Transient Stability of Grid Forming Inverters

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Melbourne, Australia

Part of the GPST/CSIRO Initiative

MONASH University

Power Engineering Advanced Research Laboratory [PEARL]

Project Partners:

Presentation Outline

1-Introduction

2-Transient Stability Analysis of Current-limited Grid-forming Inverters (GFMIs)

3-Enhancing Control

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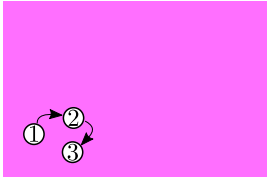
Small-signal stability

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



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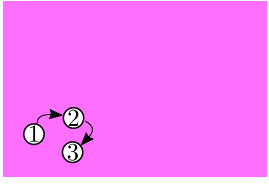
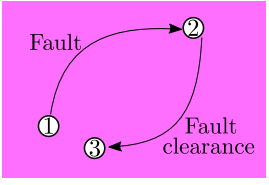


Transient stability

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



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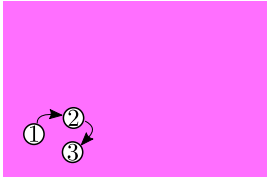

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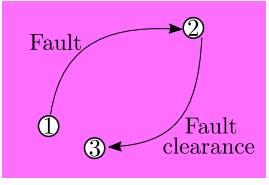

- Inverter-based resources (IBRs) are vulnerable during large-signal disturbances: faults, severe voltage sags, and phase jumps, and it is critical to study their behavior upon such disturbances.

Synchronous Generators vs. GFMIs

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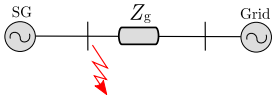
⇒ Always in a **voltage-controlled** mode.



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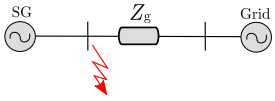

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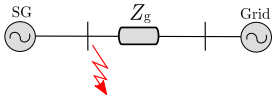

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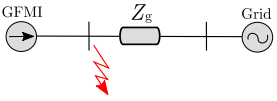
⇒ In a **current-controlled** mode if CL is engaged.



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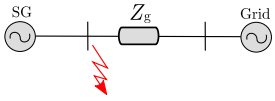

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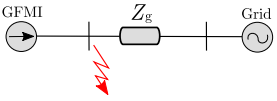

- **Flexible** structure and characteristics.

⇒ **More** flexibility to implement enhancing controls.

- Tools to analyse and estimate transient stability margin of current-limited GFMIs:
  - ☐ Single current-limited GFMI.
  - ☐ Paralleled GFMI-GFLI (without current limiter).
  - ☐ Multi-IBR (4-IBR) (with current limiter).

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- Analyse and propose remedial methods to improve TS margin of GFMIs:
  - ☐ Adaptively adjust power setpoint of GFMIs to obtain larger stability margin.
  - ☐ Enhanced current limiter.

