Transient Stability of Grid-Forming Inverters:

Differences between Grid-Forming Inverters and Synchronous Generators?

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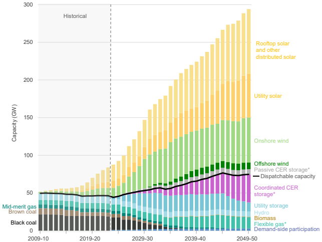
Renewable Energy Resources (RERs)

- Australia: 82% renewable electricity by 2030



Source: Australian Energy Market Operator (AEMO)

Energy Storage Systems (ESSs)

- Increasing deployment to support IBR integration

Source: 65 MW/130 MWh, Smithfield, NSW (Iberdrola Australia)

RER & ESS = Inverter-Based Resources (IBRs)

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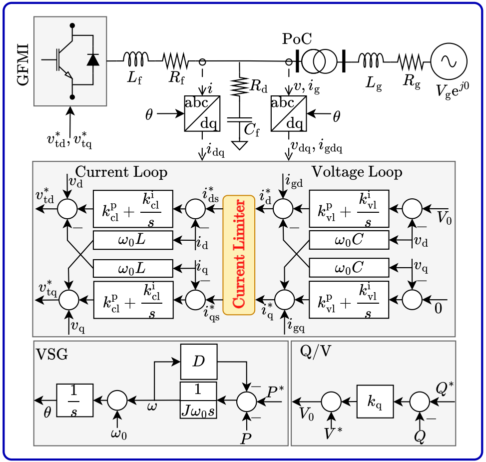
Dual-Cascaded Control for GFMIs

- **Voltage control loop**
  - Regulates the PoC voltage
- **Current control loop**
  - Regulates the terminal current
- **Current Limiter**
  - Protection and fault-ride through



Dual-Cascaded Control

PoC: Point of Connection, GFMI: Grid-Forming Inverter

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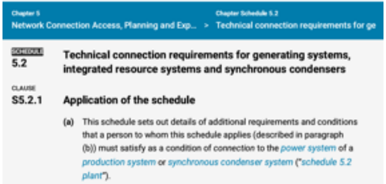
- Fault Ride–Through: IBRs stay connected and support the grid under contingency events.

Grid Code	Typical Requirement
Fault tolerance capability	$\geq$ 430 ms or until events are cleared
Dynamic voltage support	↑ LVRT: 4% of Rea. Cur. over 1% V ↓ HVRT: 6% of Rea. Cur. over 1% V
Fault-current capability	Maximum current capability
Sequence injection	• (+) seq. for symmetrical faults • (−) seq. for asymmetrical faults
Fast fault current support	Settle within 4 cycles

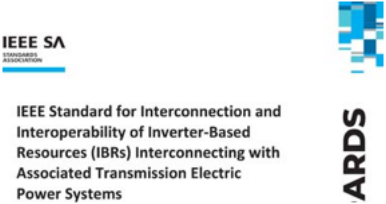

Chapter 5
Network Connection Access, Planning and Exp... > Chapter Schedule 5.2 Technical connection requirements for ge

SCHEDULE 5.2 Technical connection requirements for generating systems, integrated resource systems and synchronous condensers

CLAUSE S5.2.1 Application of the schedule

(a) This schedule sets out details of additional requirements and conditions that a person to whom this schedule applies (described in paragraph (b)) must satisfy as a condition of connection to the power system of a production system or synchronous condenser system ("schedule 5.2 plant").

Australian NER (ver. 243)


IEEE SA STANDARDS ASSOCIATION

IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems

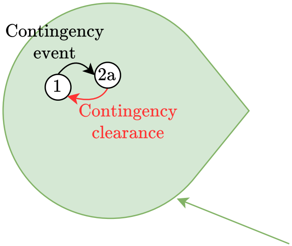
ARDS

IEEE Standard 2800-2022

- Transient Stability: the ability to return to a desired stable equilibrium point after a LARGE contingency.

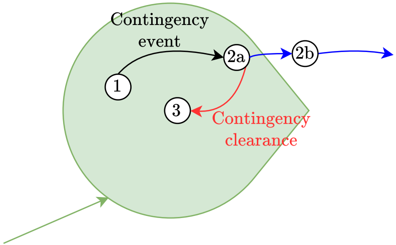
Small-signal stability

- Around one equilibrium point.
- Linearized models



Transient stability

- All equilibrium points.
- Non-linear models.



