



Transient Stability of Grid Forming Inverters

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Melbourne, Australia





Project Partners:



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ELECTRIC POWER
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1-Introduction

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

3-Enhancing Control



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

3-Enhancing Control

Transient Stability and Fault-ride Through

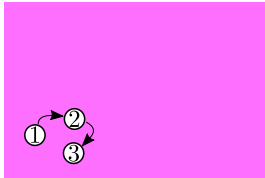
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Small-signal stability

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

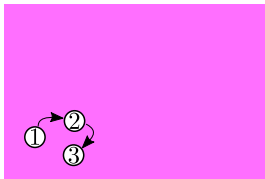


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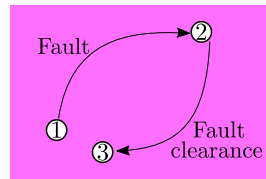
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Transient stability

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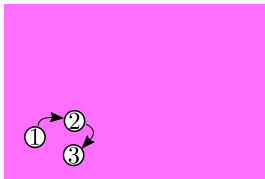


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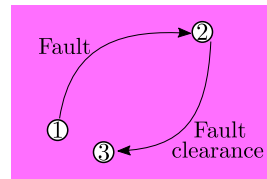
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- Inverter-based resources (IBRs) are **vulnerable** during large-signal disturbances: **faults, severe voltage sags**, and phase jumps, and it is critical to study their behavior upon such disturbances.

Synchronous Generators vs. GFMs

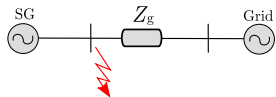
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- ⇒ **No current limitation** is required.
- ⇒ Always in a **voltage-controlled** mode.

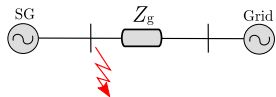


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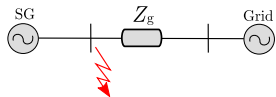
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- ⇒ **Less flexibility** to implement enhancing controls.

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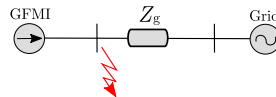
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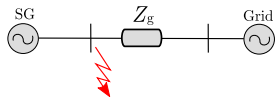


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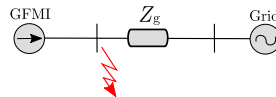
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Transient Stability Analysis and Enhancement of Current-limited GFMI

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

Transient Stability Analysis and Enhancement of Current-limited GFMs

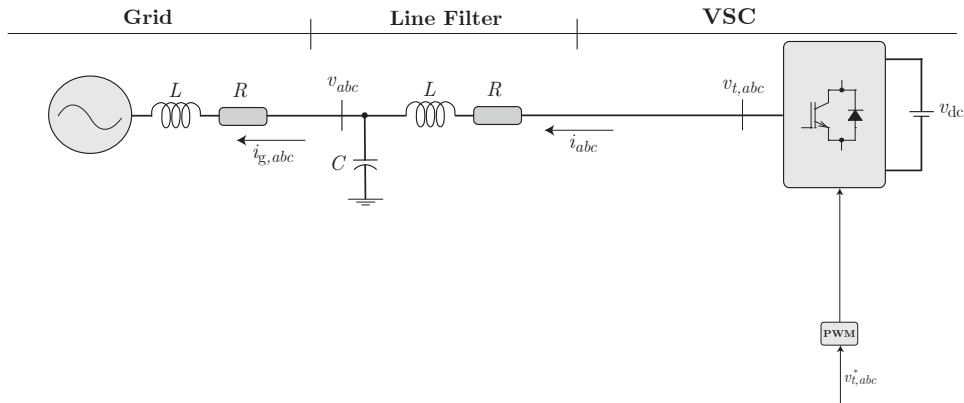
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 - ☐ Multi-IBR (4-IBR) (with current limiter).
- Analyse and propose **remedial methods** to improve TS margin of GFMs:
 - ☐ Adaptively **adjust power setpoint** of GFMs to obtain larger stability margin.
 - ☐ **Enhanced** current limiter.