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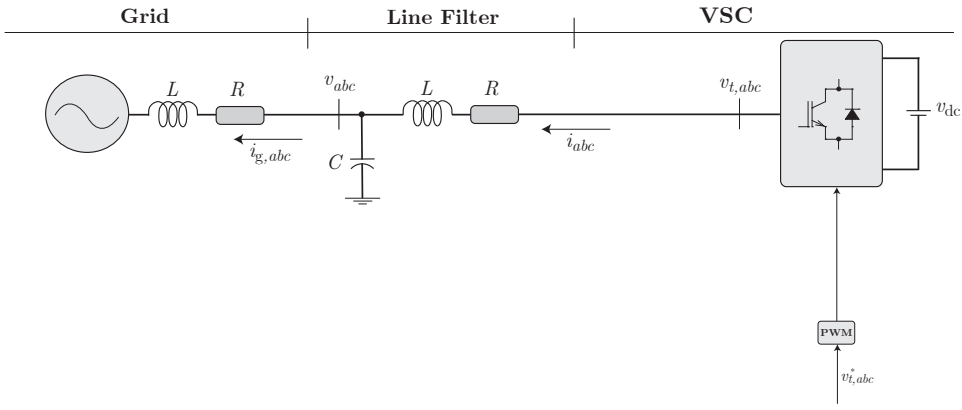
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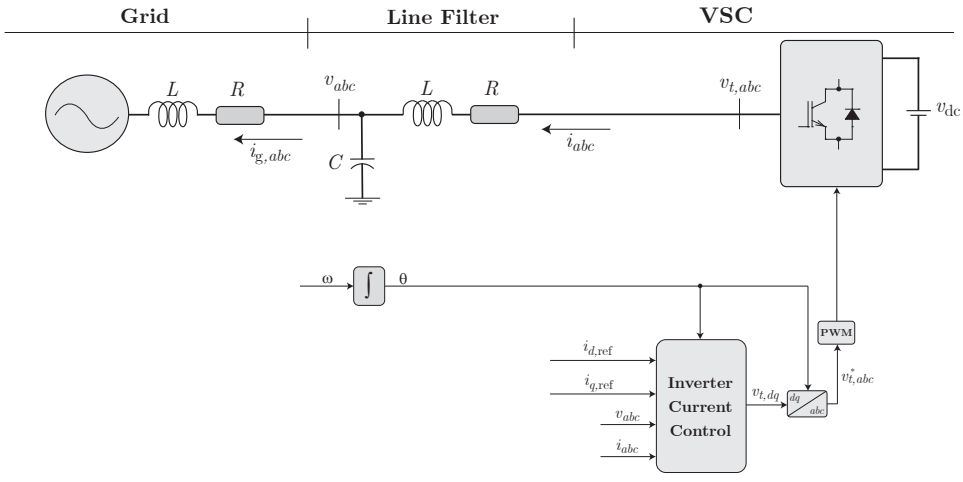
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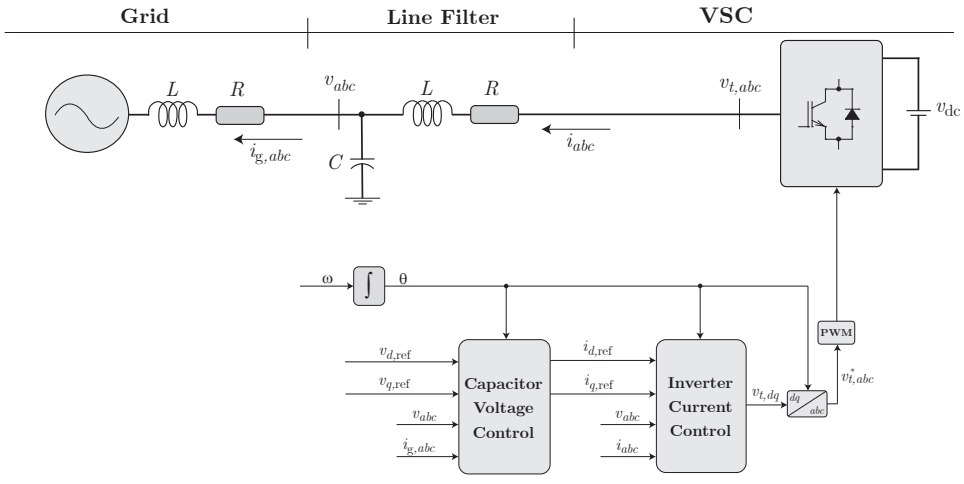
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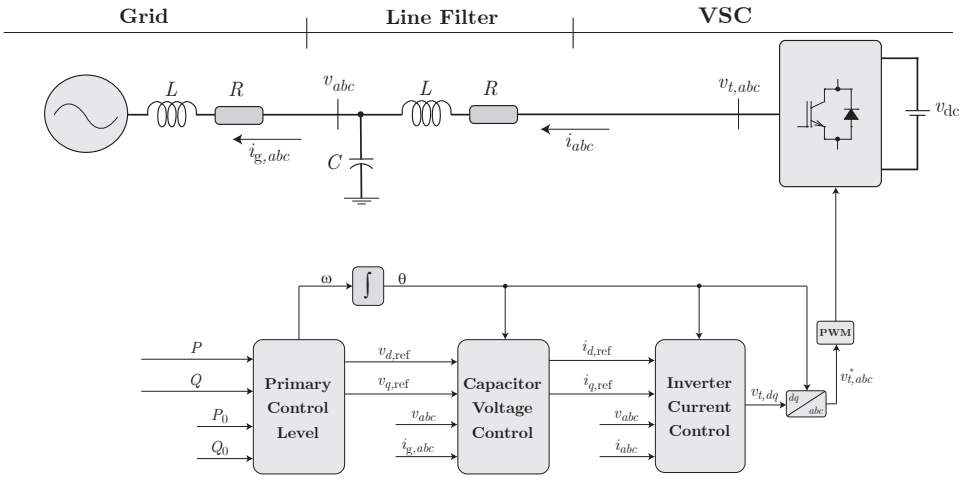
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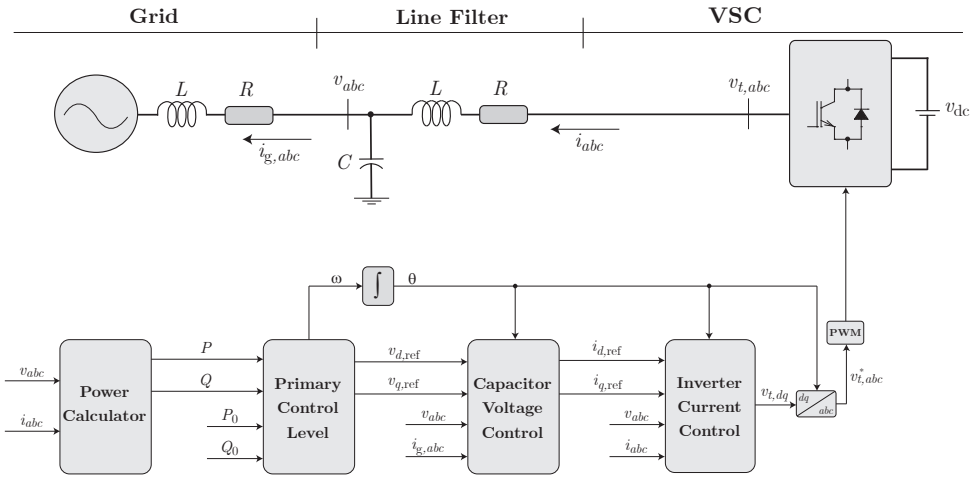
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Types of Current Limiter