Stablity margin = Region of Attraction

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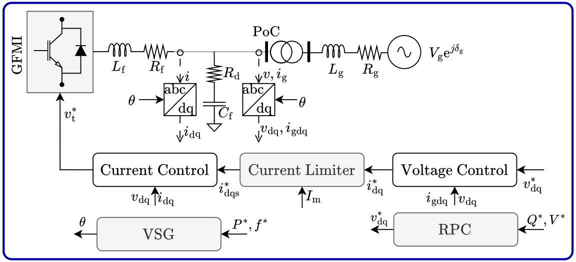
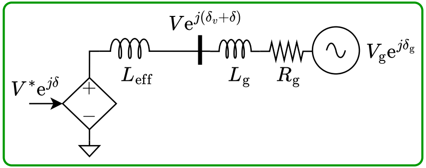
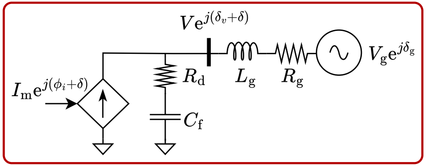
Dual-Cascaded Control Architecture



Current Limiter Inactive



Current Limiter Active



- Current limiter is inactive: a voltage-source mode.
- Current limiter is active: a current-source mode.

VSG: Virtual Synchronous Generator, RPC: Reactive Power Control

- **Distinct dynamics:** GFMIs behave differently from SGs under FAULTS.
- **Modeling gap:** SG models cannot capture GFMI dynamics.
- **Analysis limitations:** Classical SG methods need major revision.

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Research Questions

1. **Transient Dynamic Modeling:** GFMI under FAULTS.
2. **Quantification:** Effect on Stability Margin via White-box vs Black-box
3. **Large-scale system:** GFMI Integration and Stability Margin

GFMI: Grid-Forming Inverter

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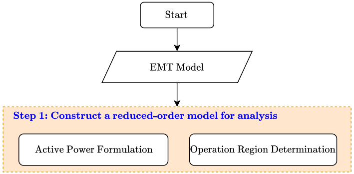

EMT: Electromagnetic Transient

Reduced-order model

$$\dot{\delta} = \omega_0 \, \omega,$$
$$J\omega_0\dot{\omega} = -D\omega + P^* - P(\delta),$$

Active power characteristic

$$P(\delta) = \begin{cases} P_{\mathrm{cum}}(\delta), & \text{current limiter active,} \\ P_{\mathrm{clm}}(\delta), & \text{current limiter inactive,} \end{cases}$$

$$P_{\mathrm{cum}}(\delta) = f(V_{\mathrm{g}}, V^*, X_{\mathrm{g}}, R_{\mathrm{g}}, \delta),$$
$$P_{\mathrm{clm}}(\delta) = g(V_{\mathrm{g}}, I_{\mathrm{m}}, X_{\mathrm{g}}, R_{\mathrm{g}}, \delta).$$

Equilibrium points

- Stable equilibrium (SEP):

$$P_{\mathrm{cum}}(\delta_{\mathrm{e}}) = P^*$$

- Unstable equilibrium (UEP):

$$P_{\mathrm{clm}}(\widehat{\delta}_{\mathrm{e}}) = P^*$$

Estimation of Transient Stability Margin

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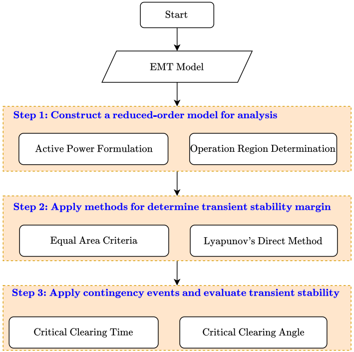
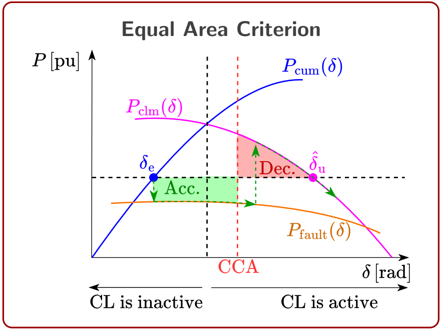
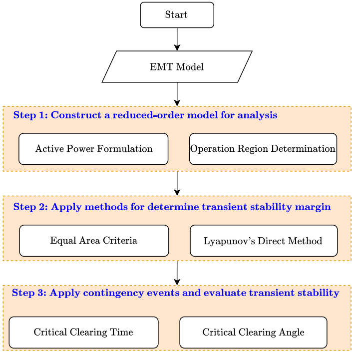


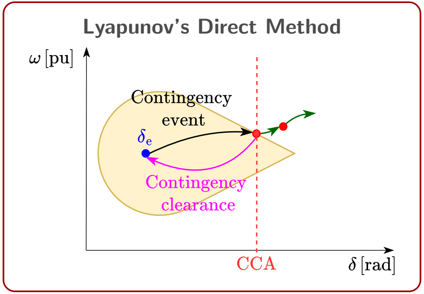


- Neglects damping → valid but conservative.
- Caution required when the current limiter is active.

EMT: Electromagnetic Transient

Estimation of Transient Stability Margin





- Hard to derive Lyapunov-based transient stability margin.
- Considering damping $\rightarrow$ valid and less conservative.