1-Introduction

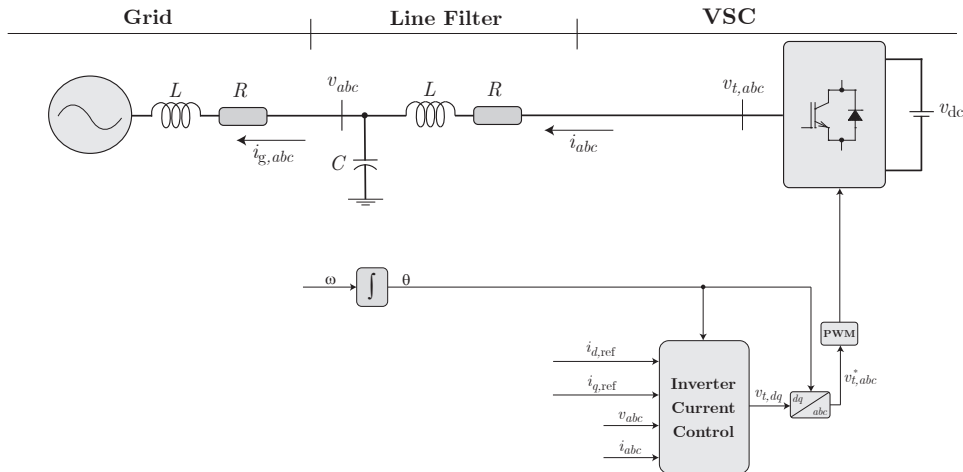
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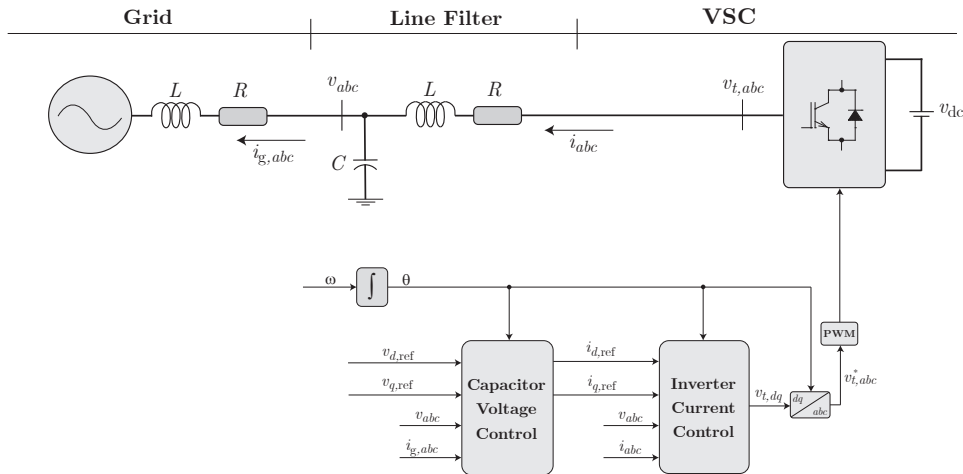
Generic Control Structure



