Analysis of IBR-driven Oscillations in the Australian Grid

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ESIG Webinar
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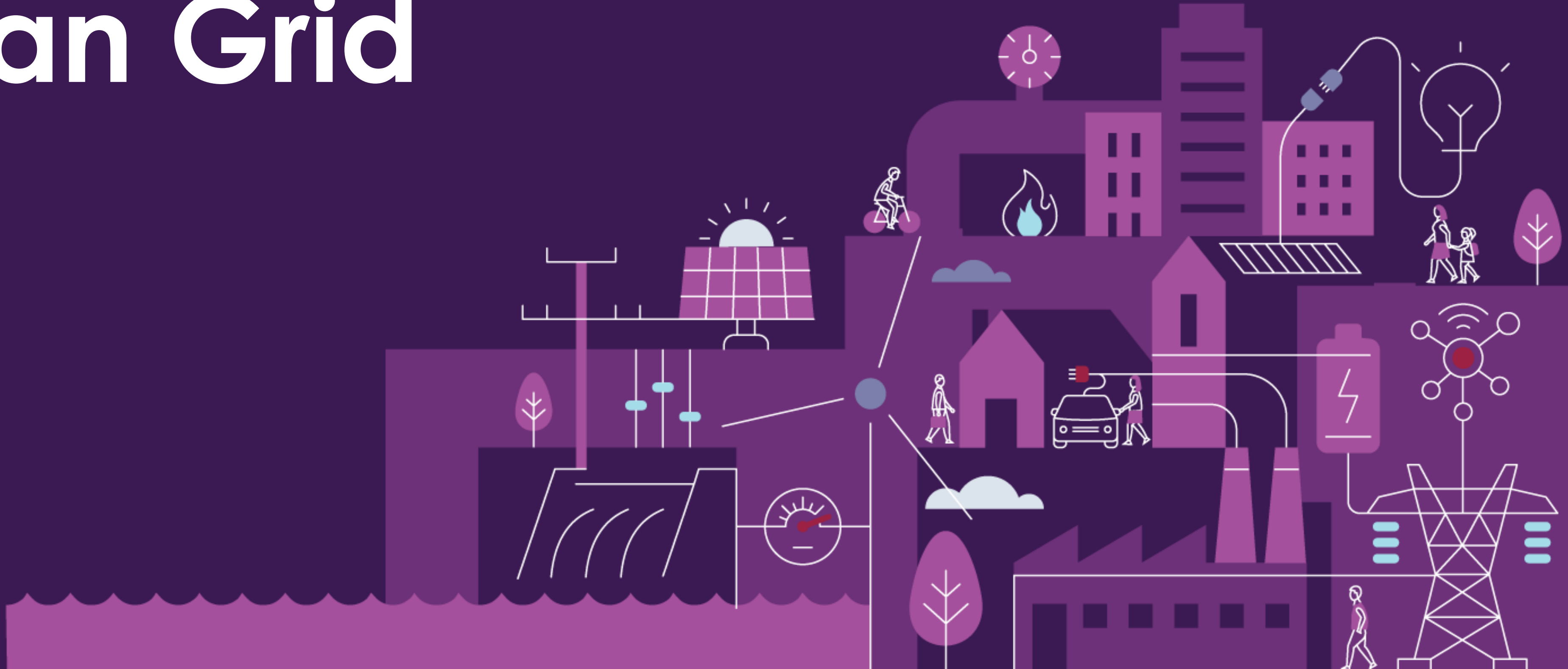


Content

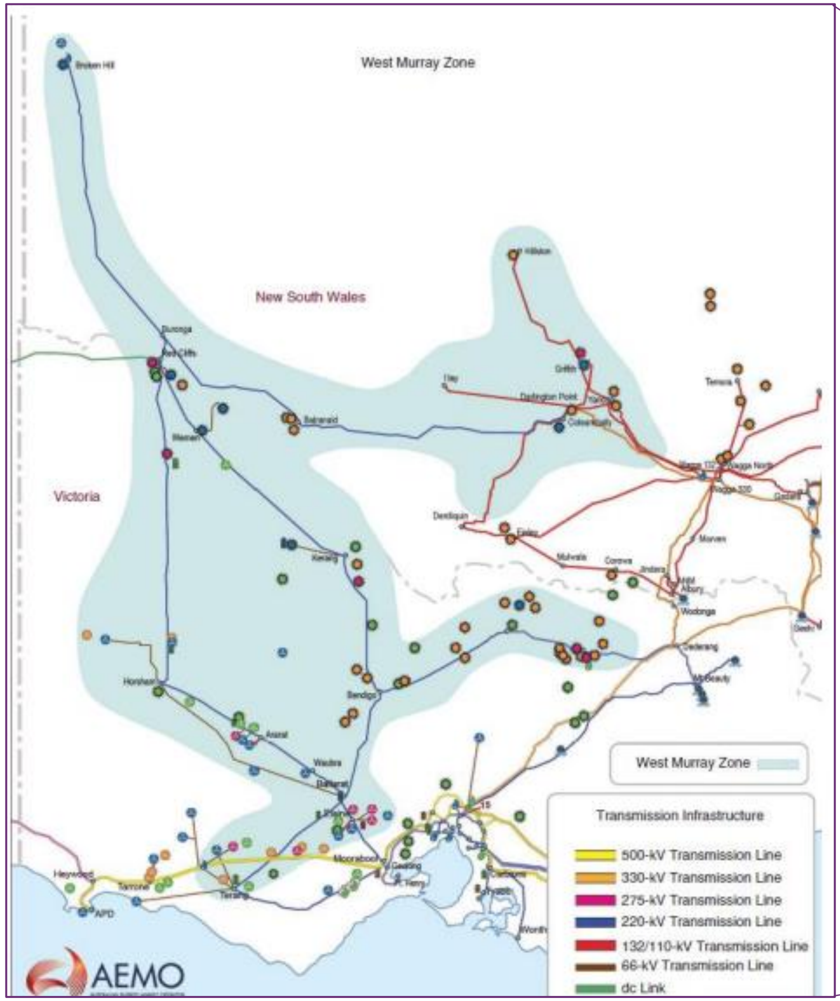
- Background
- West Murray Zone sub-synchronous oscillations
  - Real-time observations
  - Issues and challenges
  - Replication and remediation measures
- Analysis using Impedance Scans
  - Source of oscillations in West Murray Zone
  - Sizing of grid-forming resources to achieve specific grid strength

