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Capabilities and Deployment of Grid Forming Technology in the Australian Market

Background

- Vysus is engaged by the Australian Renewable Energy Agency (ARENA) to investigate the potential role of grid-forming batteries to improve system strength and enable greater penetration of IBR.

- Preliminary studies focussed on how differences in location and sizing of grid-forming batteries affect performance on suitable metrics of grid strength.

- Ongoing investigations are in progress to quantify how dynamics of grid-forming inverter controls (in a simple generic model representation) support network stability following major voltage and frequency disturbance events.

- Vysus is also providing independent advice to ARENA of grid-forming technology ‘readiness’ in the market in collaboration with OEMs.

Market Context: Centralised procurement of system strength

- Australia's National Electricity Market (NEM) is moving to an approach based on utility provision and cost recovery for 'system strength' services

- Key elements include:
  - Annual assessment by AEMO of system and minimum fault level requirements
  - New IBR connections having a gap between minimum and available fault level can self-remediate as at present, or pay for a suitable share of centrally procured system strength
  - Third parties may bid into market for centralised system strength services

- Criteria for determining 'stability of voltage waveform' in preparation

- Locational factors to be derived to quantify effect of offered service at node A on IBR connection at node B – will be critical to efficient market operation

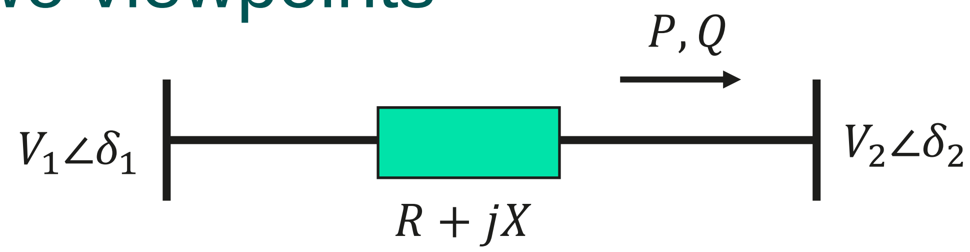
Power system operation: Electromechanical (‘analog’) perspective

- Network power flows regulated by physical rotating masses, attached to synchronous machine rotors
  - Power flows relate to bus voltage phase angle differences, inferred from machine rotor positions δ_k subject to equations of motion
- Excitation systems with AVR controls maintain voltage magnitudes
  - Voltage regulated by reactive power flows across network reactances
- During faults, generators contribute fault current determined by Ohm’s law
  - The closer a fault point to a generator, the higher the fault current
  - Thus, fault current is a proxy indicator for electrical distance

Power system operation: Electronic (‘digital’) perspective

- Power flows regulated by modulation angles of synthetic voltage sources
  - Modulation angles may be programmed to obey synthetic equations of motion → ‘virtual synchronous machine’
- Outer loop V controls on inverters, SVCs etc. maintain voltage magnitudes
  - Functionally equivalent to AVR controls, but no magnetic circuit
- During faults and large disturbances, inverters contribute capacitive current determined by explicit control
  - Currents generally hard limited to capability of switching modules
  - Fault current may not reflect distance to the generator

System strength: two viewpoints



- Voltage magnitude stiffness

$$Q + \frac{R}{X} P \approx \frac{|V_1|}{X} \cdot (|V_1| - |V_2|)$$

- When *R*/*X* is small, reactive power couples to regulation of voltage magnitudes across network nodes

- Voltage angle stiffness

$$P - \frac{R}{X} Q = \frac{|V_1||V_2|}{X} \cdot \sin(\delta_1 - \delta_2)$$

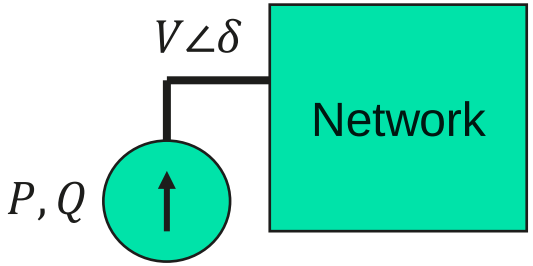
- When *R*/*X* is small, active power couples to displacement of voltage phase angles across network nodes – and changes in active power to displacement of frequency