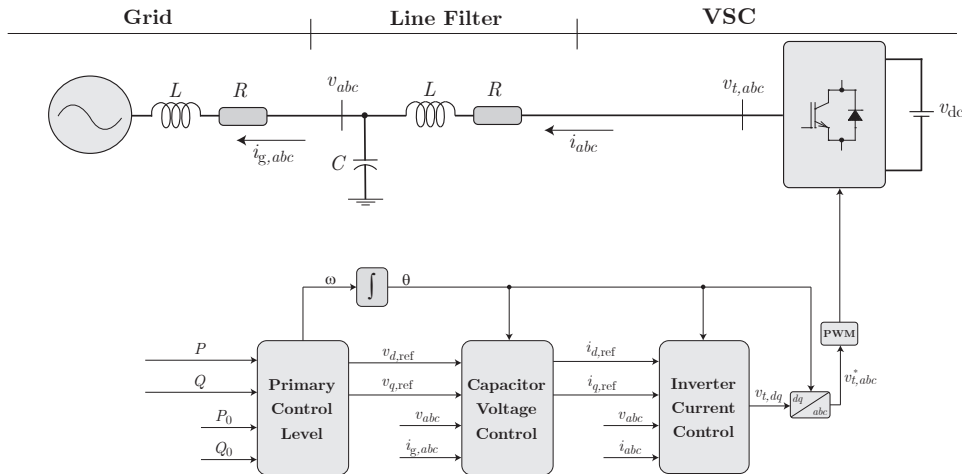
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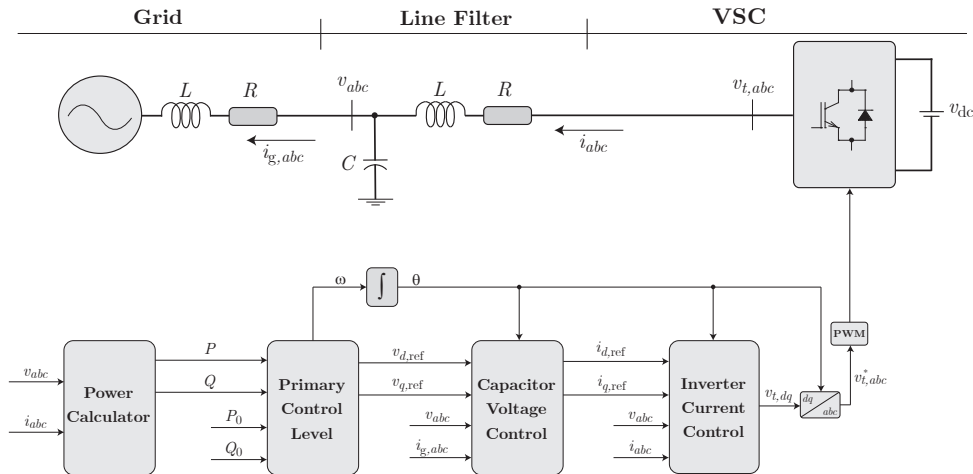


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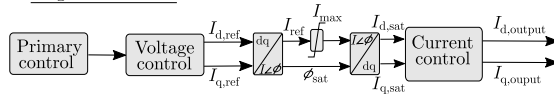
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Types of Current Limiter

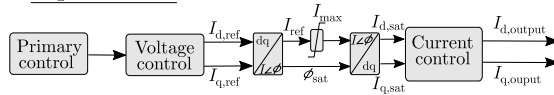
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- Each type of current limiters impacts the transient stability differently.

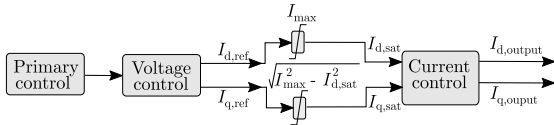
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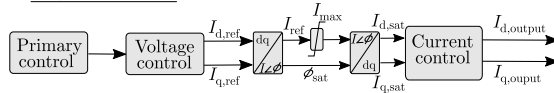
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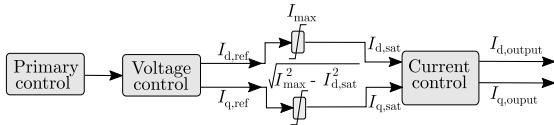


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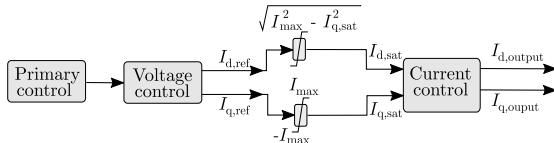
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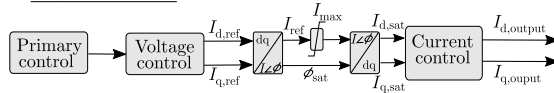
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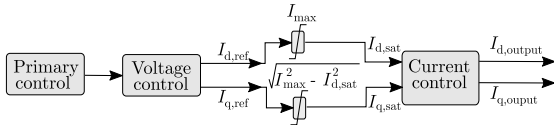
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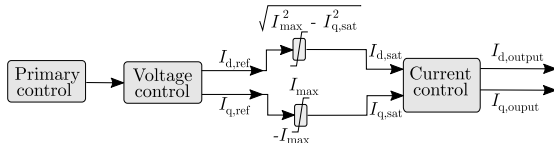
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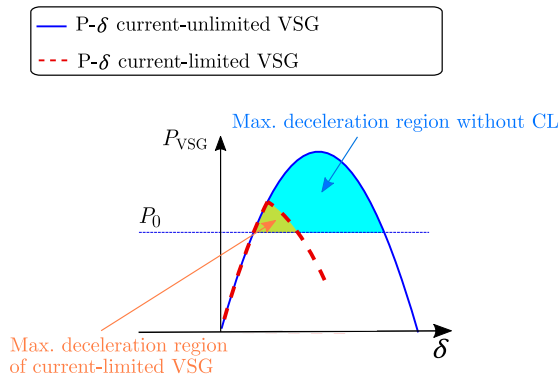
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⇒ We studied **q-prioritised limiter** due to the requirement on **reactive current**.