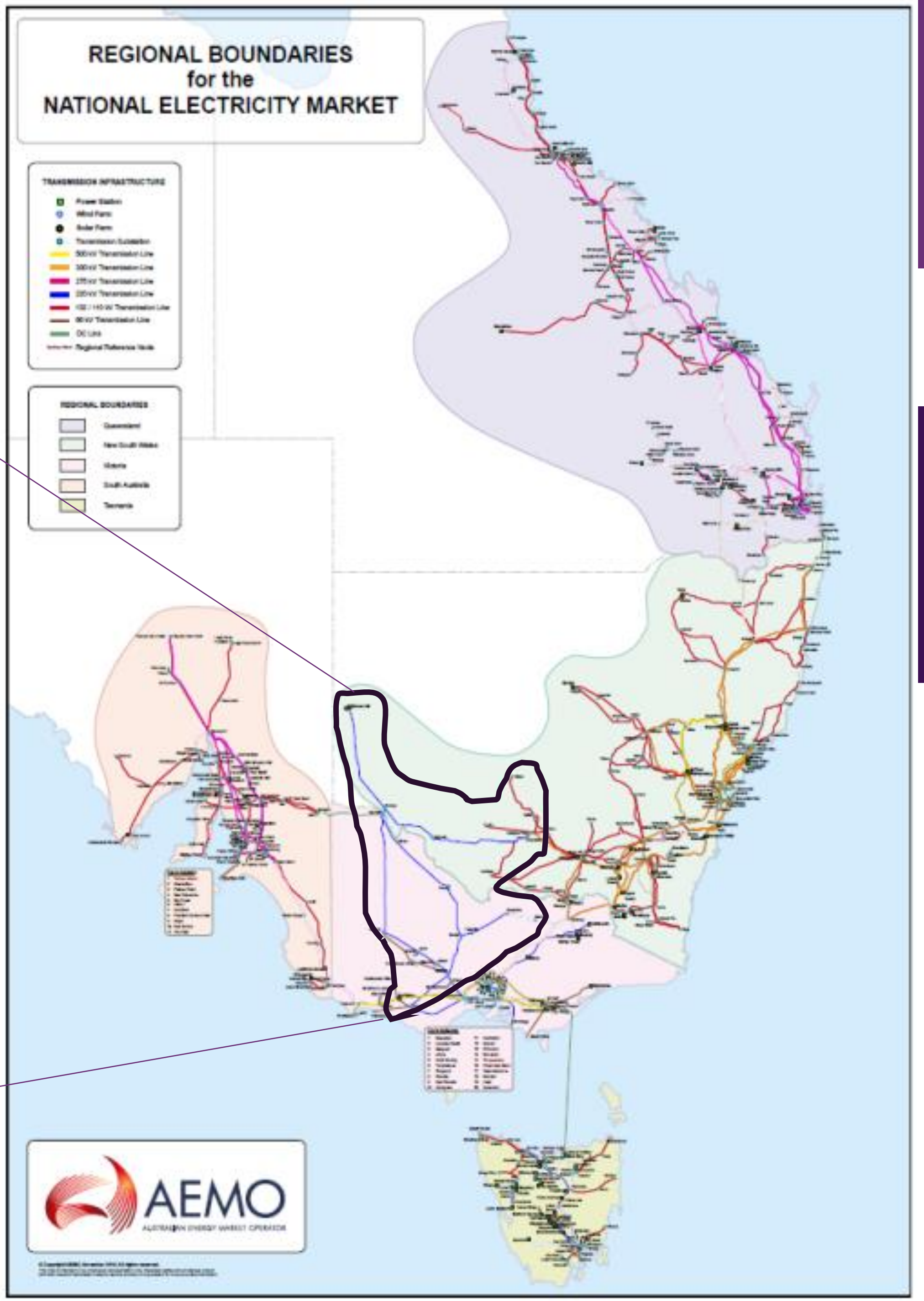
Collaboration

Market participants

Original Equipment Manufacturers

West Murray Zone



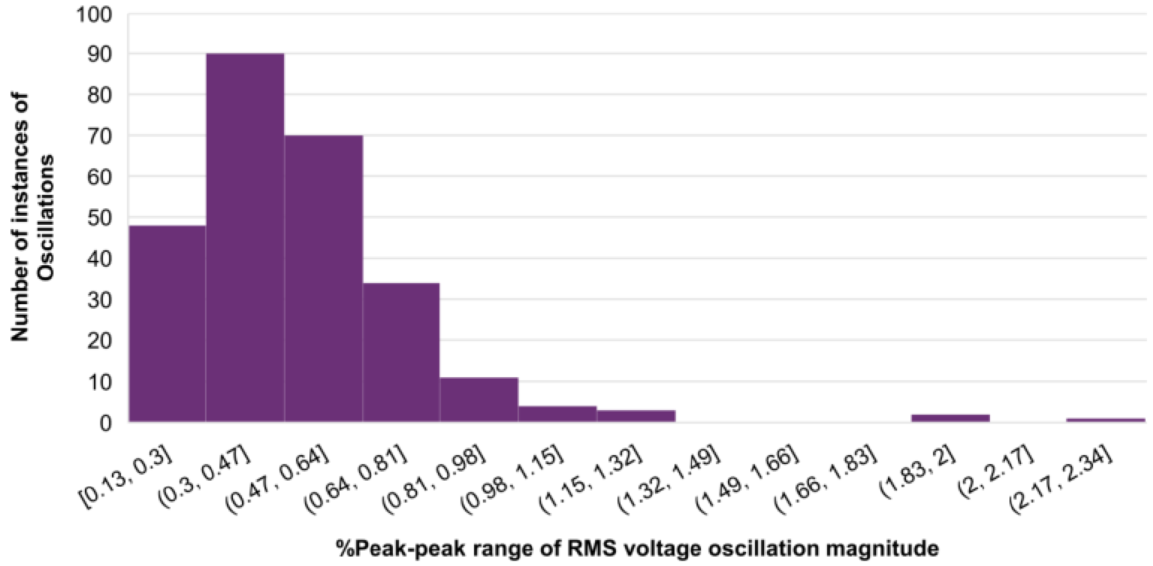


https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/high-level-summary-of-wm:

Background

- First identified while investigating a system incident
- Magnitude of oscillations up to 2.2 % (at Red Cliffs)
- Duration of oscillations ranging from few seconds to several minutes
- Appearing without any major network disturbance or system configuration change

Figure 1 Summary of oscillations observed at Red Cliffs Terminal Station 220 kV, August 2020 to December 2021



Characteristic of oscillations

- Oscillations contained within North-West of Bendigo (VIC) and west of Darlington Point (NSW)

Figure 3 West Murray RMS voltages at 1235 hrs on 20 August 2020

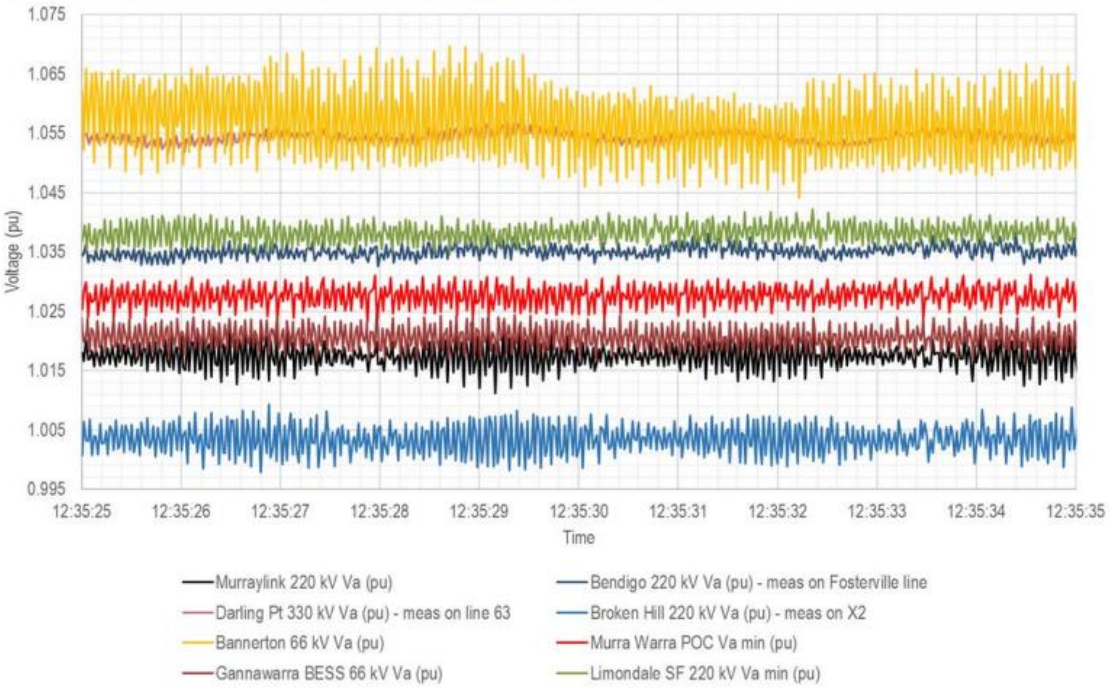
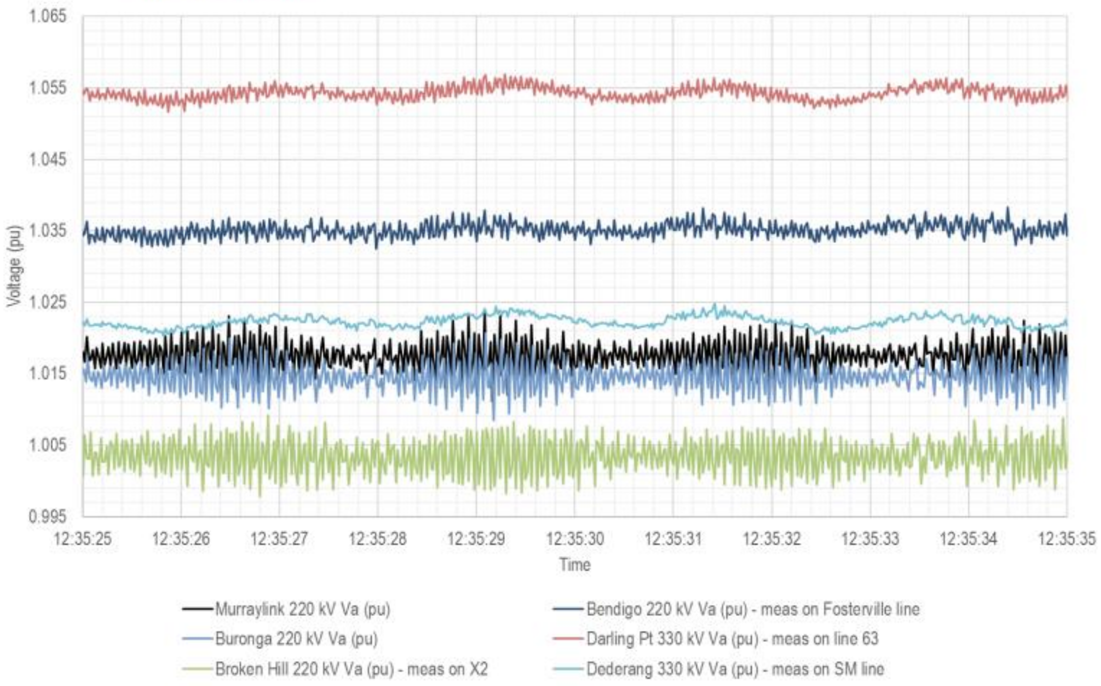


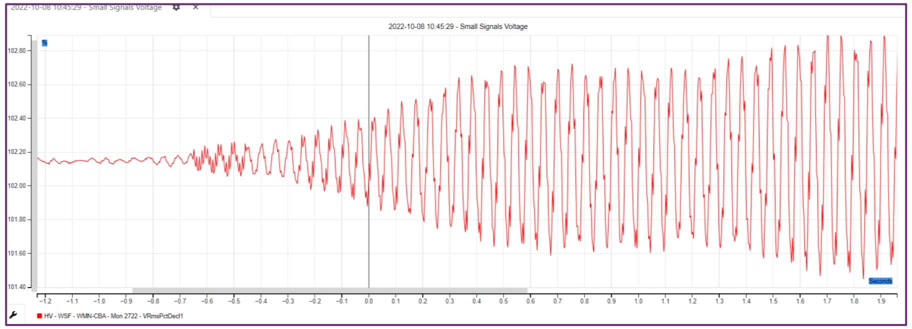
Figure 4 West Murray RMS voltage oscillations on 20 August 2020 contained to the west of Darlington Point and Bendigo