Since $|V_1|/X$ is the short circuit current when $V_2 = 0$, short circuit fault level (equivalently SCR) has become a useful proxy indicator for the coupling strength in both instances

Sensitivity metrics for system strength

- In place of measuring short circuit currents, the preceding suggests the strength at a given busbar can be quantified using sensitivity of local voltage magnitude and angle to incremental changes in *P* and *Q* injection…

$$\begin{bmatrix} A_P & A_Q \\ M_P & M_Q \end{bmatrix} \equiv \begin{bmatrix} \dfrac{\partial \delta}{\partial P} & \dfrac{\partial \delta}{\partial Q} \\ \dfrac{\partial |V|}{\partial P} & \dfrac{\partial |V|}{\partial Q} \end{bmatrix}$$



- To correctly reflect transient strength of the network, these sensitivities should be determined not relative to the conventional load flow solution, but rather the 'naturalistic' network solution $Y_{bus}V_{bus} = I_{bus}$ where P and Q are represented by equivalent currents $I_P = P/V_{nom}$ and $I_Q = Q/V_{nom}$ in I_{bus}.
  - (In PSS/E® load flow software, this solution is obtained using the activity TYSL)

Sensitivity metrics, continued

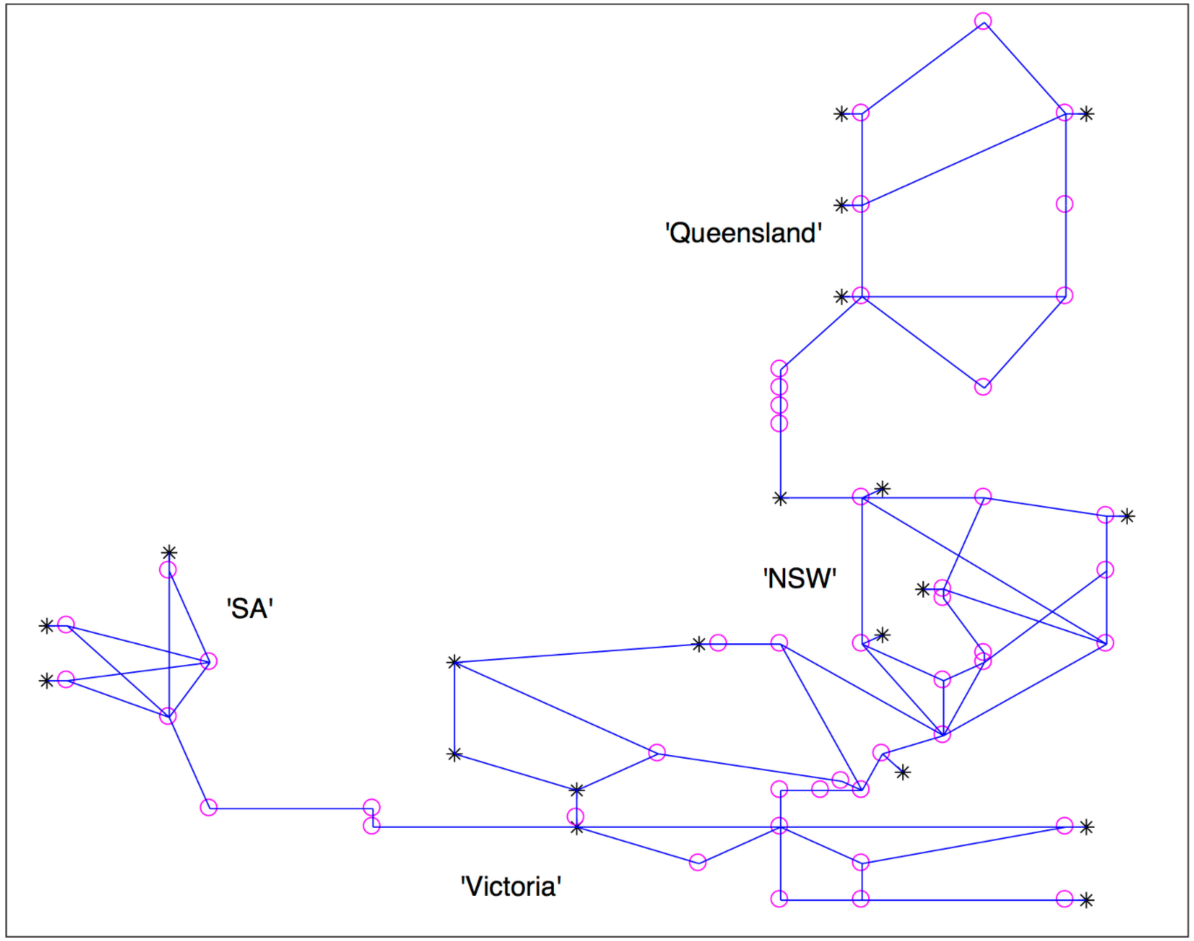
- When the network is a single equivalent impedance $R + jX$ to an infinite bus and R is small, then clearly