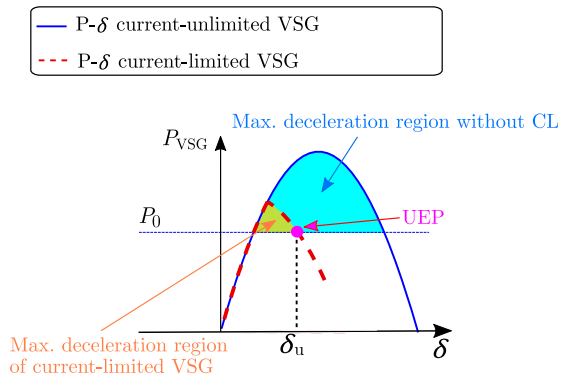
Single Current-Limited GFMI: stability of power-angle control



VSG: Virtual synchronous generator.

UEP: Unstable equilibrium point.

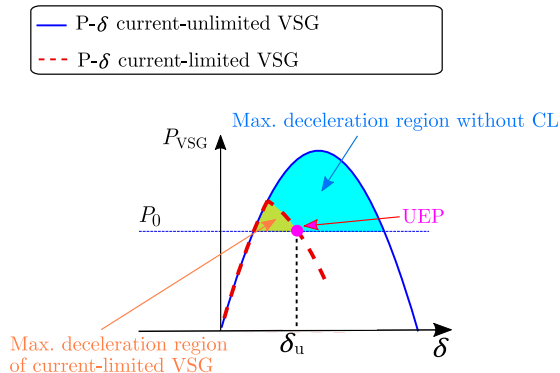
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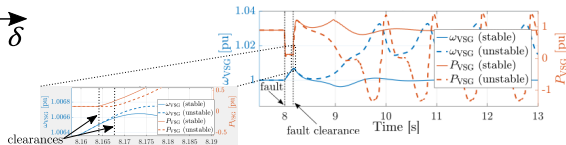
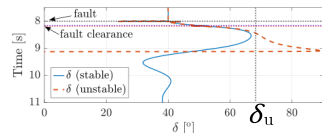
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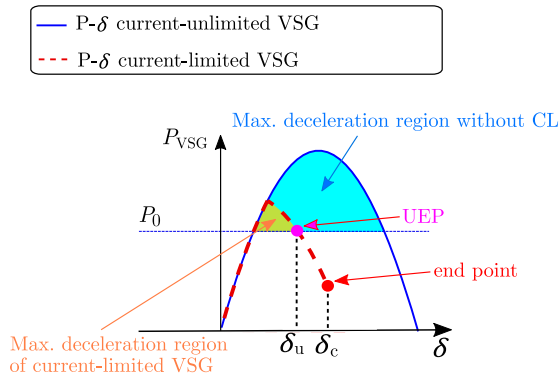
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- a **stable** case (shorter fault duration)
 δ_u is not exceeded
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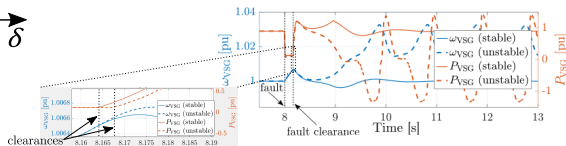
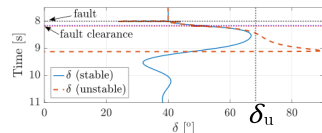
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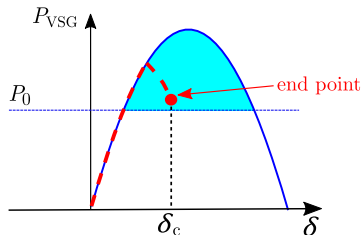
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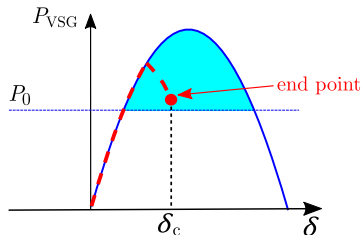
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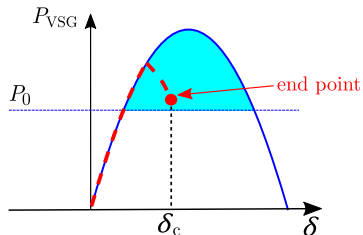
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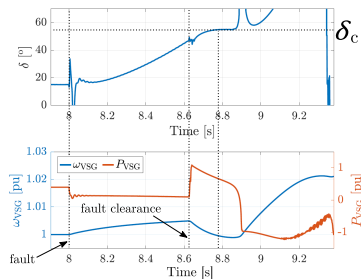
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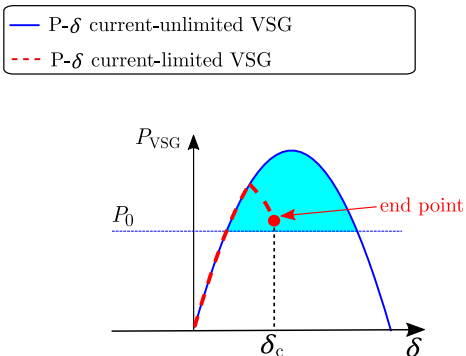


