Advanced inverter applications (and requirements) for current-limited grid-forming inverters

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Monash University
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Presentation Outline

Topic 1: Transient Stability of GFMIs

- **Current limitation and Transient Stability of GFMIs**
- **q-prioritized Current-Limited GFMIs**

Topic 2: Stability Tools and Analytical Methods

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- **Current limitation and Transient Stability of GFMIs**
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Topic 2: Stability Tools and Analytical Methods

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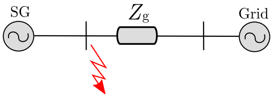
Synchronous Generators

- **High** overcurrent capability, i.e., 6 - 7 pu.

⇒ **No current limitation** is required.

⇒ Always in a **voltage-controlled** mode.



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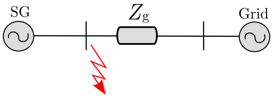
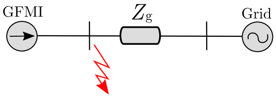


GFMIs

- **Low** overcurrent capability, i.e., 1.1 - 2 pu.

⇒ A **current limiter (CL)** is required.

⇒ In a **current-controlled** mode if CL is engaged.



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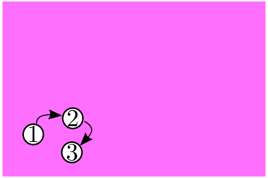
Small-signal stability

- Stability around an equilibrium point (EP).
- Linearised model can be employed.



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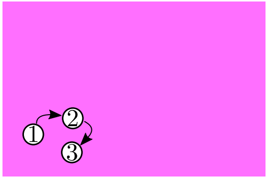

Figure 1: Small-signal disturbance.

Transient stability

- Stability in a wider range of operating condition.
- A non-linear model of the system is required.

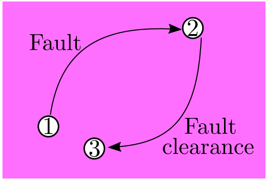

Figure 2: Large-signal disturbance.

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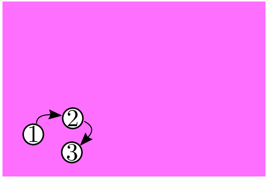

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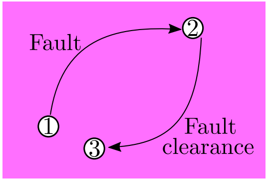

Figure 2: Large-signal disturbance.

- It is important to understand the TS limit and the mechanism of instability of a current-limited GFMI.

⇒ Beneficial for tuning and proposing enhanced control.

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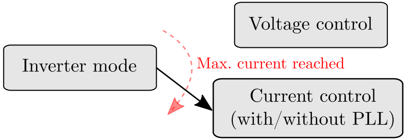

  - Switch to (PLL-based or PLL-less) current-controlled mode.

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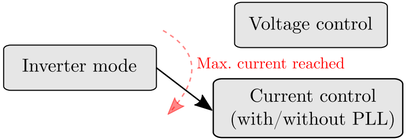

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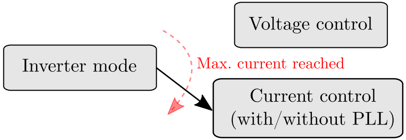

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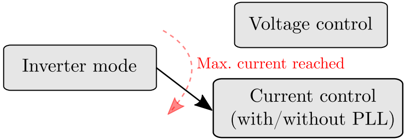

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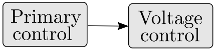

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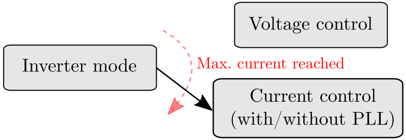

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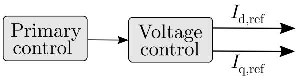

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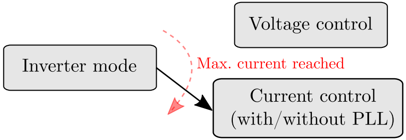