$$\frac{1}{A_P} \approx \frac{V_{\text{nom}}^2}{X} = \text{F.L.} \qquad \frac{1}{M_Q} \approx \frac{V_{\text{nom}}}{X} = \frac{\text{F.L.}}{V_{\text{nom}}}$$

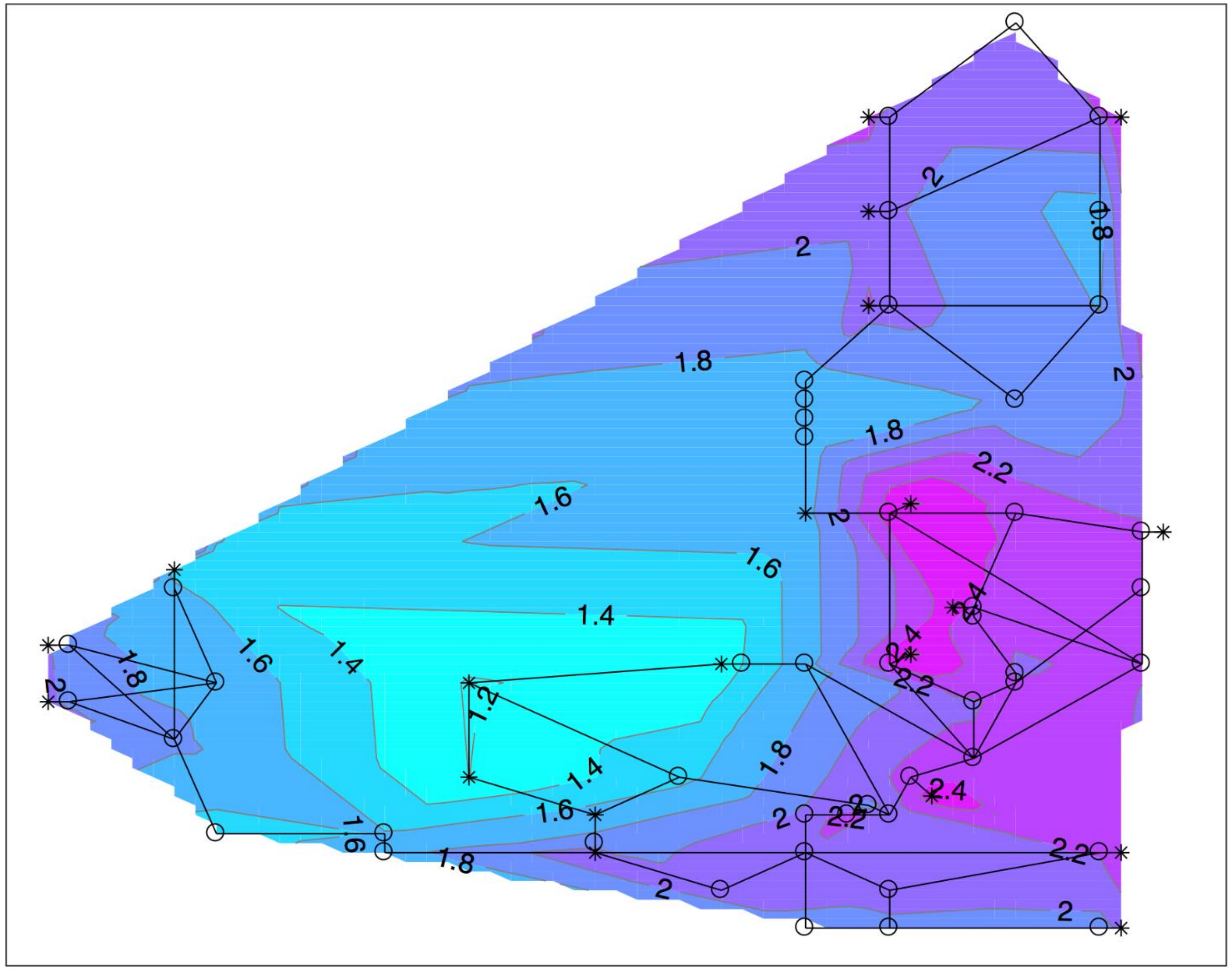
- In a per-unit representation, both $1/A_P$ and $1/M_Q$ correspond here to the usual SCR measure of system strength (thus smaller A_P = higher strength) – but note that no short-circuit calculation was used to obtain these metrics.
- Like SCR, these are essentially 'steady state' based metrics
- A convenient gauge for 'heat mapping' is $L = -\log_{10}(A_P)$ (for example)
  - Counts the number of leading zeros in the raw decimal value of A_P
  - Note larger values of L correspond to higher strength

68 bus test network

(Adapted from UAdelaide 14 generator system: Gibbard & Vowles 2010)