Time-domain response of an unstable case,
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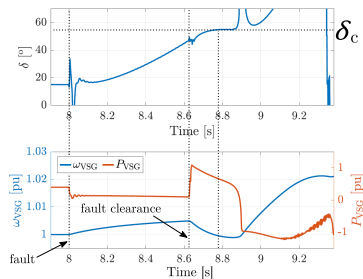


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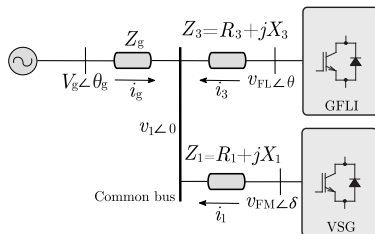
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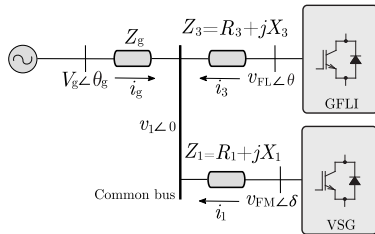
- The end point is caused by the loss of stability in the **voltage control loop**.
- A stability criterion for the transient stability of the voltage control is available in:

S. P. Me, et al., "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

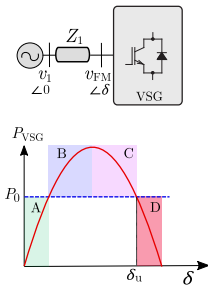


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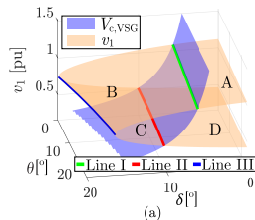


- A virtual synchronous generator (VSG).
- A grid-following inverter (GFLI).
- A common bus between the VSG and the GFLI.
- An infinite bus.
- Transmission lines emulated by impedance.

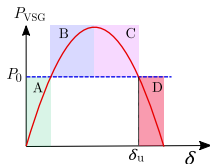
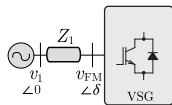
Paralleled GFLI-GFMI: stability boundaries.