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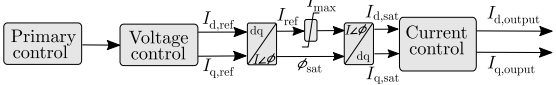

- Each type of current limiters impacts the transient stability differently.

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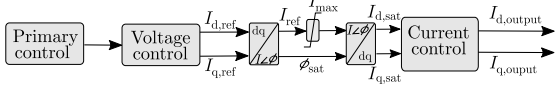

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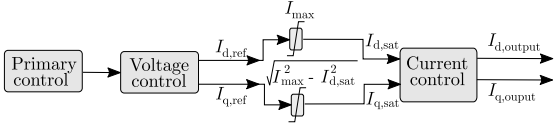

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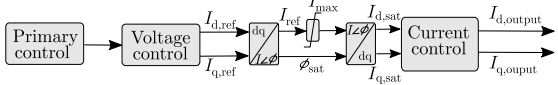

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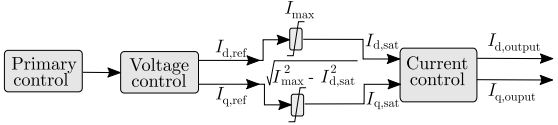
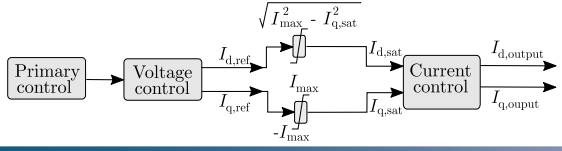


3- Quadrature- (q-) prioritized limiter:



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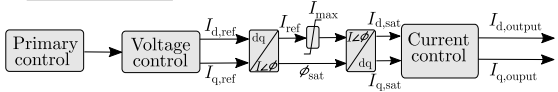

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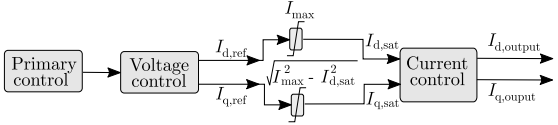

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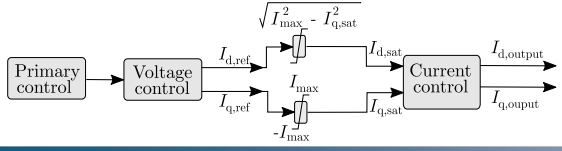

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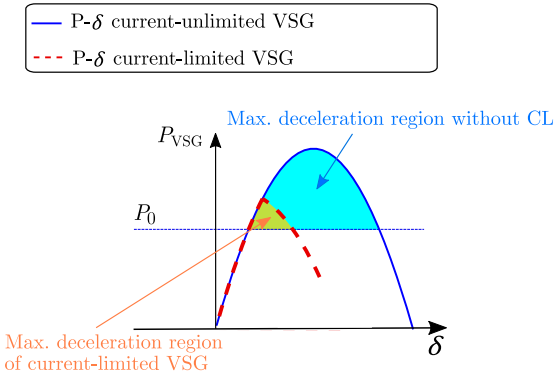
⇒ We studied q-prioritised limiter due to the requirement on reactive current.