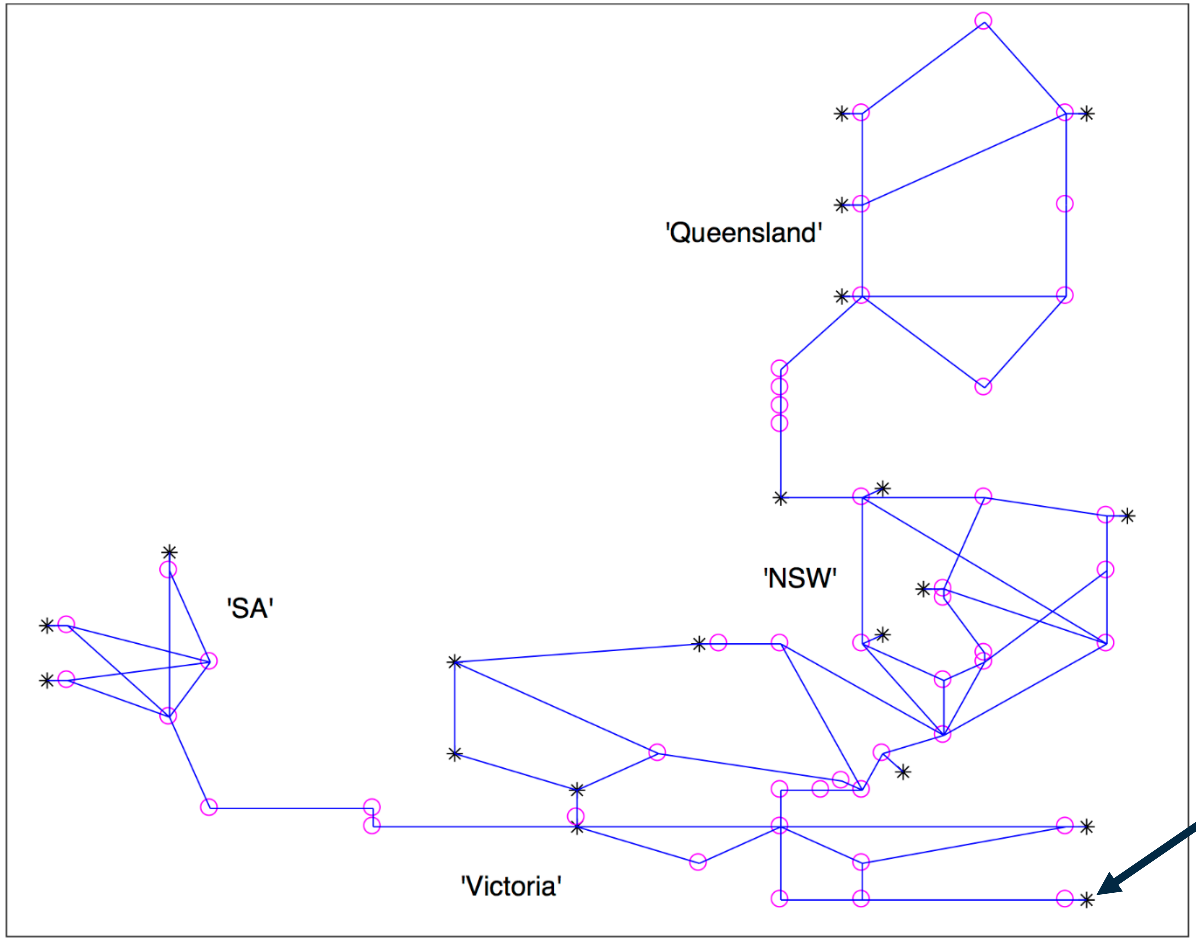


Sample heat map of A_P metric



Case study of dynamic fault response

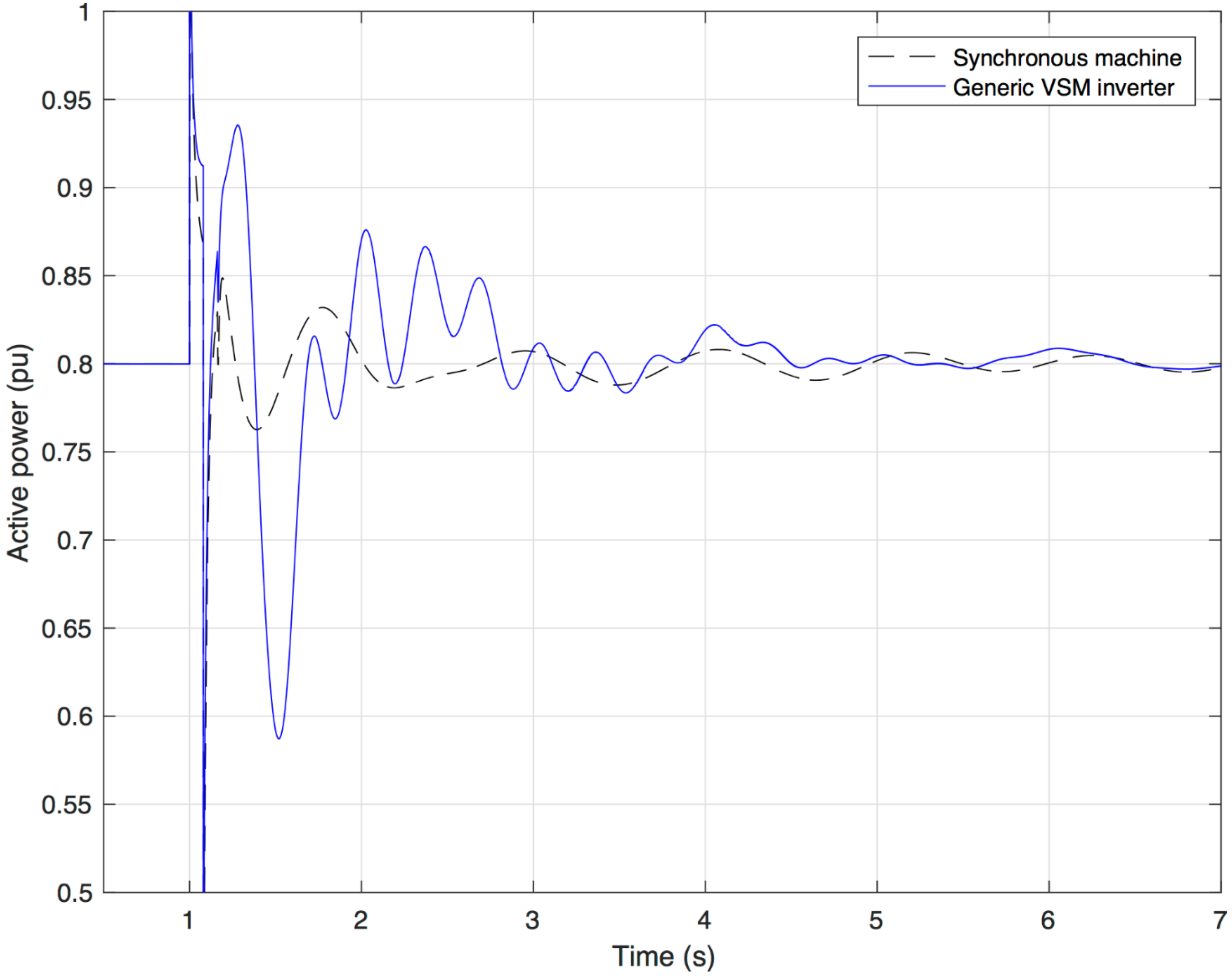
Existing generation comprising mixture of machines and grid-following inverter plant mimicking existing system at high level