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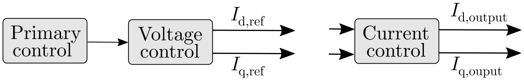

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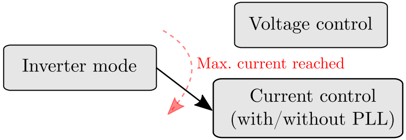

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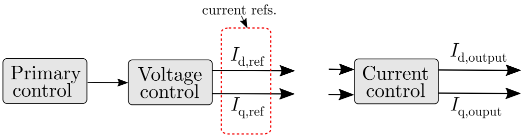

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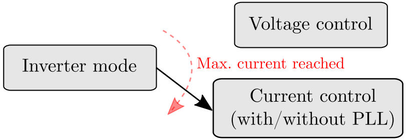

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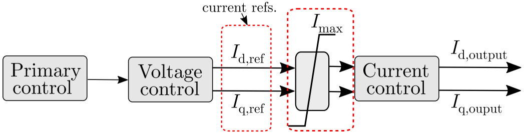
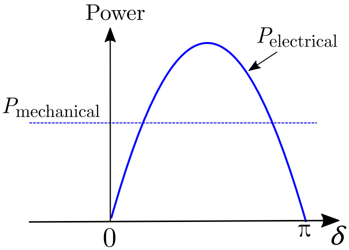


source: https://www.powerstations.uk/tilbury-turbines/tilbury-b-power-station-turbines-9/



- Power-Angle curve and the equal-area-criterion are employed for TS study of SGs.

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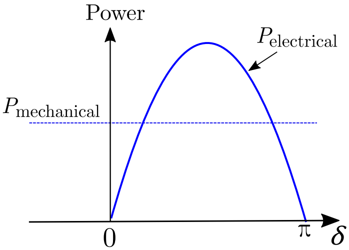

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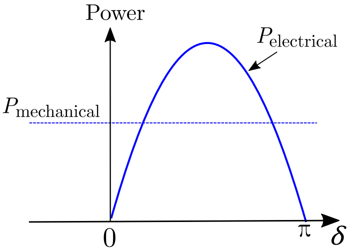
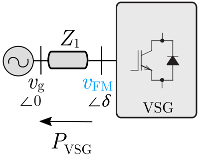
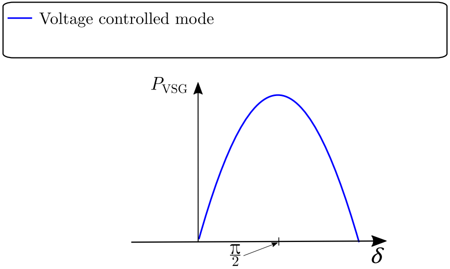


- Power-Angle curve and the equal-area-criterion are employed for TS study of SGs.
- We aim to derive the Power-Angle curve of current-limited GFMIs.
- A virtual synchronous generator (VSG) is studied in the next slides.

Power-Angle Curve of Current-Limited GFMIs





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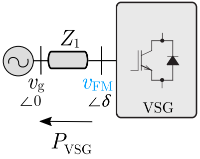
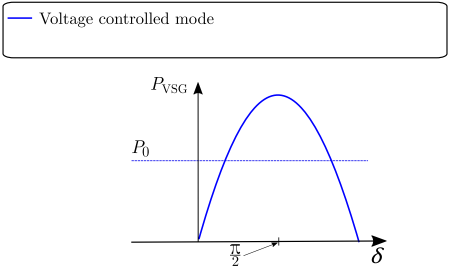
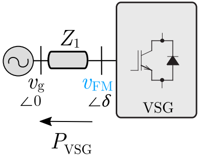
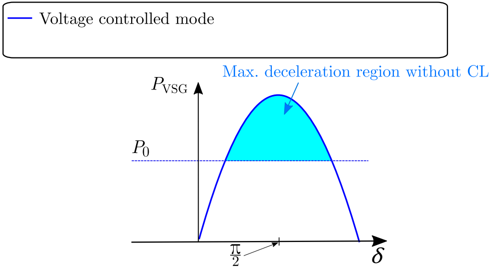