Single Current-Limited GFMI: stability of power-angle control



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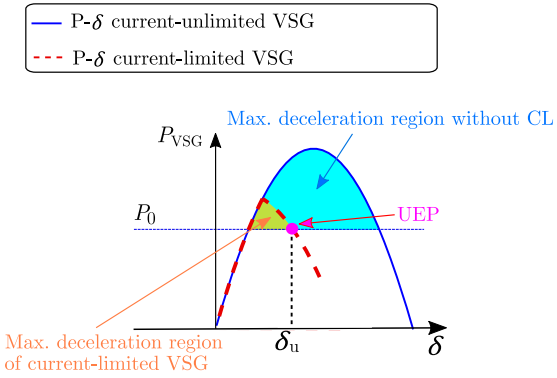

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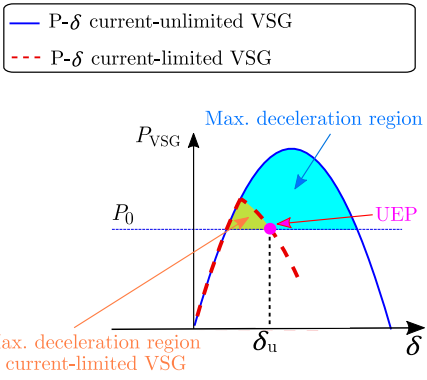

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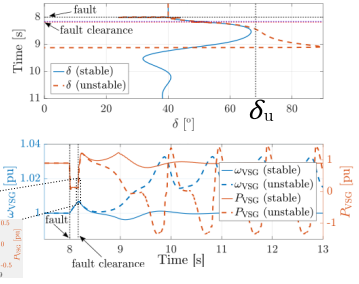

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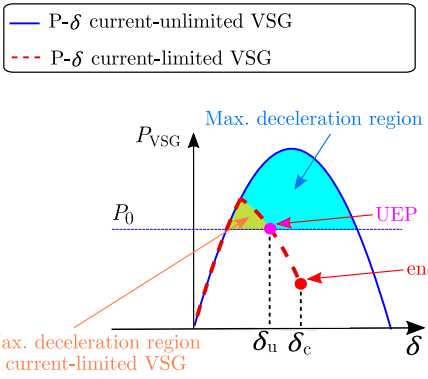

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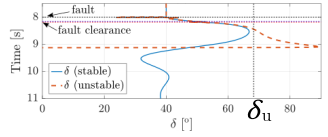
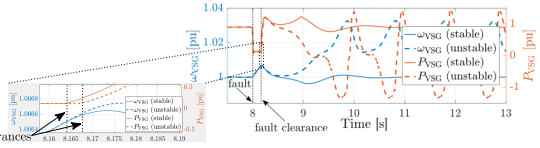
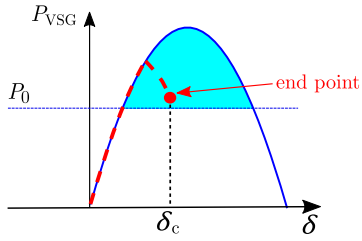




Single Current-Limited GFMI: stability of voltage control

P-δ current-unlimited VSG
P-δ current-limited VSG



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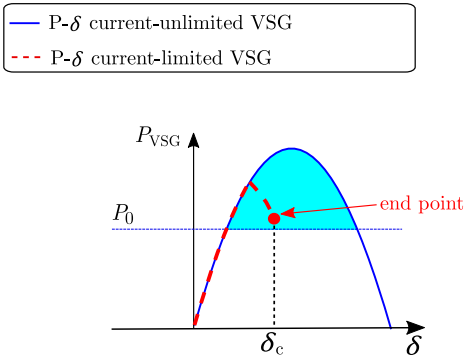
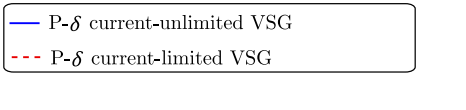
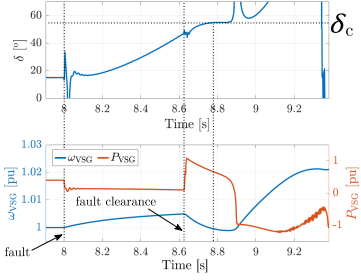


- The end point is caused by the loss of stability in the voltage control loop.