EMT: Electromagnetic Transient

Proposed Framework for GFMI Transient Stability

Grid-Code Check and Enhancement if Required

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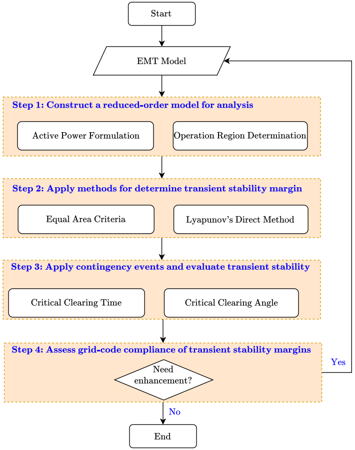


EMT: Electromagnetic Transient

Grid-Code Check:

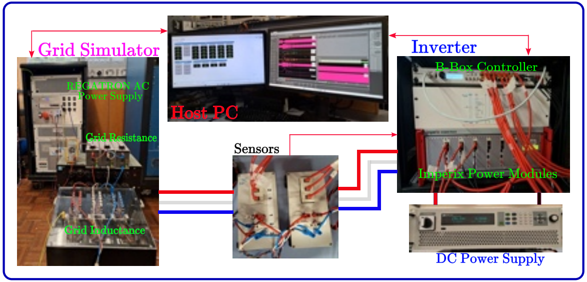
- Tolerate fault up to (e.g., 430 ms)?
  - Yes. Terminate process.
  - No. Let's enhance.

Enhancement methods:

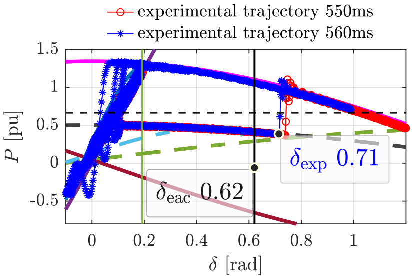
- ✓ Adjust active power reference
- ✓ Temporarily increase inertia and damping
- ✓ Add virtual impedance/admittance
- ✓ Advanced strategies (e.g., *advanced current limiters*)

Experimental Setup

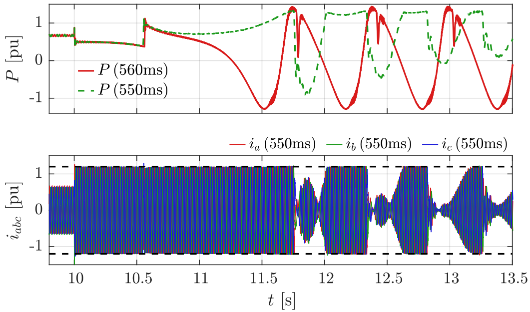
- Regatron AC.TCS: a grid voltage emulator.
- Imperix Inverter (1.5 kVA, 110 V): a GFMI.
- iTECH-500-40 DC Supply.
- Impedance, sensors, and monitoring.



Experimental setup



Estimated Transient Stability Margin



Experimental Response (SCR = 6.3)

- Estimated critical clearing angle: 0.62 rad
- Experimental critical clearing angle: 0.71 rad
- Estimation error: 13%

SCR: Short Circuit Ratio

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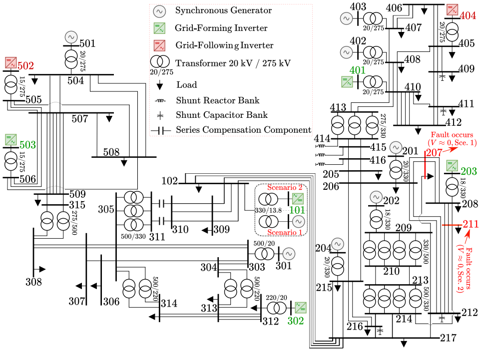
Problem

- Current limiter of GFMIs.
- Nonlinear damping of GFLIs.
- Losses in loads and transmission lines.
- Strong interactions caused by nearby IBRs.

Solution

- Reduced-order model
- Use tools: coherency of IBRs
- Method: Lyapunov's Direct Method



Simplified 14-Generator Australian Power System

GFMI: Grid-Forming Inverter, GFLI: Grid-Following Inverter, IBR: Inverter-Based Resource, VSG: Virtual Synchronous Generator

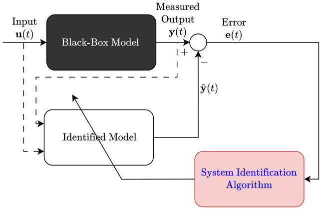
⚠ Problem

- Tools rely on white-box models
- OEM-only access
- Small-signal: impedance scan
- **Transient stability: ???**

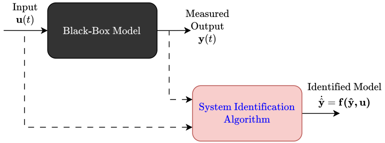
Solution

- Non-linear Black-box identification:
  - Extended Kalman Filter
  - Neural Network-based identification
- Verification via white-box methods:
  - Equal Area Criterion
  - Bifurcation theory

Online Back-Box Identification



Offline Back-Box Identification



Thank you!

Q & A?