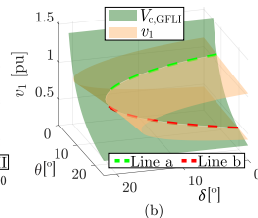
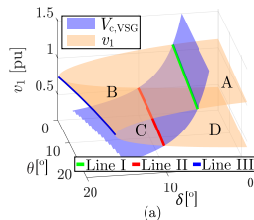
(a) Stability boundary of the VSG.



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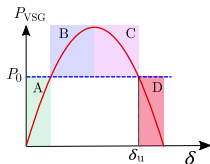
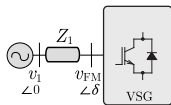
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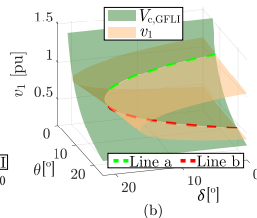
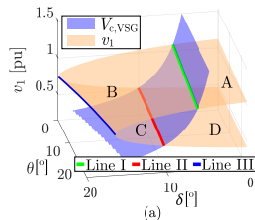
(b) Stability boundary of the GFLI.

Transient Stability Analysis of Current-limited GFMI

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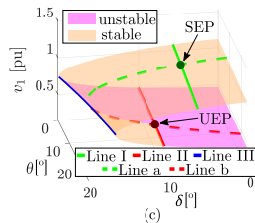


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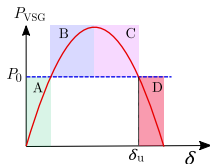
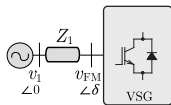
(b) Stability boundary of the GFLI.

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

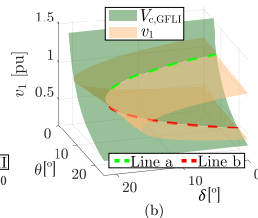
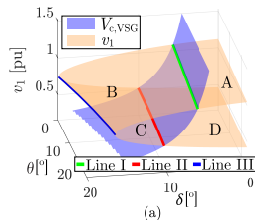


Transient Stability Analysis of Current-limited GFMI

Paralleled GFLI-GFMI: stability boundaries.

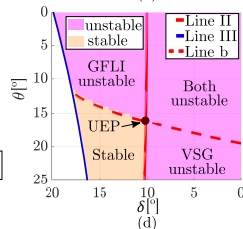
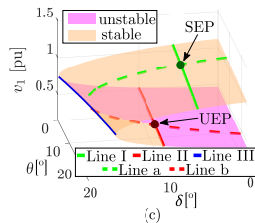


(a) Stability boundary of the VSG.



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(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.

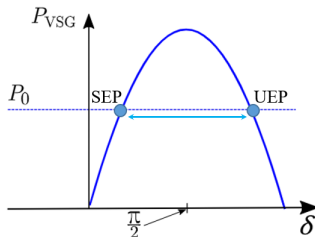
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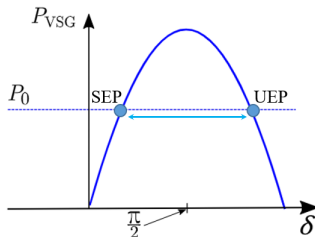
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- Potential to extend to multi-IBR system.
- More details are available in: S. P. Me, M. H. Ravanji, M. Z. Mansour, S. Zabihi and B. Bahrani, " *Transient Stability of Paralleled Virtual Synchronous Generator and Grid-following Inverter*," in IEEE Transactions on Smart Grid, doi: 10.1109/TSG.2023.3255168.