Time-domain response of an unstable case, δ_{c} is exceeded



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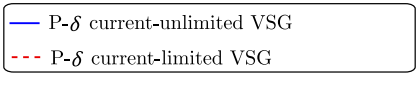

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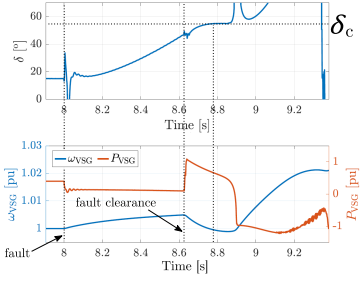
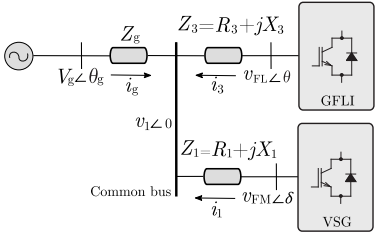


- The end point is caused by the loss of stability in the voltage control loop.
- A stability criterion for the transient stability of the voltage control is available in:

S. P. Me, at el., "*Transient Stability Analysis of Virtual Synchronous Generator Equipped with Quadrature-Prioritized Current Limiter*". IEEE Transactions on Power Electronics, 2023.

Paralleled Grid-following inverter (GFLI)-GFMI: system diagram



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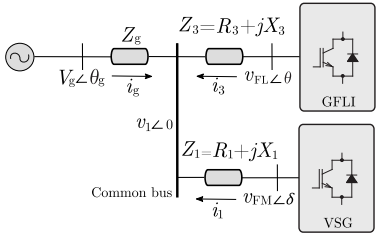
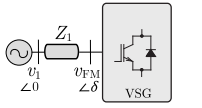
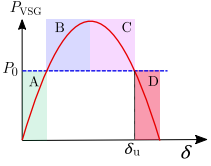


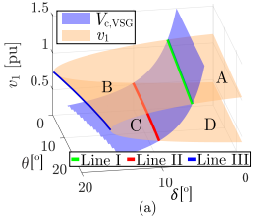
- A virtual synchronous generator (VSG).
- A grid-following inverter (GFLI).
- A common bus between the VSG and the GFLI.
- An infinite bus.
- Transmission lines emulated by impedance.

Paralleled GFLI-GFMI: stability boundaries.



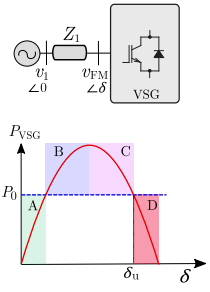


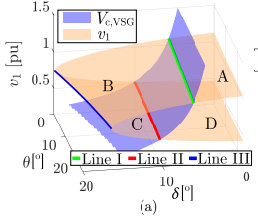
(a) Stability boundary of the VSG.



(a)

Paralleled GFLI-GFMI: stability boundaries.





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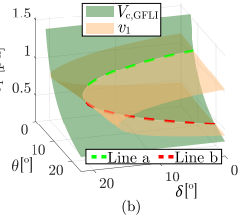
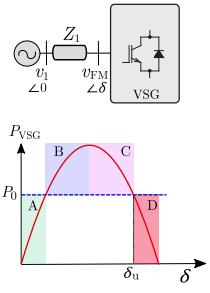
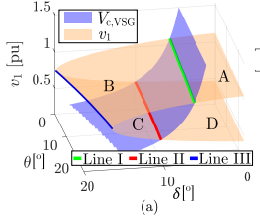


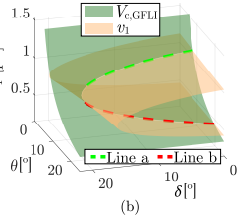
(b) Stability boundary of the GFLI.

Paralleled GFLI-GFMI: stability boundaries.



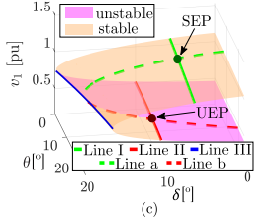
(a) Stability boundary of the VSG.





(b) Stability boundary of the GFLI.

(c) Stability boundaries of the VSG-GFLI system.



Transient Stability Analysis of Current-limited GFMIs

Paralleled GFLI-GFMI: stability boundaries.