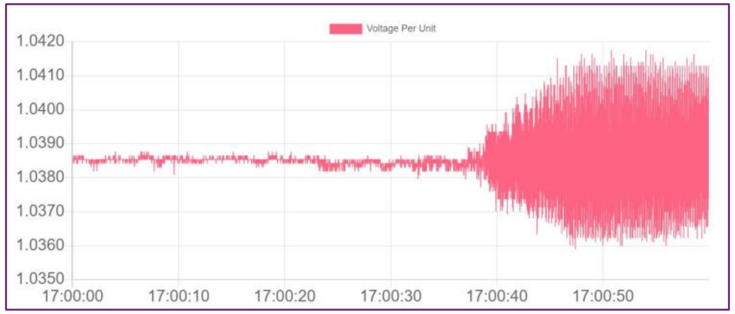


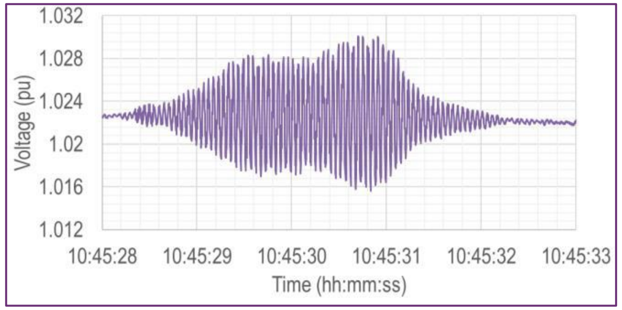
https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/high-level-summary-of-wmz-subsynchronous-oscillations.pdf

Characteristic of oscillations

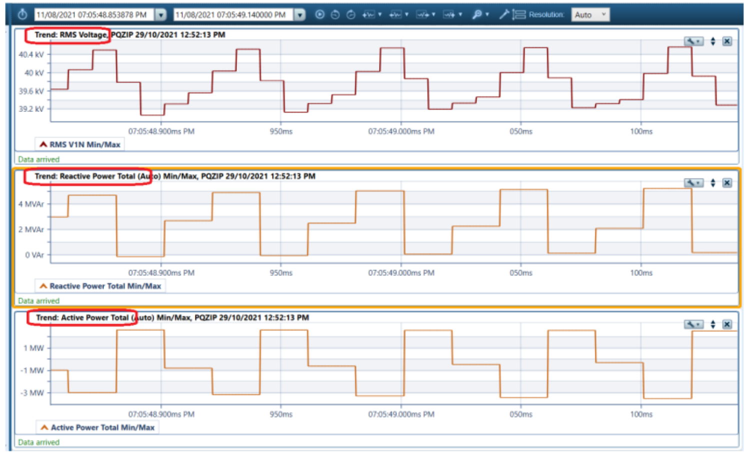
- Gradual increase in oscillations magnitude







- No clear relationship between P, Q and V



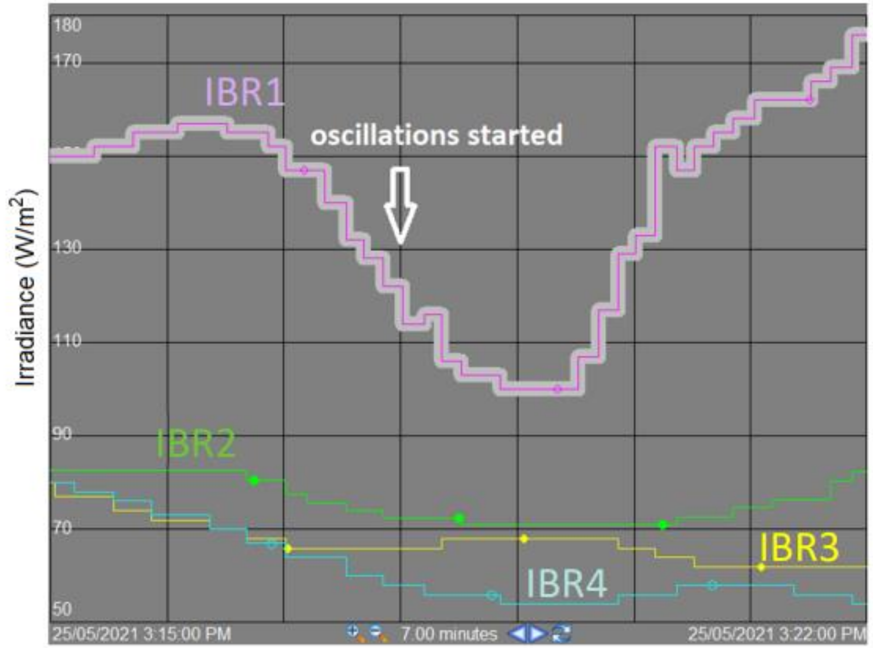
https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/west-murray-zone-power-system-oscillations-2020--2021.pdf

Complexities

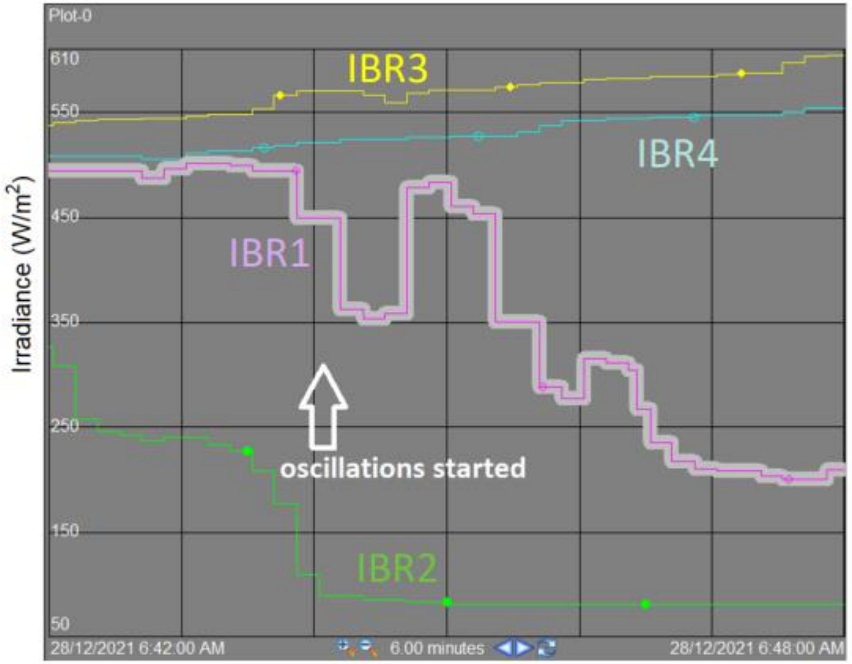
- Limited high-resolution visibility
- Intermittent (with variable duration and magnitude)
- No clear correlation with
  - Line loading
  - Active and reactive power generation from IBRs
  - Local loads (ramping of load)
  - Status of nearby HVDC link
  - Status of SVC and mode of operation of SVC

Power system oscillations and irradiance change

- 25 May 2021
  - No clear network disturbance.
  - 16.5 Hz, 12 minutes, 2.2% peak-to-peak at Red Cliffs



- 28 December 2021
  - No clear network disturbance.
  - 19 Hz, 2.5 minutes, 2% peak to peak at Red Cliffs

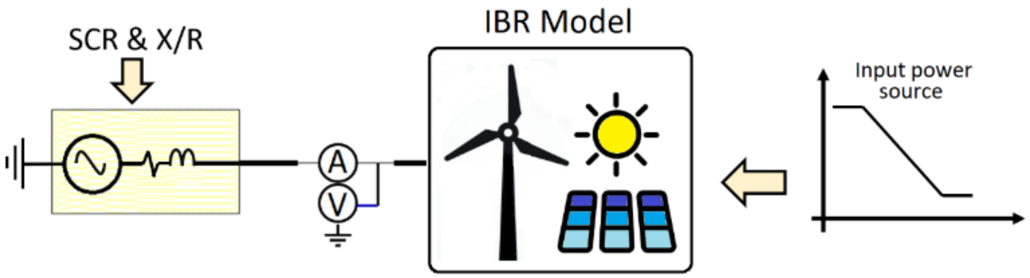


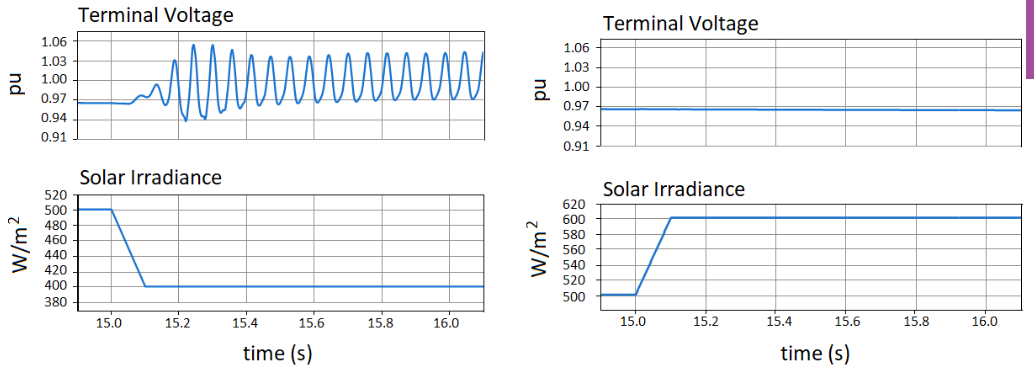
https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/west-murray-zone-power-system-oscillations-march-2023-update.pdf