Multi-IBR system: distance between SEP and UEP



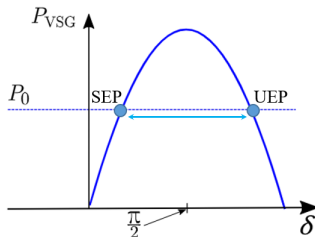
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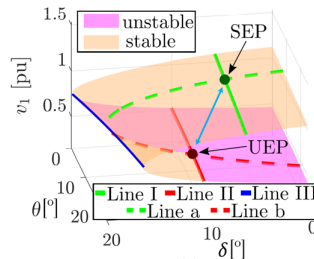
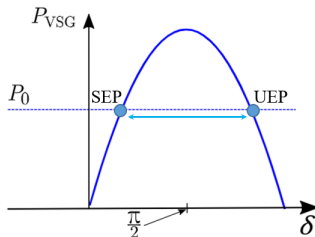
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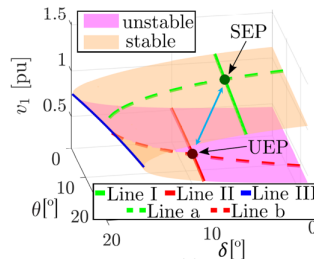
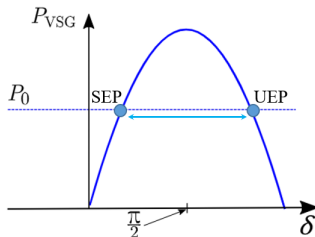
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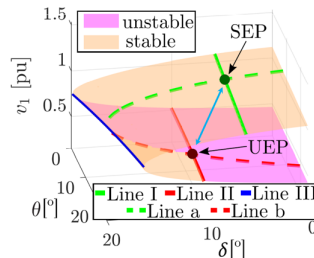
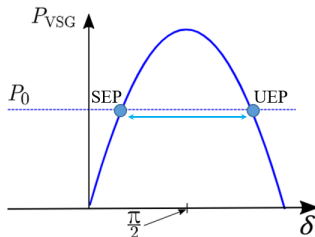
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- ⇒ **Beneficial for system design and operation.**

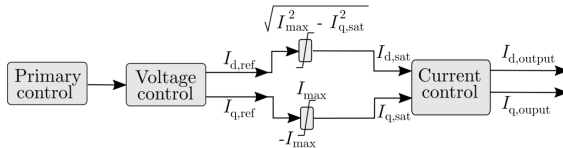


1-Introduction

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

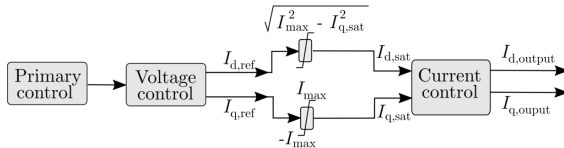
3-Enhancing Control

Modified q-prioritised Current Limiter (mod-q-CL)

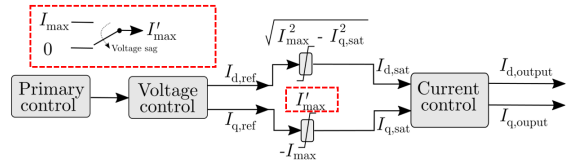


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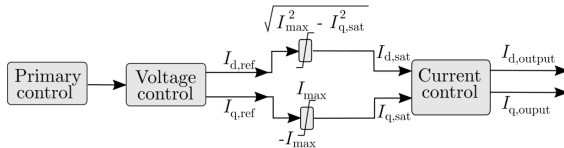


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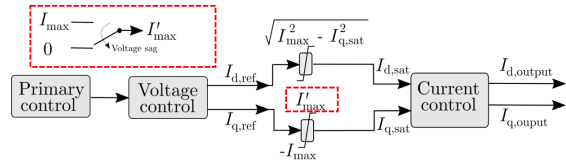


- The **upper limit** of the q-current is set to zero during voltage sags.
- **Prevent** the voltage control loop from entering a **positive feedback mode**.
⇒ **Prevent the instability caused by the failure of the voltage loop.**

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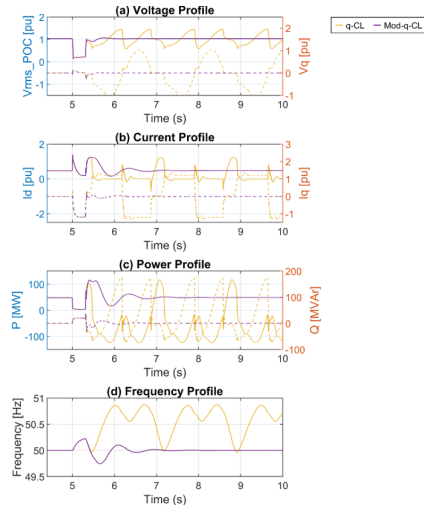