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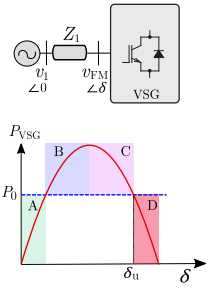
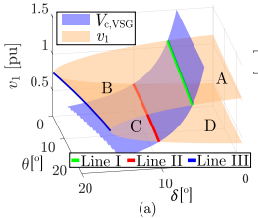
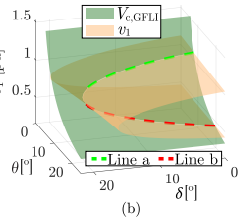
Power Engineering Advanced Research Laboratory [PEARL]

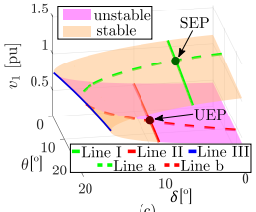




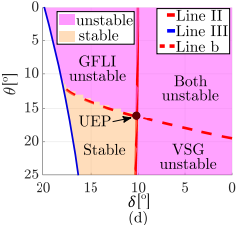
(a) Stability boundary of the VSG.



(b) Stability boundary of the GFLI.



(c) Stability boundaries of the VSG-GFLI system.



(d) 2-D top view of the stability boundaries.

Paralleled GFLI-GFMI: summary

- Quickly show transient stability boundaries of the paralleled system.
- Obtain stability margin of the paralleled system.

Paralleled GFLI-GFMI: summary

- Quickly show transient stability boundaries of the paralleled system.
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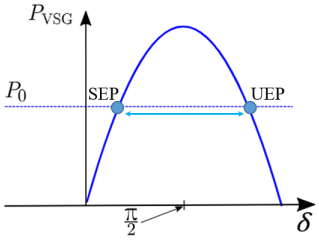
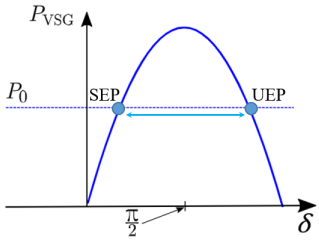
Paralleled GFLI-GFMI: summary

- Quickly show transient stability boundaries of the paralleled system.
- Obtain stability margin of the paralleled system.
- No requirement of solving differential equations or conducting integration.
- Potential to extend to multi-IBR system.
- More details are available in: S. P. Me, M. H. Ravanji, M. Z. Mansour, S. Zabihi and B. Bahrani, "*Transient Stability of Paralleled Virtual Synchronous Generator and Grid-following Inverter*," in IEEE Transactions on Smart Grid, doi: 10.1109/TSG.2023.3255168.



- The operating point is at the stable equilibrium point (SEP) in a normal operation.

Multi-IBR system: distance between SEP and UEP



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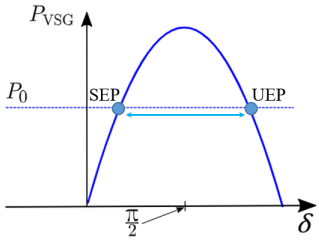

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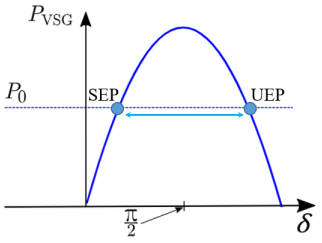

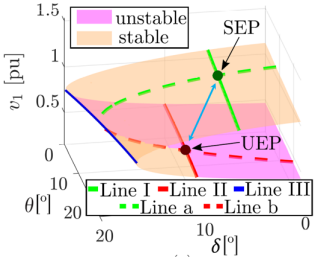

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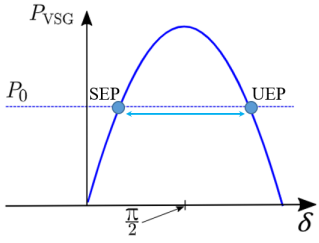

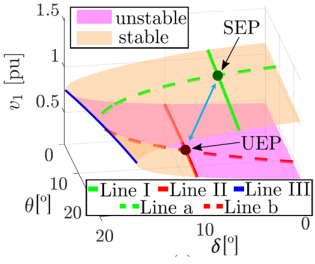

- The operating point is at the stable equilibrium point (SEP) in a normal operation.
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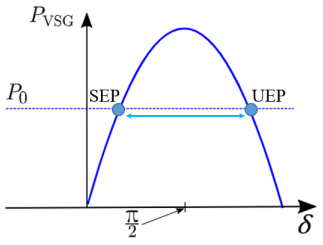
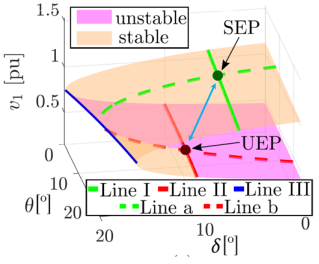
- The further the SEP is away from the UEP, the more stable the system is.
- Measure the distance between the SEP and UEP of a multi-IBR system and use it as a stability margin indicator.