Power system modelling

- Single machine infinite bus (SMIB)
  - Solar farm in isolation, with site-specific vendor model
  - SCR and X/R ratio from a typical system snapshot
  - Gradual reduction in irradiance without changing active power reference
  - Sensitivity : Variation in SCR
- Wide-area
  - Four-state EMT model
  - Case set up to match the oscillation signature: magnitude and frequency
  - All solar farms connected, with irradiance reduced at one solar farm each simulation
  - Aim to identify which solar farm is more prone to triggering the oscillations

SMIB modelling



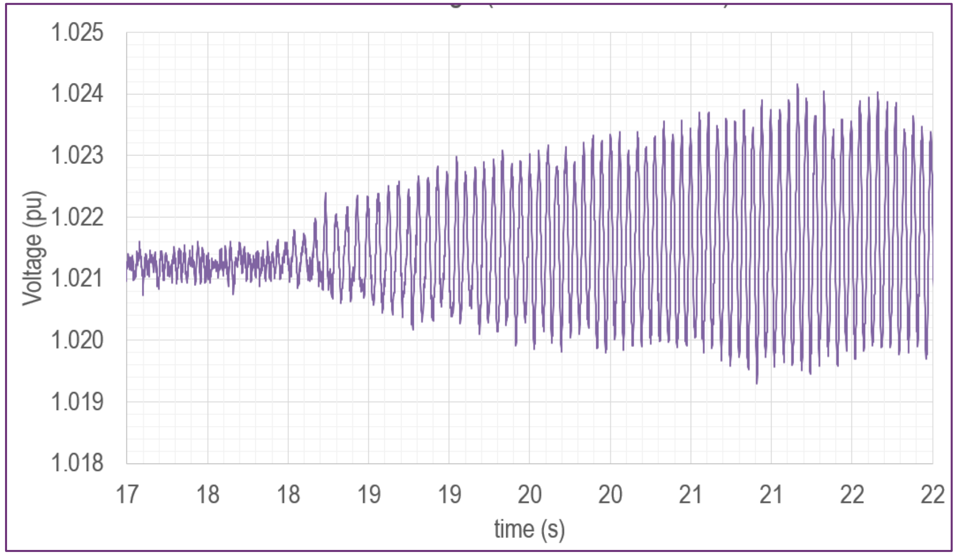


IBR	Irradiance ramp up (at 1.0 pu output)	Irradiance ramp down (at 1.0 pu output)	Irradiance ramp up (at 0.5 pu output)	Irradiance ramp down (at 0.5 pu output)
IBR1	No oscillations	18 Hz oscillations (Undamped)	No oscillations	18 Hz oscillations (Undamped)
IBR2	No oscillations	22 Hz oscillations (Damped within 1 sec)	No oscillations	No oscillations
IBR17	No oscillations	No oscillations	No oscillations	No oscillations
IBR18	No oscillations	25 Hz oscillations (Damped within 1 sec)	No oscillations	25 Hz oscillations (Damped within 1 sec)

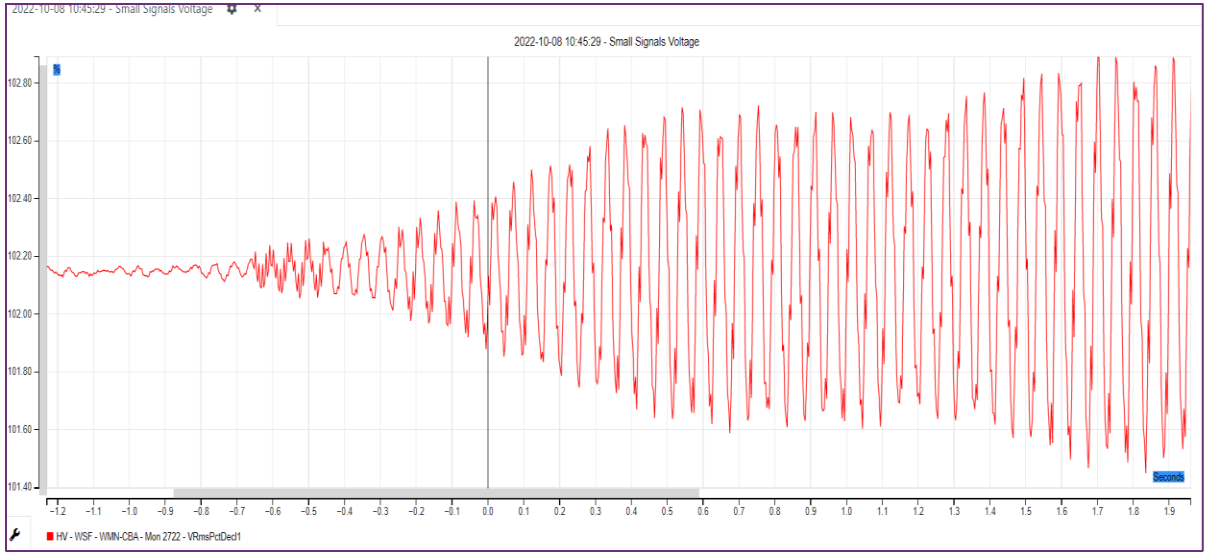
“Replication of Real-World Sub-Synchronous Oscillations in Inverter-Based Resources Dominated Grid”, Nilesh Modi, Ehsan Farahani, A Jalali, J Ramamurthy, C Chin, B Soetantijo, IEEE Transactions on Power Delivery, vol. 39, no. 3, pp. 1399-1406, June 2024, doi: 10.1109/TPWRD.2024.3364156.

Wide-area modelling – base case

- Simulation results (left) matched with operation measurement (right), in terms of growing oscillation magnitude and oscillation frequency



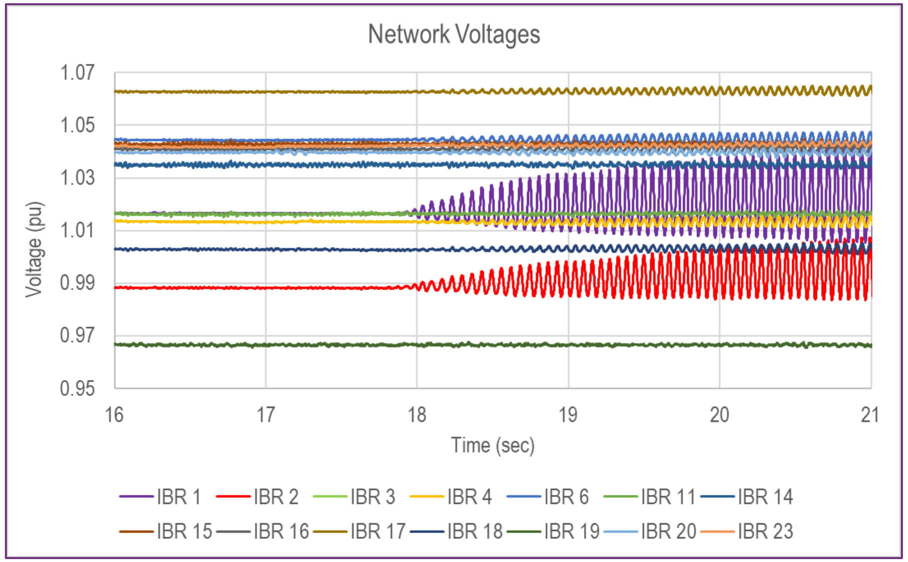
EMT Simulation



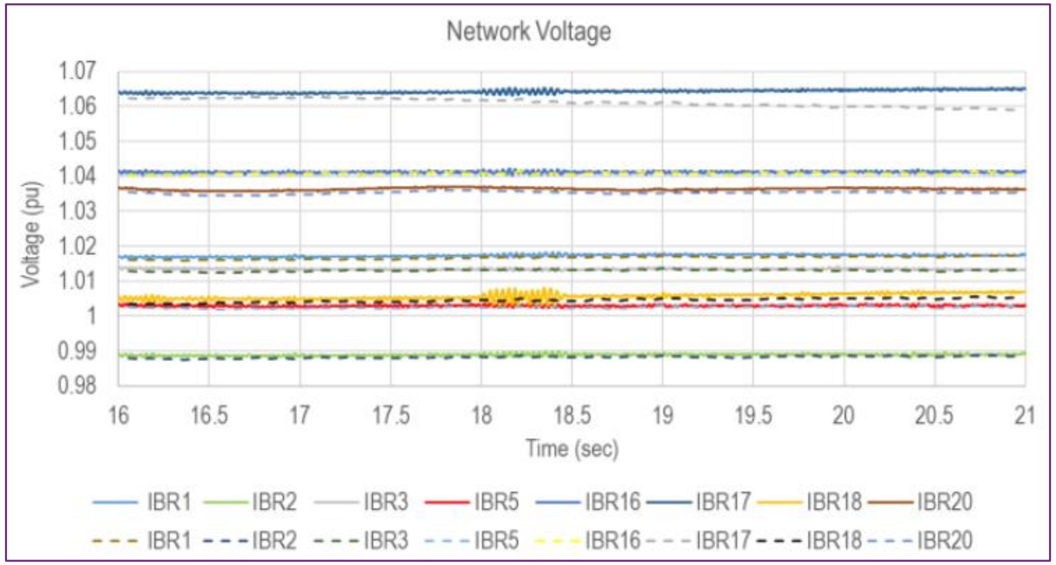
Field measurement

Wide-area modelling – IBR comparison

- Decreasing irradiance at one IBR (left) triggered the oscillation, while decreasing irradiance at another IBR (right) did not