Z_1
v_g
$\angle 0$
v_{FM}
$\angle \delta$
VSG
P_{VSG}


Voltage controlled mode
Max. deceleration region without CL
P_{VSG}
P_0
$\frac{\pi}{2}$
δ

Power-Angle Curve of Current-Limited GFMIs

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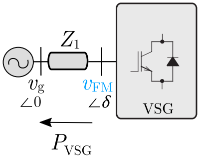

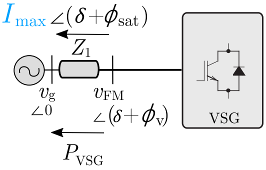

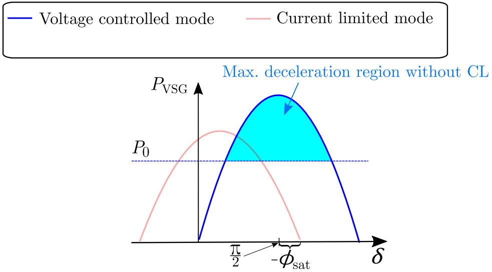

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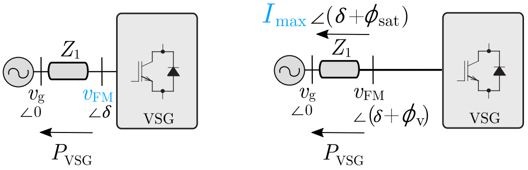

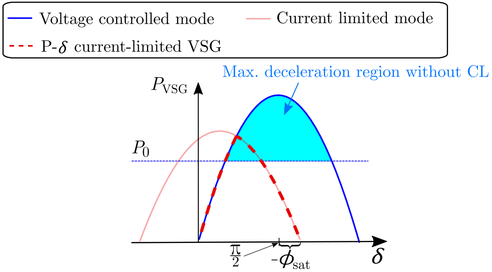

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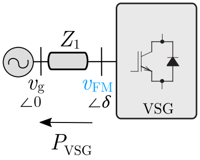

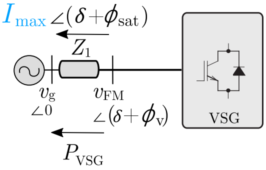

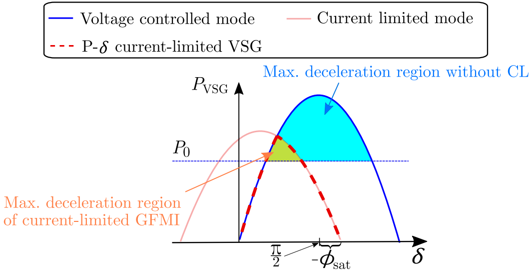

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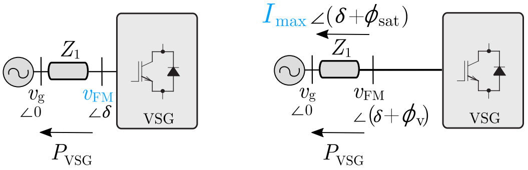