Multi-IBR system: distance between SEP and UEP





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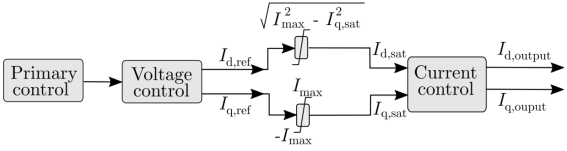
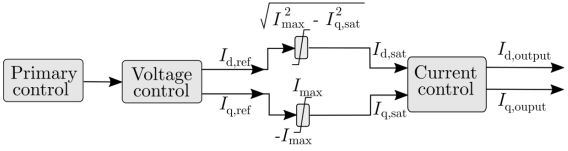
- Measure the distance between the SEP and UEP of a multi-IBR system and use it as a stability margin indicator.

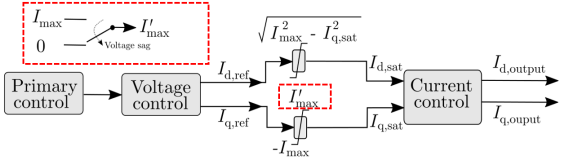
  $\Rightarrow$ Beneficial for system design and operation.

Presentation Outline



- A conventional q-CL makes voltage controller prone to instability.

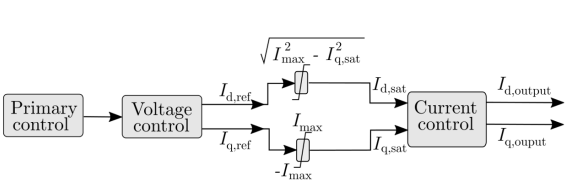


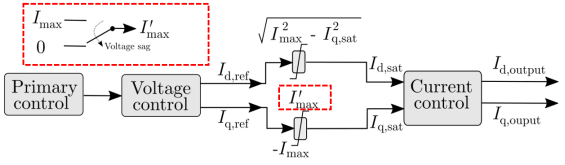


- A conventional q-CL makes voltage controller prone to instability.

- The upper limit of the q-current is set to zero during voltage sags.
- Prevent the voltage control loop from entering a positive feedback mode.

  $\Rightarrow$ Prevent the instability caused by the failure of the voltage loop.





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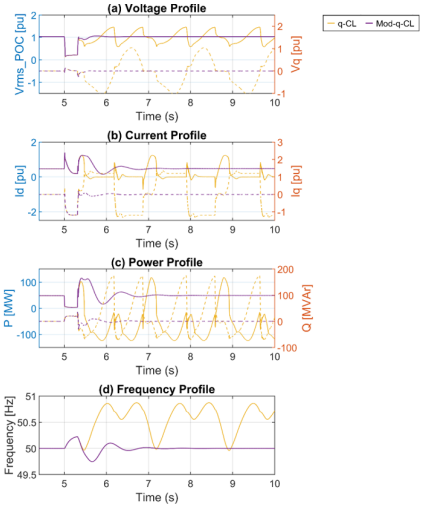
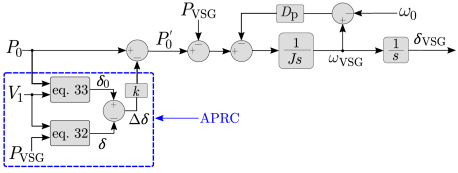
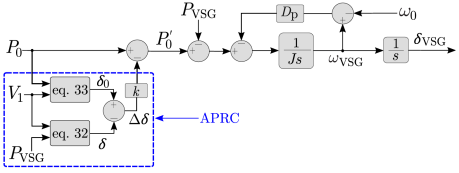
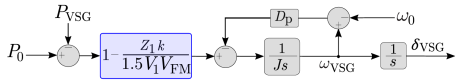
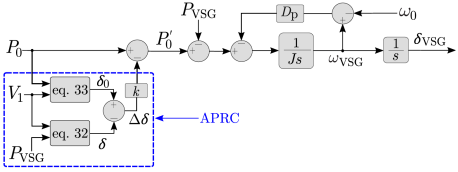