EMT Simulation

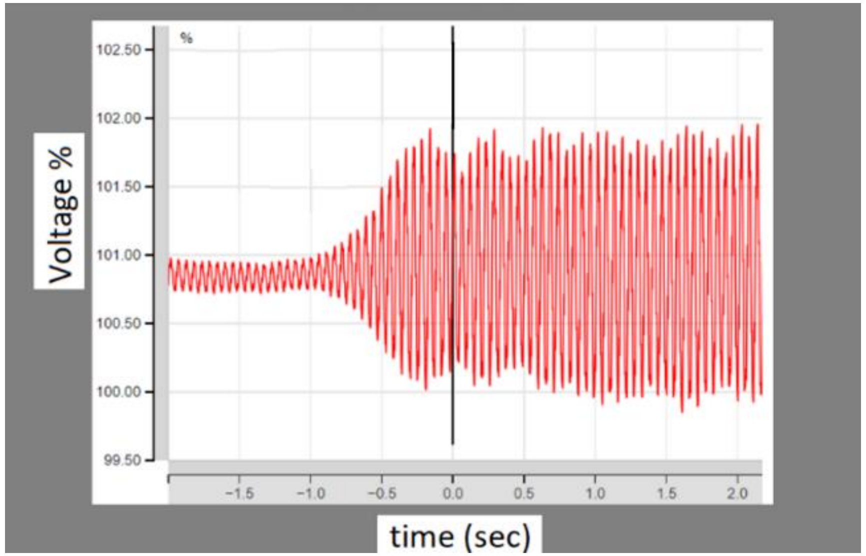


EMT Simulation

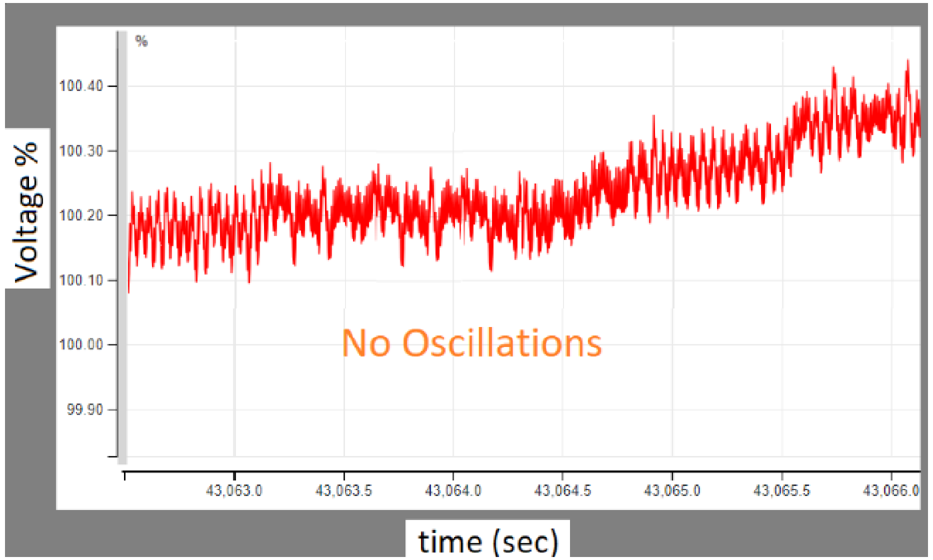
"Replication of Real-World Sub-Synchronous Oscillations in Inverter-Based Resources Dominated Grid", Nilesh Modi, Ehsan Farahani, A Jalali, J Ramamurthy, C Chin, B Soetantijo, IEEE Transactions on Power Delivery, vol. 39, no. 3, pp. 1399-1406, June 2024, doi: 10.1109/TPWRD.2024.3364156.

Remediation

- Improved DC link control strategy
- Staged implementation of the new settings on the site



Field measurement - before control system upgrade

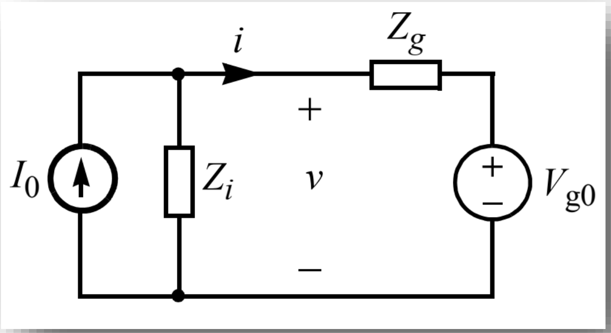


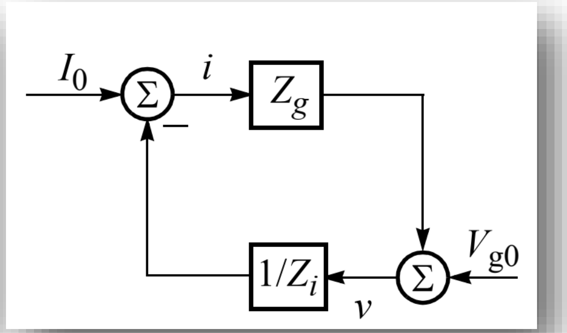
Field measurement - After control system upgrade

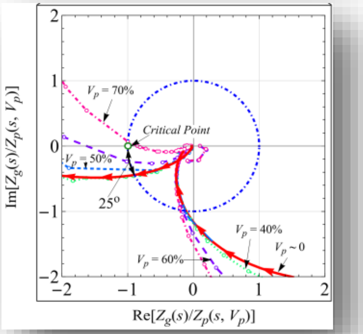
Impedance Scan Analysis of Source of Oscillations

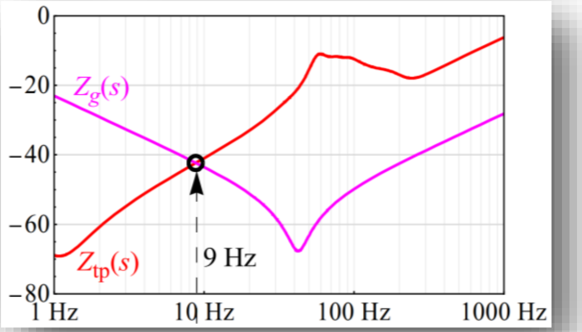
Impedance-Based Stability Analysis

- **Loop Gain**: $Z_g(s)/Z_i(s)$
- **Pre-requisite:**
  - *Standard Criterion*: IBR and the Grid are Separately Stable
  - *Reversed Criterion*: IBR and the Grid are Stable when Interconnected









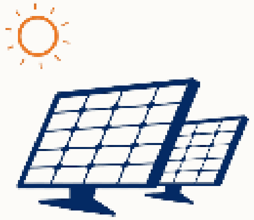
Steps for Analyzing IBR-driven Oscillations

- **Step 1**: Start with IBRs that are likely source of oscillations.
- **Step 2**: Perform impedance scans of IBRs in SMIB format
  - Identify resonance modes and SCR-based stability boundary of IBRs
- **Step 3**: Perform impedance scans of the real grid at the POI of an IBR using wide-area system EMT model
  - Identify resonance modes of the grid and damping contribution from the IBR
  - Repeat this step at other IBRs

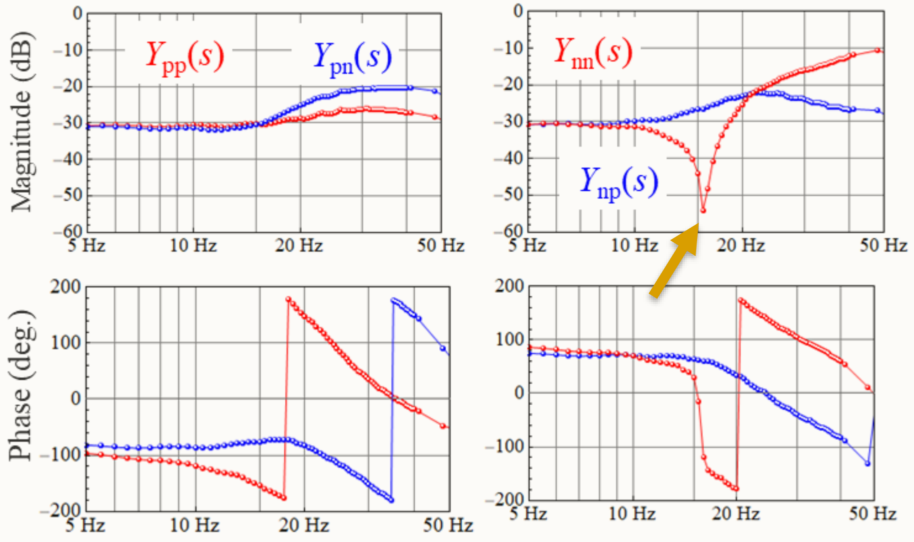
GIST

Stability Analysis of a PV Plant with **SMIB Grid**

PV Plant



$Z_i(s)$



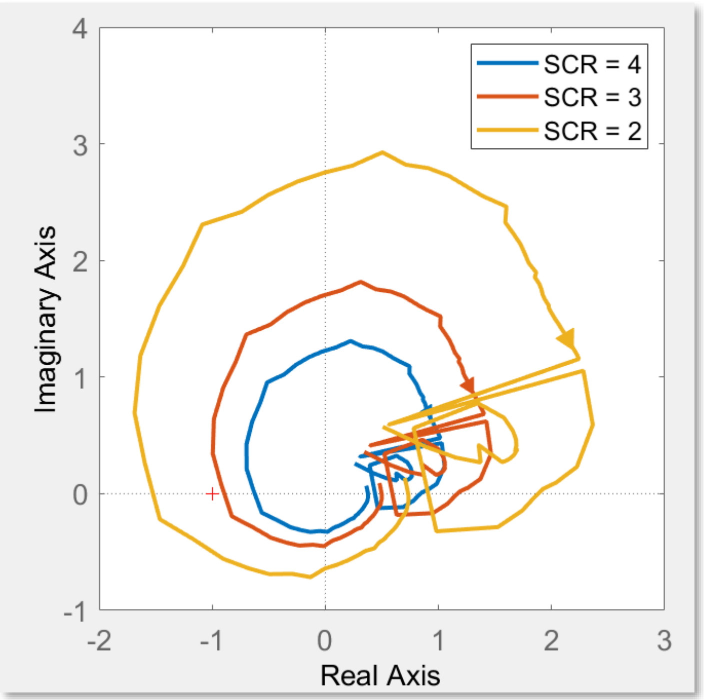
- The PV plant has an under-damped mode at 17 Hz for low irradiance conditions.

