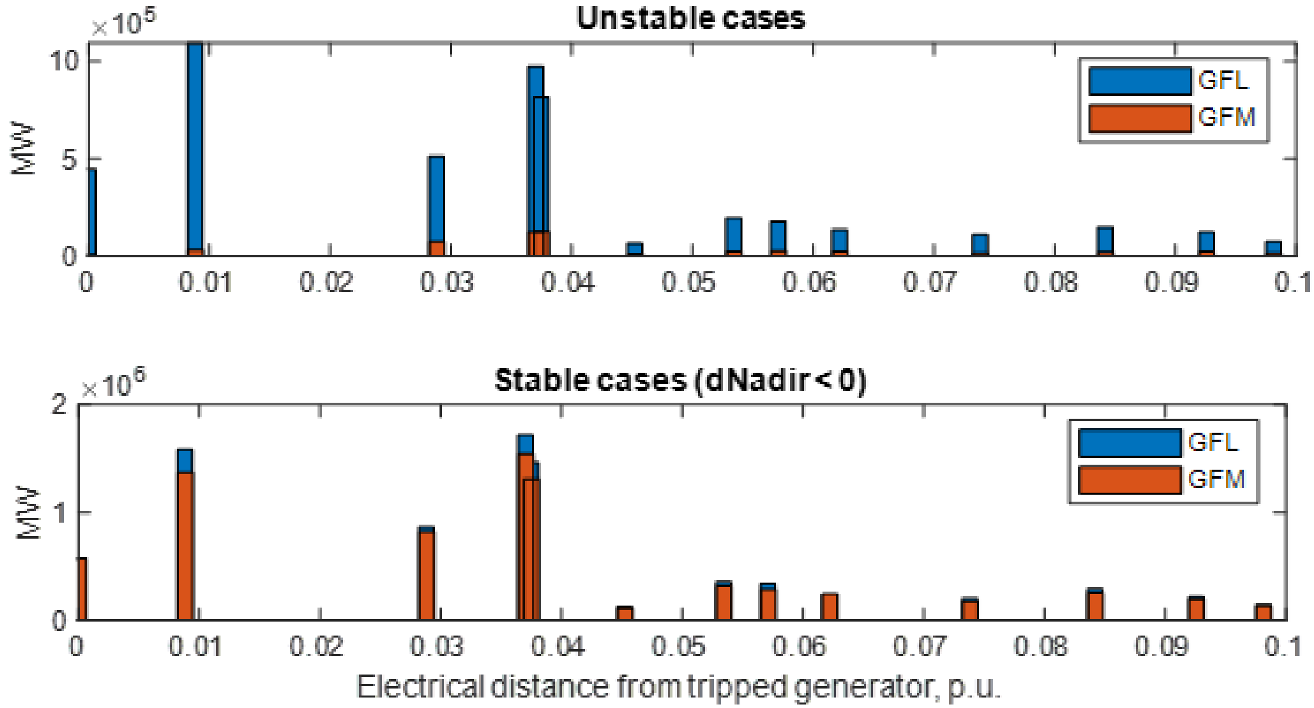
Cumulative MW of GFL and GFM IBRs



- Instability is caused by significant presence of GFL at low SCR locations
- Instability can be avoided by adding GFM at locations with low SCR

Impact of IBRs location: "distance from tripped generator" metric

Cumulative MW of GFL and GFM IBRs



- Instability is caused by significant presence of GFL close to tripped generator
- Instability can be avoided by adding GFM at locations close to tripped generator

Observations and conclusions

- Massive "proper" replacement of synchronous generators by GFM IBRs:

  1. Improves system dynamic properties
     - A. Eliminates inter-area oscillations
     - B. Increases damping of oscillations
     - C. System response became localized

  2. Improves stability and frequency response
     - A. Possibility to use uniform GFM parameters across the system

- "Proper" replacement means

  1. Sufficient total "MW head room" for control

  2. No big "holes" in the system having GFM with insufficient "MW head room" for control

- The use of GFL is acceptable combined with GFM having adequate total and local "MW head room" for control

  1. GFL parameters will likely require tuning per operating conditions

Observations and conclusions, cont.

- A reasonable metric for system health monitoring at increased IBR penetration should include
  1. Sufficient MW head room at GFM IBRs available for frequency and voltage control at any moment of time
     A. System-wide and
     B. Locally
- "System Inertia" as monitoring parameter related to the risk of lowering frequency nadir can be disregarded.

- Use of RMS model of GFM suggests quite positive and optimistic conclusions
- Need to verify these by using more accurate EMT model