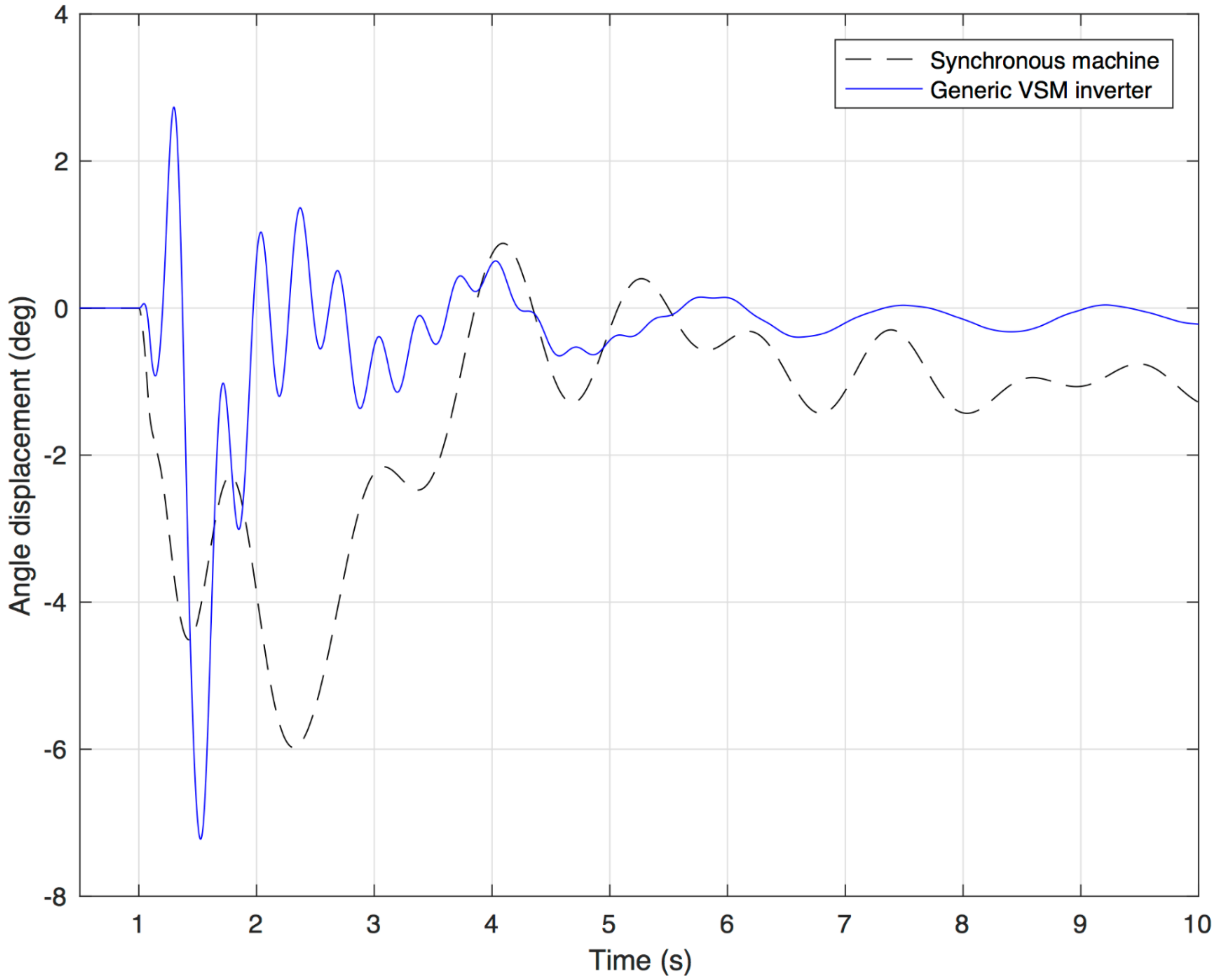
Apply 3-phase faults on main transmission nodes (for which original system remains stable)

Compare responses of 800MVA synchronous machine and VSM grid-forming inverter replacement at this location