$Z_g(s)$

SMIB GRID

$Z_g(s) = R_g + sL_g$

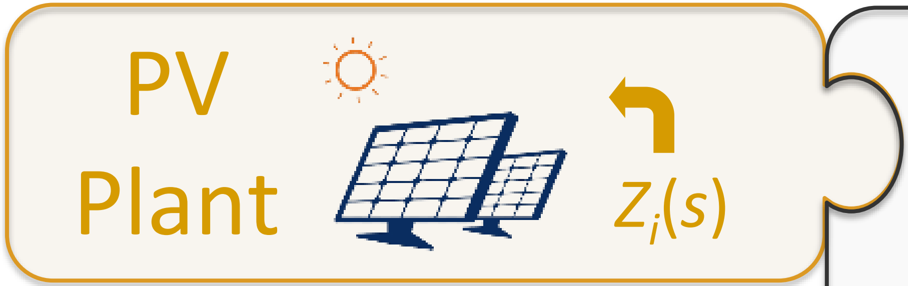
Nyquist Plot of $Z_g(s)/Z_i(s)$

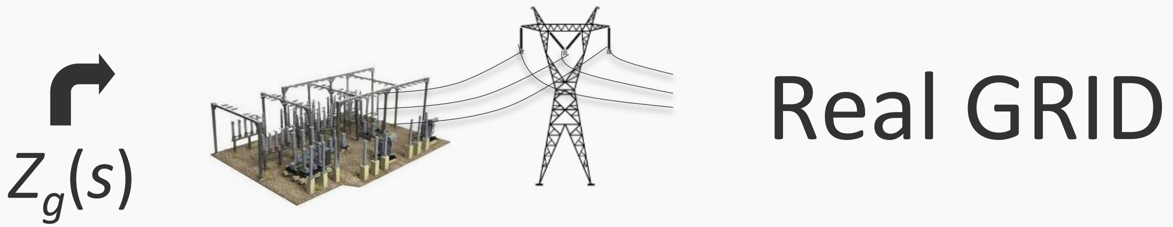


- The 17 Hz mode of the PV plant becomes unstable if the grid SCR is less than 3
- The actual grid SCR is significantly higher.
- Hence, SMIB analysis does not (completely) explain 17-19 Hz oscillations in the Australian grid.

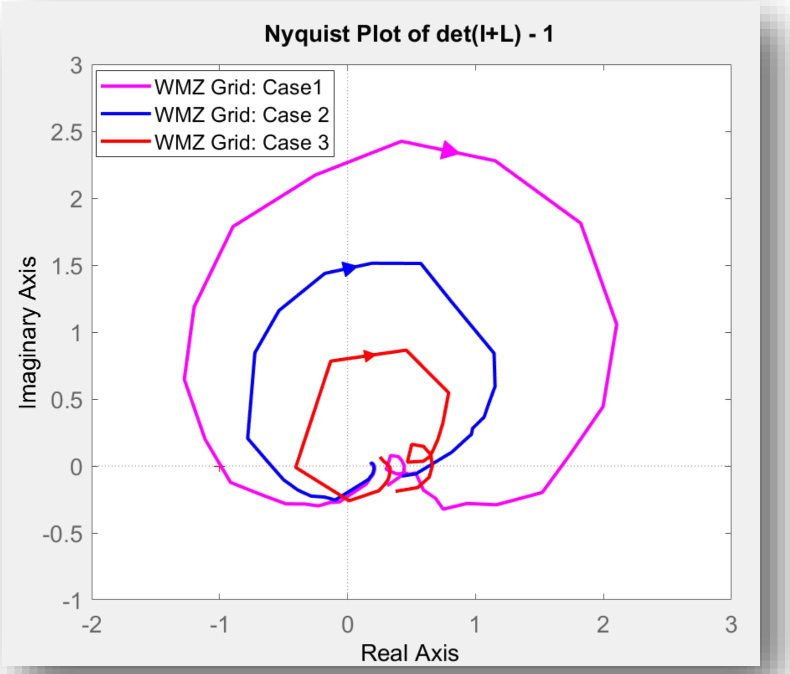
GIST

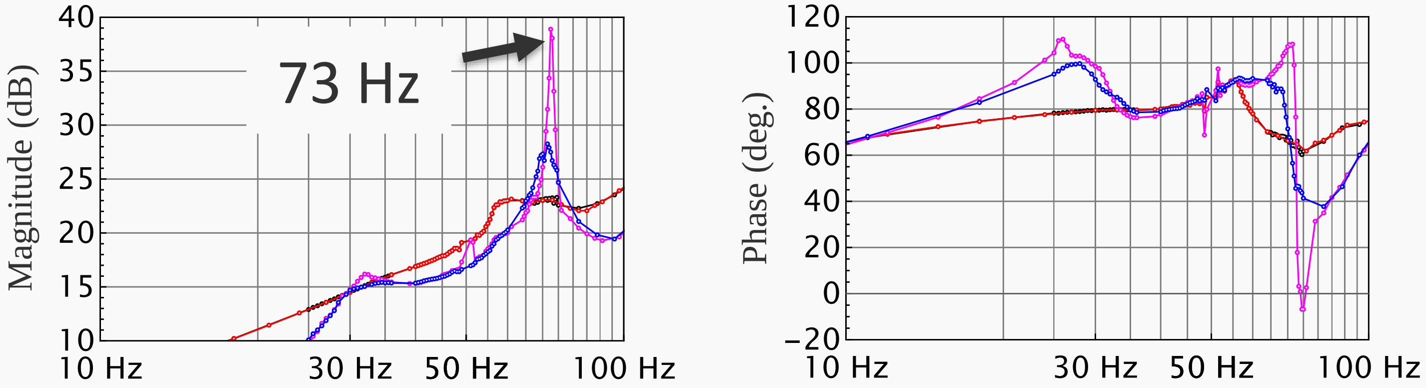
Stability Analysis of a PV Plant with **Real Grid**





Nyquist Plot of $Z_g(s)/Z_i(s)$



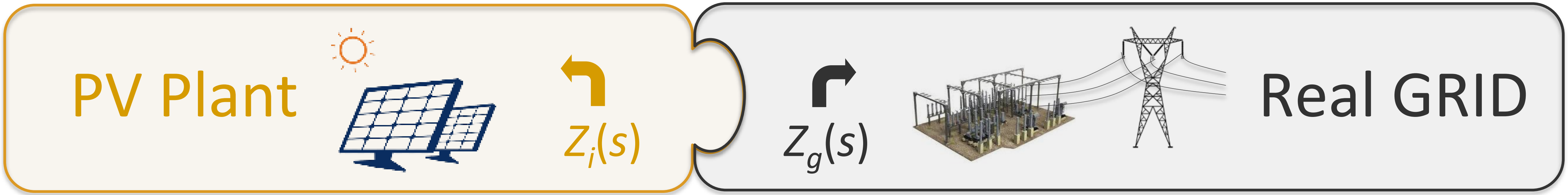


Two nearby PV plants have low irradiance
One nearby PV plant has low irradiance
Nearby PV plants have high irradiance
Nearby PV plants are disconnected

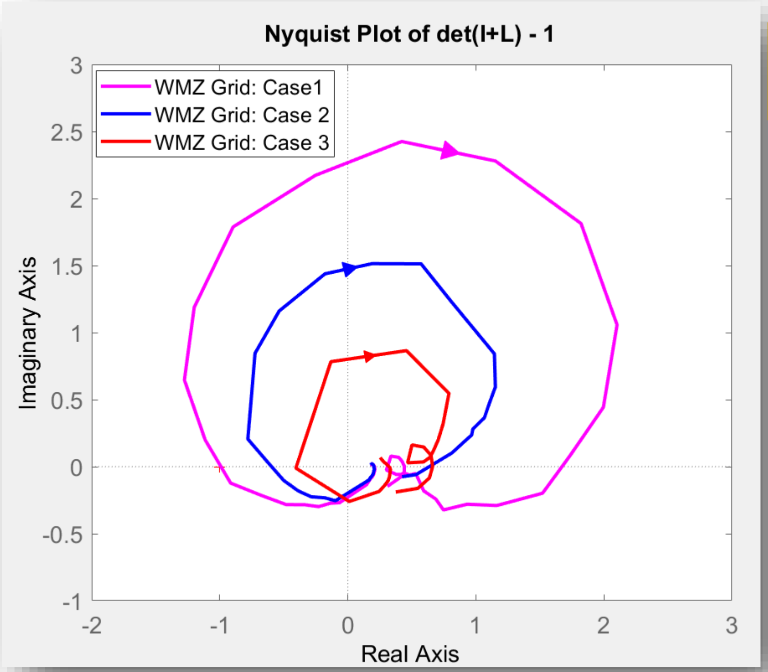
- The real grid has an underdamped mode at 23 Hz (= 73 - 50 Hz) formed by nearby IBRs.