(a) Voltage Profile
q-CL
Mod-q-CL
Vrms_POC [pu]
Vq [pu]
Time (s)
(b) Current Profile
Id [pu]
Iq [pu]
Time (s)
(c) Power Profile
P [MW]
Q [MVAr]
Time (s)
(d) Frequency Profile
Frequency [Hz]
Time (s)

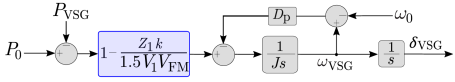

P_{VSG}
D_{p}
ω_0
P_0
P_0'
$\frac{1}{Js}$
ω_{VSG}
$\frac{1}{s}$
δ_{VSG}
V_1
eq. 33
δ_0
k
$\Delta\delta$
APRC
eq. 32
δ
P_{VSG}



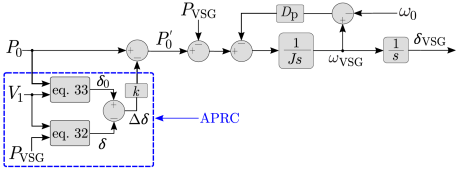


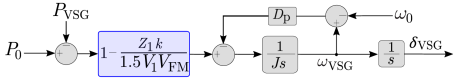
- Equivalent to **reducing droop gain** during voltage sag.



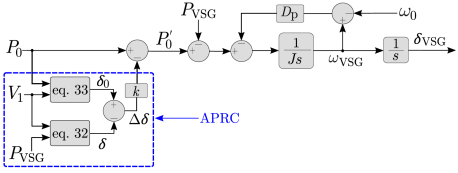


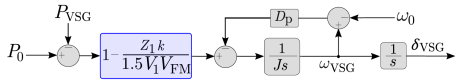
- Equivalent to **reducing droop gain** during voltage sag.
- The **damping** of the active power controller (APC) of the VSG is **improved** by the APRC.





- Equivalent to **reducing droop gain** during voltage sag.
- The **damping** of the active power controller (APC) of the VSG is **improved** by the APRC.
- Active **only during voltage sags** to avoid interfering with other controllers, e.g., governor.

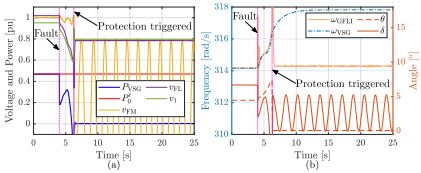




- Equivalent to **reducing droop gain** during voltage sag.
- The **damping** of the active power controller (APC) of the VSG is **improved** by the APRC.
- Active **only during voltage sags** to avoid interfering with other controllers, e.g., governor.

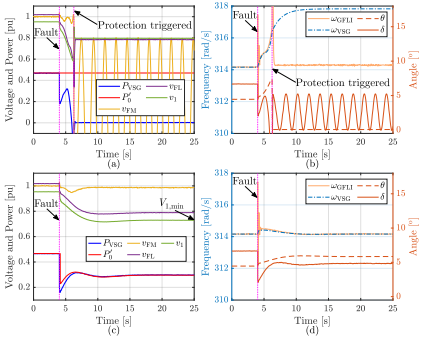
  $\Rightarrow$ Keep the system in its stable operating region, even when no SEP exists.

Without the APRC:



Without the APRC:

With the APRC:

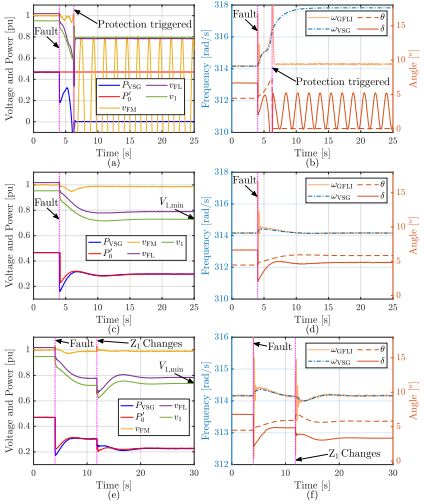


APRC: validations - without any SEP

Without the APRC:

With the APRC:

With the APRC and a line tripping:



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Summary

- Transient stability of GFMIs is negatively impacted by the current limiter.
- In q-prioritised current-limited GFMIs, excessive power angle growth can lead to instability of the voltage loop.
- Analysis tools are developed to quickly estimate stability limits and margin of:
  - ☐ a single GFMI,
  - ☐ a paralleled GFMI-GFLI system,
  - ☐ and a multi-IBR system.
- Based on these analyses, enhancing control solutions are proposed to extend stability margin GFMI and the connected systems.

Thank you for your attention!

Q/A