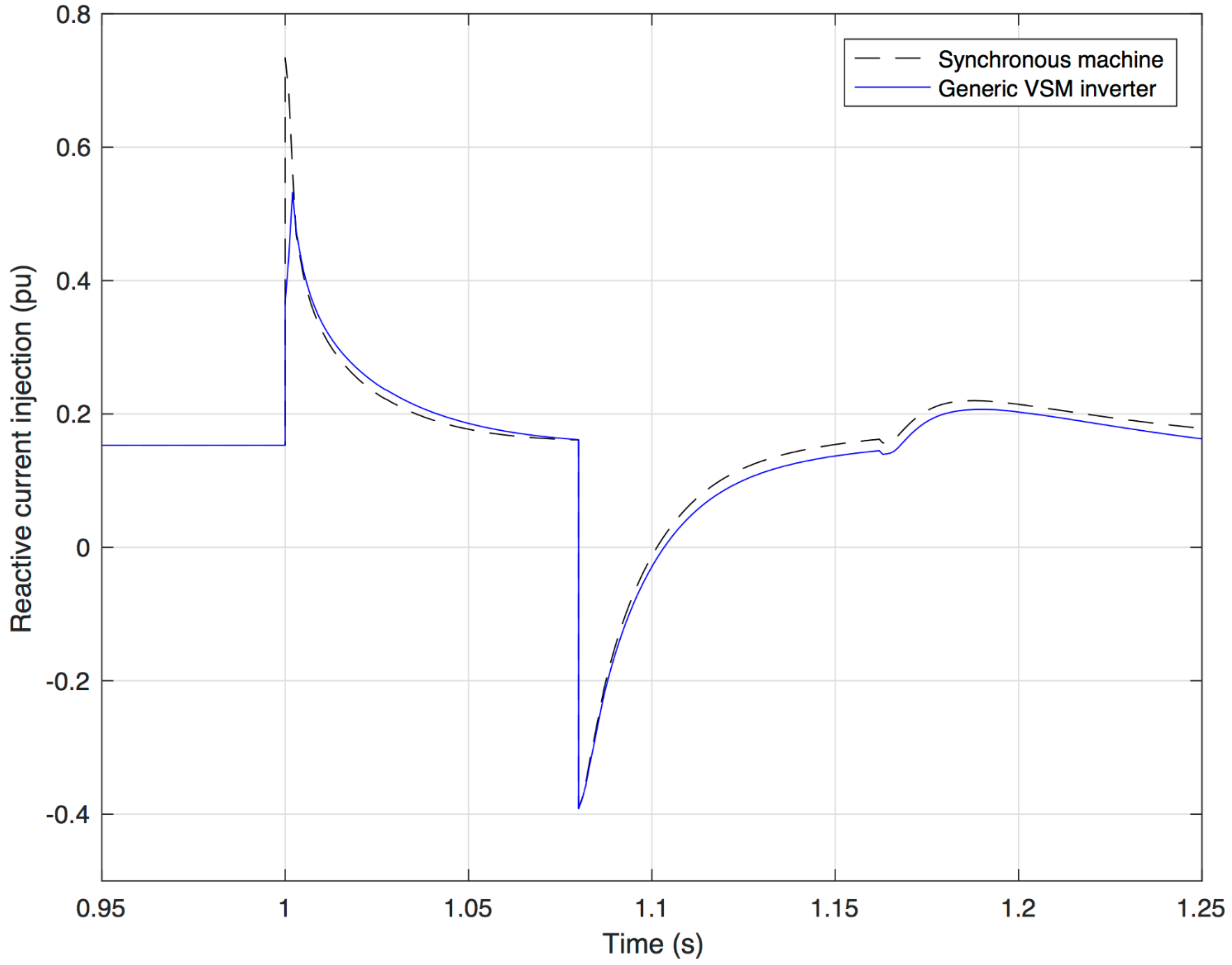
Fault response of active power



Fault response of angle variable



Fault response of reactive current



Grid-forming battery studies: preliminary findings

- Comparison of metrics (in particular A_P and M_Q) provides strong evidence for a positive system strength contribution related to the aggregate size of grid-forming batteries.
- Contribution is mildly nonlinear (diminishing returns) – stiffness effect of 200MW of plant is more than one-quarter that of 800MW, all else being equal.
- There is a mildly positive effect from subdividing into smaller plants in diverse locations, relative to concentrating in a single location.
- There is a fairly strong location effect: locating grid-forming plants in ‘highest load’ or ‘urban’ areas has greater effect overall than locating at ‘regional’ sites (though the latter provide substantial *local* benefit).
- Synchronous condensers as modelled have larger effects than grid-forming batteries of similar size; this is a direct consequence of the conservative modelling assumptions used. This finding is sensitive to the technology considered and is subject to further review.
- The strength contribution is mildly greater when charging than when discharging (but this may be an indirect effect of the surplus generation).

Ongoing Investigations

Vysus' ongoing technical advice to ARENA includes independent assessment of OEM technology for system strength and inertia contribution, and investigation of further technical considerations for this technology.

- Strategies to incorporate PSS type feedbacks in voltage and/or frequency loops
  - Theory of oscillation damping largely carries over from classical approaches
- Comparison of different current limiting strategies
  - Freezing modulation angle ≠ Reactive current prioritization
- Comparison of results / robustness using RMS models (PSS/E) and EMT models (PSCAD)

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