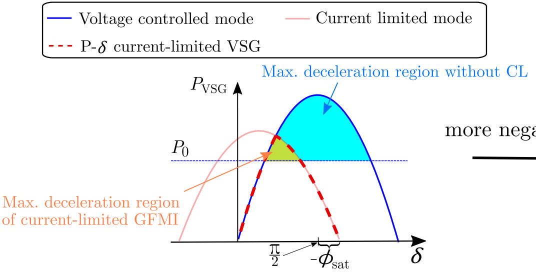

more negative ϕ_{sat} →

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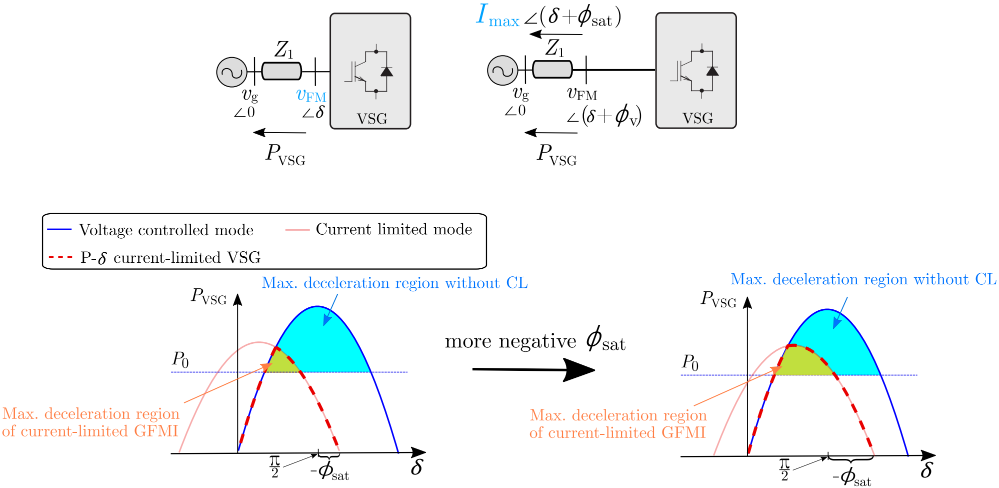
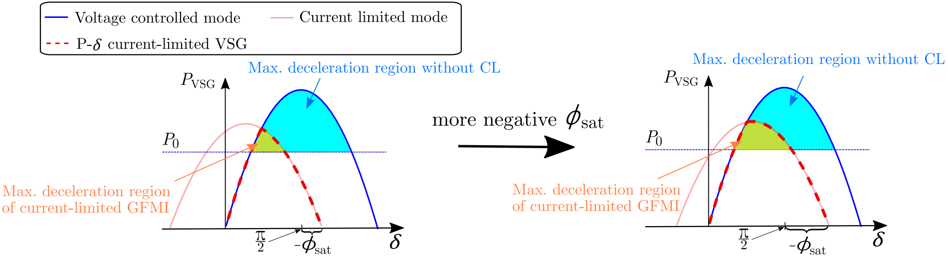


Power-Angle Curve of Current-Limited GFMIs (cont.)



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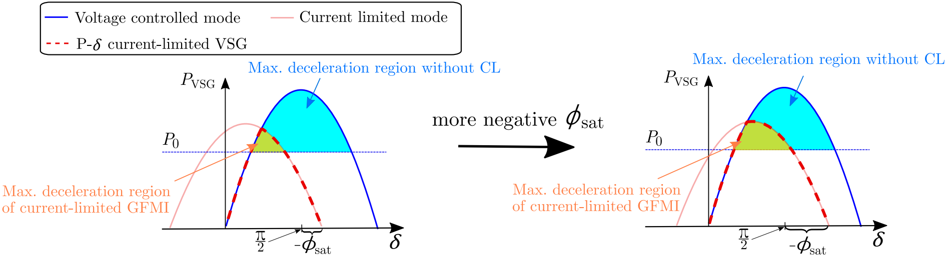