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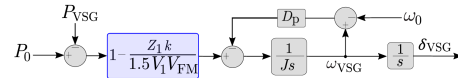
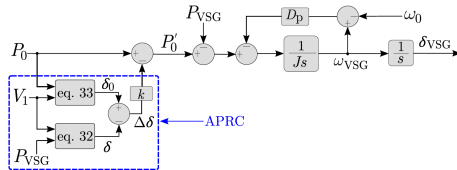
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- More details are available in: S. P. Me, et al., "Transient Stability Analysis of Virtual Synchronous Generator Equipped with Quadrature-Prioritized Current Limiter". IEEE Transactions on Power Electronics, 2023.

Modified q-prioritised Current Limiter (mod-q-CL): validation

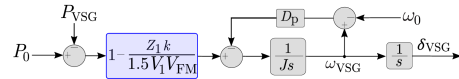




Adaptive Power Reference Control (APRC)

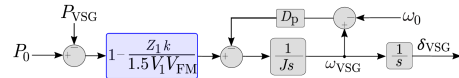
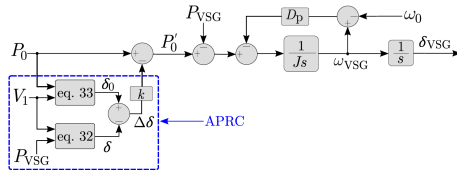


- Equivalent to **reducing droop gain** during voltage sag.



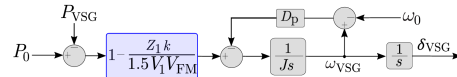
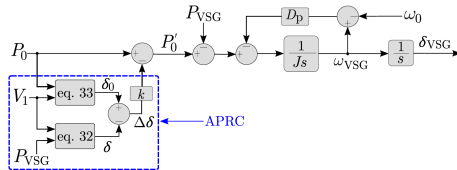
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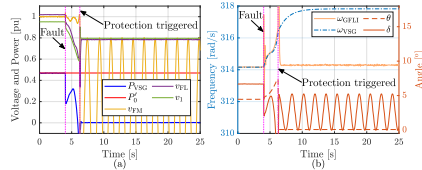
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 - The **damping** of the active power controller (APC) of the VSG is **improved** by the APRC.
 - Active **only during voltage sags** to avoid interfering with other controllers, e.g., governor.
- ⇒ **Keep the system in its stable operating region, even when no SEP exists.**

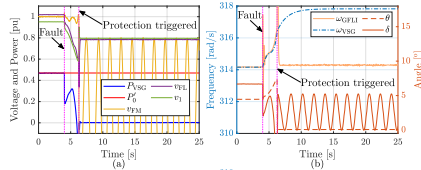
APRC: validations - without any SEP

Without the APRC:

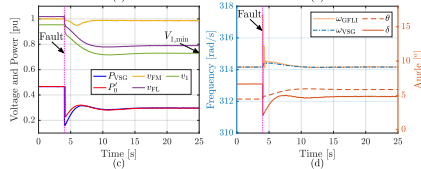


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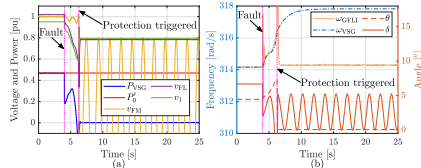


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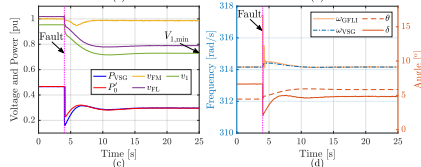


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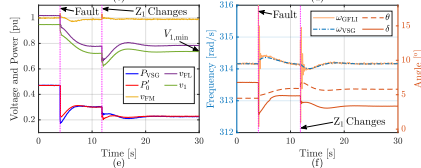
Without the APRC:



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With the APRC and a line tripping:



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Summary

- Transient stability of GFMI is negatively impacted by the current limiter.
- In q-prioritised current-limited GFMI, 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