GIST

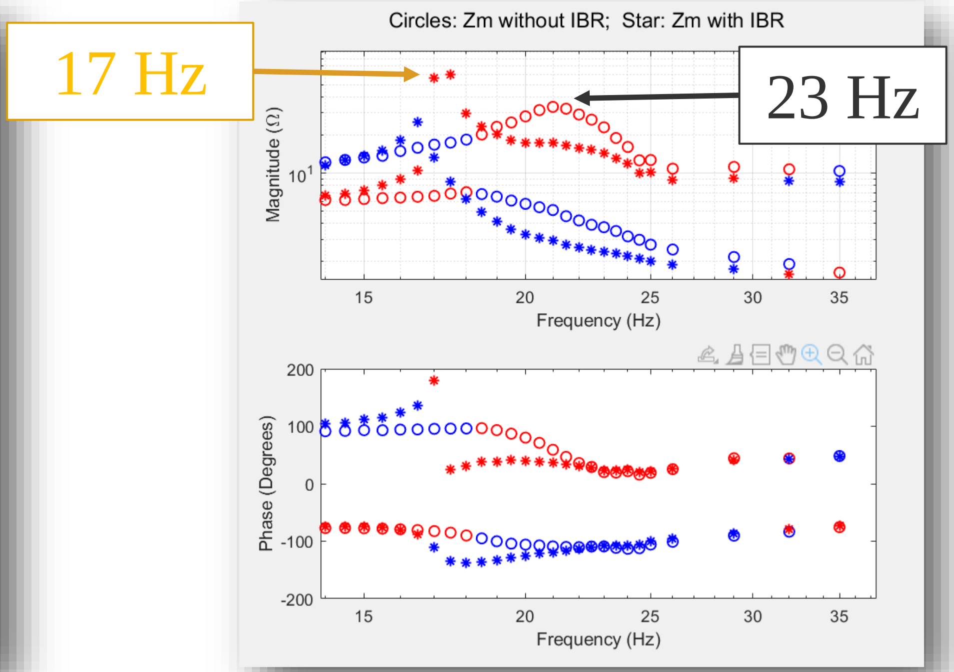
Stability Analysis of a PV Plant with **Real Grid**



Nyquist Plot of $Z_g(s)/Z_i(s)$



Modal Impedance at POI



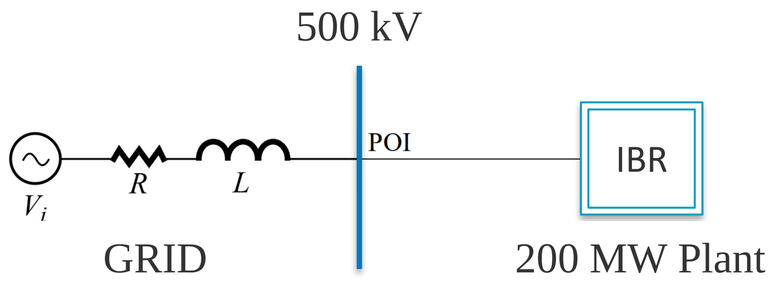
The PV plant moves a grid resonance mode from 23 Hz to 17 Hz and significantly reduces its damping to a negative value.

Summary of Analysis at Three PV Plants

Solar Farms with Low Irradiance	Resonance Mode: Frequency	Resonance Mode: Damping	Oscillation Risk
A, B, C	17 Hz	--	Very High
A, B	17 Hz	-	High
B	17 Hz	+	Low
A, C	23 Hz	+	Low
A	23 Hz	++	Very Low
C	N/A	N/A	None

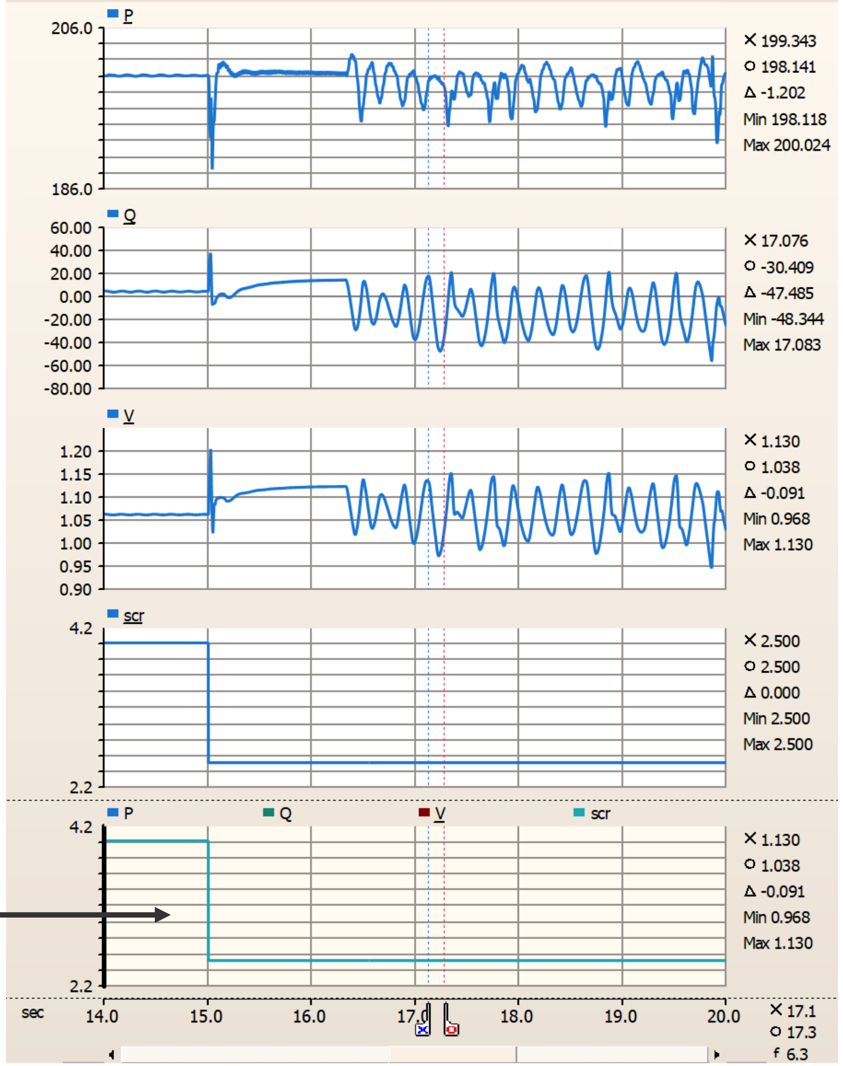
Sizing of a GFM Resource to Provide Specific Grid Strength

Weak Grid Instability of a 200 MW IBR



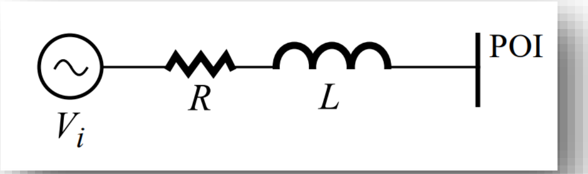
- The IBR becomes unstable if the grid SCR is less than 3
  - It starts oscillating at around 6 Hz under weak grid conditions
- Objective: Stabilize the IBR using a GFM resource for SCR of 1.5

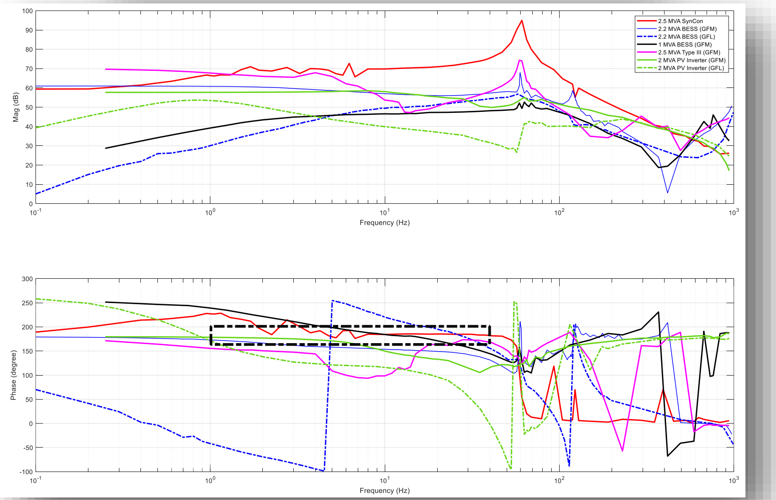
SCR reduced to 2.5 at 15 seconds



Recap: Q/V and P/θ Scans of GFM Resources

- Characteristics of an ideal voltage source behind reactor during the sub-transient to transient time scales can be used for quantifying voltage source behavior of GFM resources
- Frequency scans Q/V, P/θ, and V/I can be used for quantifying grid strength.