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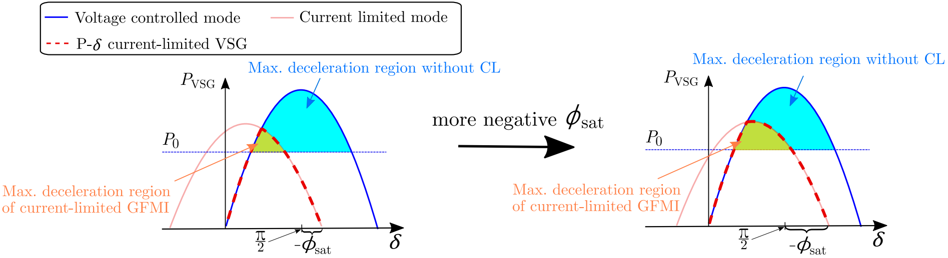

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$$\phi_{\mathrm{sat}} = \tan^{-1}\left(\frac{i_{\mathrm{q}}}{i_{\mathrm{d}}}\right), \tag{1}$$

where i_{d} and i_{q} are d- and -q components of the current, more negative ϕ_{sat} (or i_{q}) results in larger stability margin.

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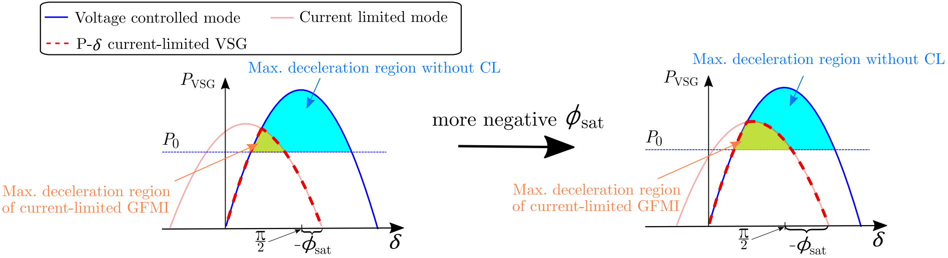
Power-Angle Curve of Current-Limited GFMIs (cont.)



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⇒ q-prioritized CL is studied in this project.

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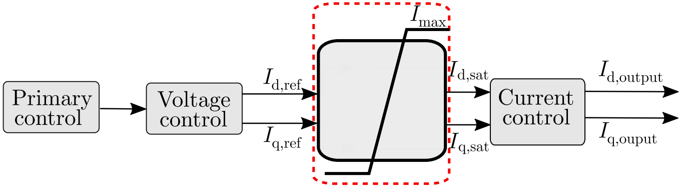
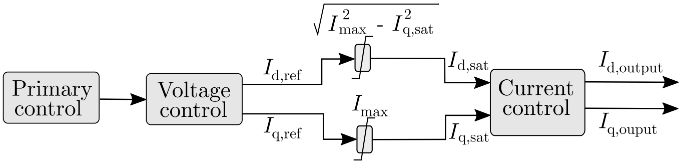
q-prioritized Current-Limited GFMIs



q-prioritized Current-Limited GFMIs



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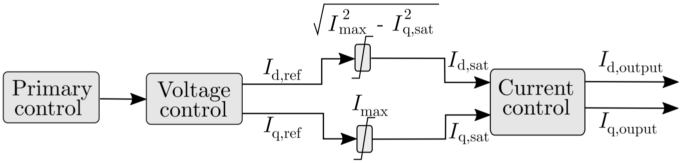
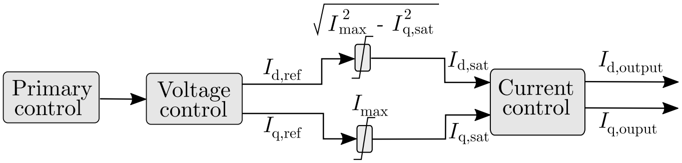


- Derived the P-angle curve of a q-prioritized current-limited GFMI



- Derived the P-angle curve of a q-prioritized current-limited GFMI
- Voltage control loop can contribute to the transient instability.

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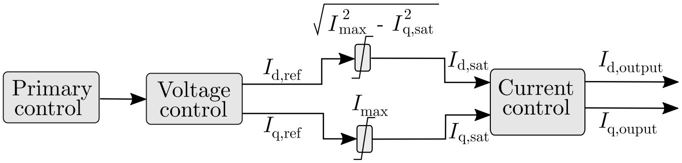

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⇒ Determine the power angle limit of current-limited GFMIs.

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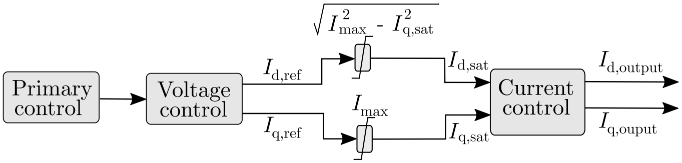

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- Voltage control loop can contribute to the transient instability.

⇒ Determine the power angle limit of current-limited GFMIs.

- Expanded the study to a paralleled system, consisting of a GFMI and a grid-following inverter.

- Analyse and propose remedial methods to improve TS margin of GFMIs:
  - ☐ Implementing freezing mechanism or other anti-windup methods.
  - ☐ Adaptively adjust power setpoint of the GFMI to obtain larger stability margin.
  - ☐ Enhanced q-prioritised current limiter.

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  - ☐ Implementing freezing mechanism or other anti-windup methods.
  - ☐ Adaptively adjust power setpoint of the GFMI to obtain larger stability margin.
  - ☐ Enhanced q-prioritised current limiter.
- Extend the studies to multiple-inverter-based-resource (multi-IBR) networks.
  - ☐ Derive a measurement for transient stability for a multi-IBR network.
  - ☐ Analyse and validate impacts of GFMIs in supporting nearby assets during faults.

Topic 1: Transient Stability of GFMIs
- Current limitation and Transient Stability of GFMIs
- q-prioritized Current-Limited GFMIs

Topic 2: Stability Tools and Analytical Methods

- **Background:**

  ☐ The inverter-based resources in the Australian power network are growing rapidly.

  ☐ Therefore, the ability to maintain the system stability, security, and reliability under operating points variations becomes a challenging task.

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- **Motivation:**

  ☐ To enable system planners/operators to determine the operating point of various IBR.

  ☐ To assess the system stability as the operating condition of the network changes.

Background, Motivation and Objectives

- **Background:**

  ☐ The inverter-based resources in the Australian power network are growing rapidly.

  ☐ Therefore, the ability to maintain the system stability, security, and reliability under operating points variations becomes a challenging task.

- **Motivation:**

  ☐ To enable system planners/operators to determine the operating point of various IBR.

  ☐ To assess the system stability as the operating condition of the network changes.

- **Objectives:**

  ☐ Development of a framework to assess IBR possible operating point region [EPRI].

  ☐ Development of black-boxed stability analysis framework of IBRs considering operating points variation [Monash University].

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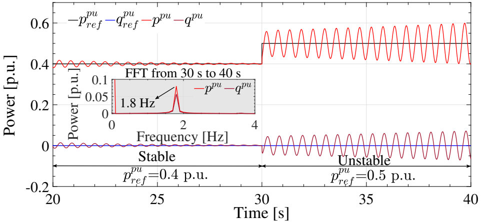
Power Engineering Advanced Research Laboratory [PEARL]

Project outline

- Variations of the operating point may cause instability. For example, increasing the active power from 0.4 p.u. to 0.5 p.u. causes low-frequency oscillation at 1.8 Hz.