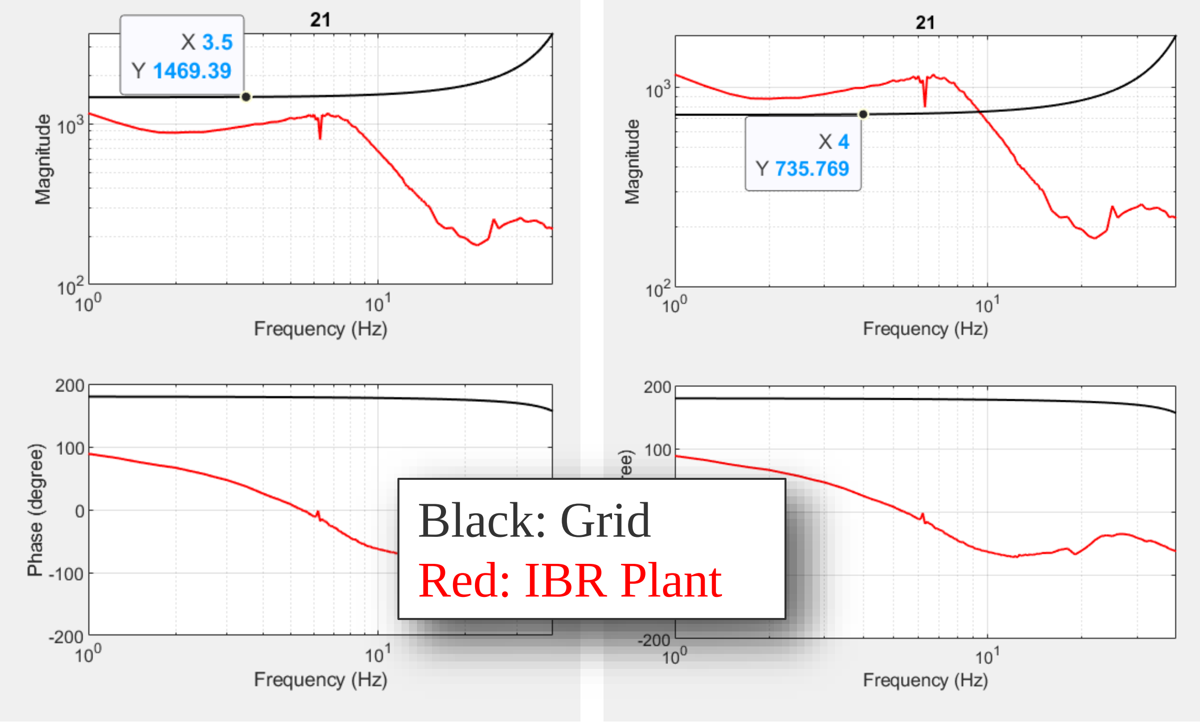


1. (presentation) Frequency Scans for GFM Performance Verification – 2024 IEEE Power and Energy Society General Meeting - https://www.nrel.gov/docs/fy25osti/90780.pdf
2. (presentation) Frequency Scans for GFM Performance Verification – 2023 IEEE Power and Energy Society General Meeting - https://www.nrel.gov/docs/fy23osti/87061.pdf
3. (presentation) GFM Inverter Hardware Testing – 2024 ESIG Spring Technical Workshop - https://www.nrel.gov/docs/fy24osti/89421.pdf
4. (paper) A Testing Framework for GFM Resources – 2023 IEEE Power and Energy Society General Meeting - https://www.nrel.gov/docs/fy23osti/84604.pdf

Q/V Response of Grid with Different SCR

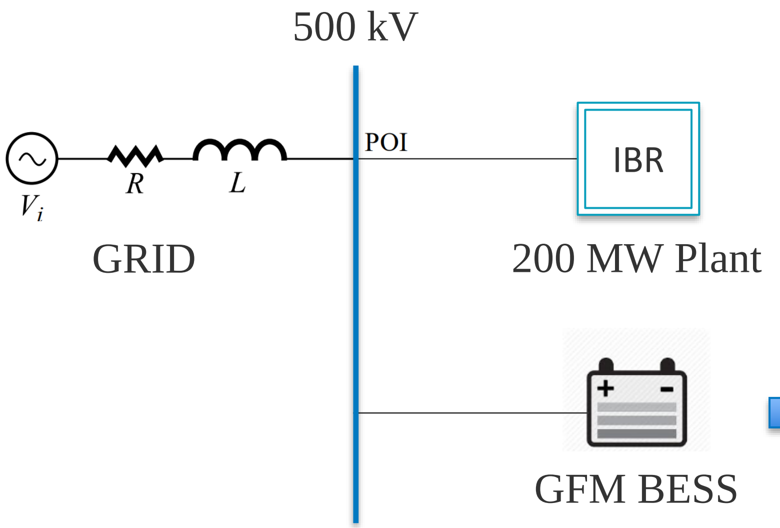
- SCR = 3 ➔ 1470 VAR/V
- SCR = 1.5 ➔ 735 VAR/V

SCR = 3 SCR = 1.5

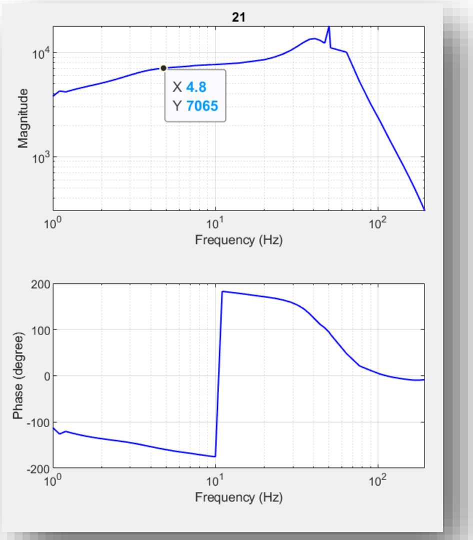


- Grid provides 1470 VAR/V for SCR of 3
- The grid only provides 735 VAR/V for SCR of 1.5
  – For the 200 MW IBR to operate stably when the grid SCR is only 1.5, the remaining 735 VAR/V should come from a grid-forming resource.

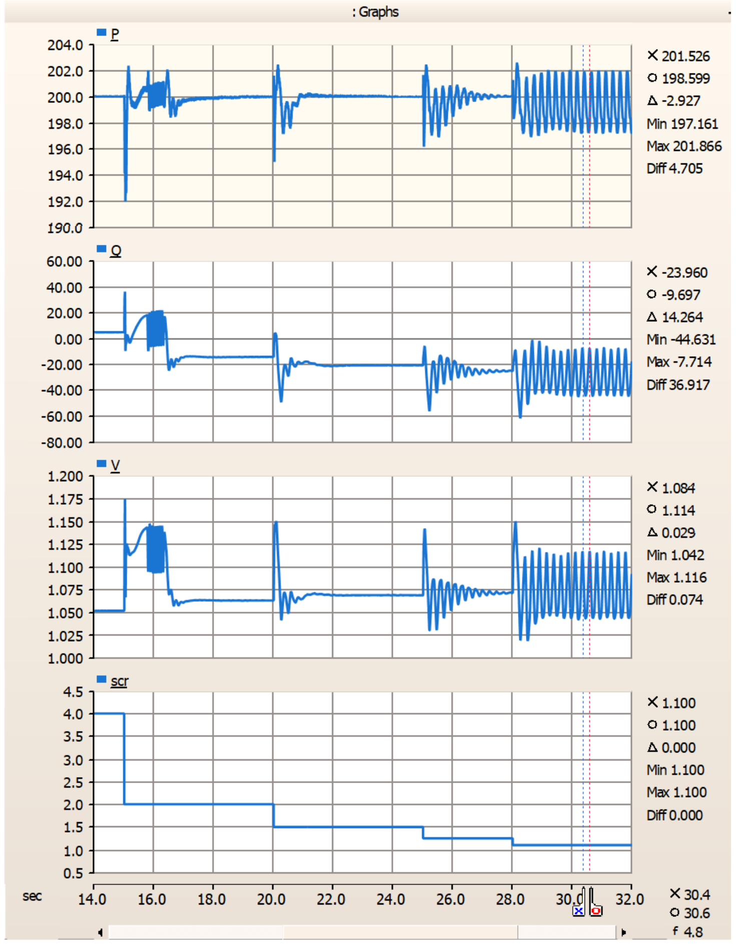
Stabilization of a 200 MW IBR using GFM BESS



Q/V Scan of GFM BESS



Response of the IBR



- GFM BESS provides 7000 VAR/V at 66 kV bus
  - This is equivalent to 924 VAR/V at the 500 kV bus where IBR is connected
  - This is equivalent to response of grid with SCR 1.9
  - Hence, with this GFM BESS, the 200 MW IBR can operate stably for grid with SCR > 1.1 (= 3 – 1.9)

GIST

Sizing of GFM (without Models or EMT Studies)

Demand for Grid Strength

- IBR Developers Guarantee Stability for Grid with SCR Above a Threshold

Available Grid Strength

- System Planner Estimates SCR Deficit at POI and Required Q/V and P/θ Response

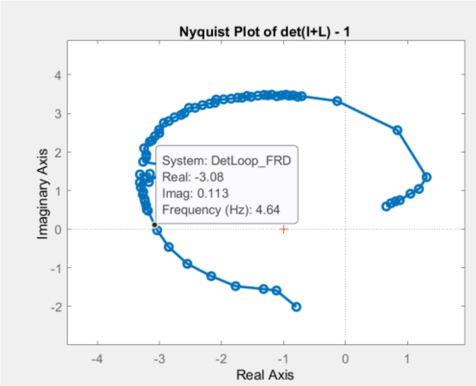
Deficit Supplied by GFM BESS

- GFM BESS is Sized to Provide Necessary Q/V and P/θ Response at the POI

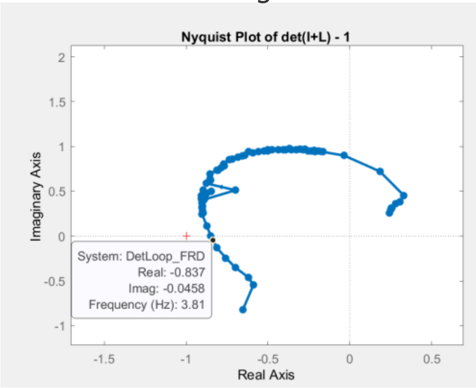
Dynamic SCR or *d*SCR: GFM BESS provides short-term active and reactive power response to supply grid strength deficit

- Impedance Analysis

Nyquist Plot of $Z_g(s)/Z_i(s)$



Nyquist Plot of $[Z_g(s)+Z_{BESS}(s)]/Z_i(s)$



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