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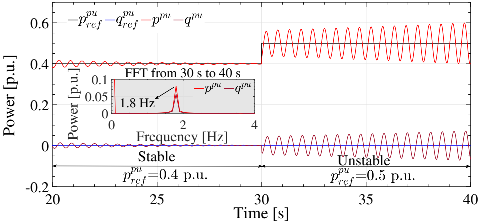
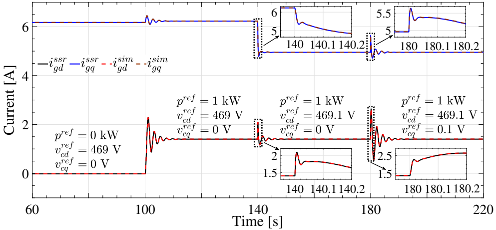


- Therefore, topic 2 aims to
  1. Develop a black-box model for IBRs considering the operating point variations, where the full-order state-space/impedance model should be derived for verification purposes.
  2. Develop power flow scenarios.
  3. Evaluate system strength across an entire region.
  4. Identify the voltage control areas of the region.
  5. Determine priority of active and reactive power injection.

State-space modeling and verification

The active power reference, d-axis voltage reference, and q-axis voltage reference are changed at 100, 140, and 180 s, respectively.



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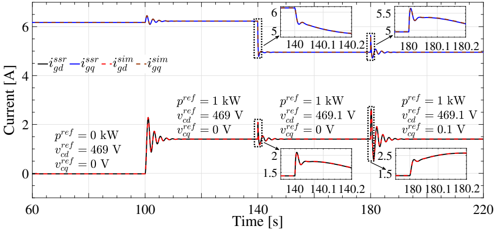
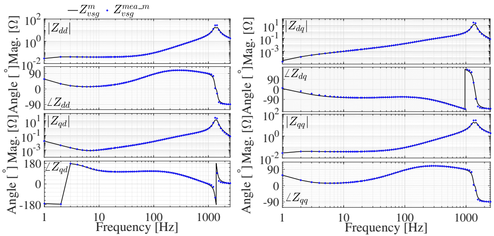


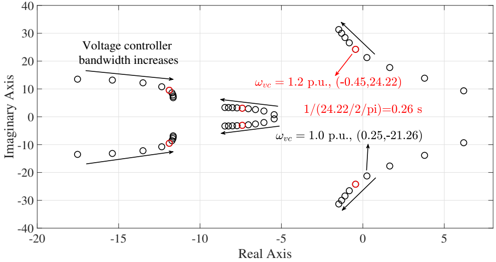
Impedance modeling and verification

Z_{vsg}^{m} and $Z_{vsg}^{mea\_m}$ represent the derived and measured impedance frequency responses, respectively.



Eigenvalues loci of the VSG-Grid system (SCR=3.0) as the voltage controller bandwidth increases

The eigenvalues loci indicates that the system becomes stable of the voltage controller bandwidth increases.



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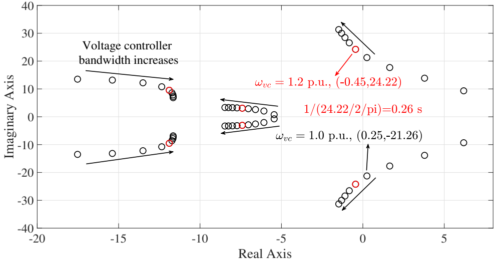
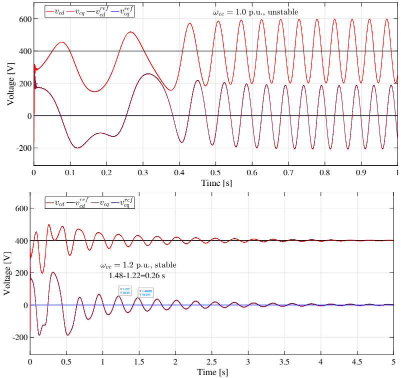


Time-domain verification



- Being undertaken for small-signal stability.
  - Derived and verified the state-space model of the VSG.
  - Derived and verified the impedance model of the VSG.
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- Future works for small-signal stability.
  - Perform the participation factor analysis for the VSG-Grid system.
  - Modify the conventional impedance-based stability criterion of the grid-following inverters for the emerging grid-forming inverters.
  - Develop the small-signal stability enhancement strategies of the VSG by reshaping the derived input impedance.

Thank you for your attention!

Q/A