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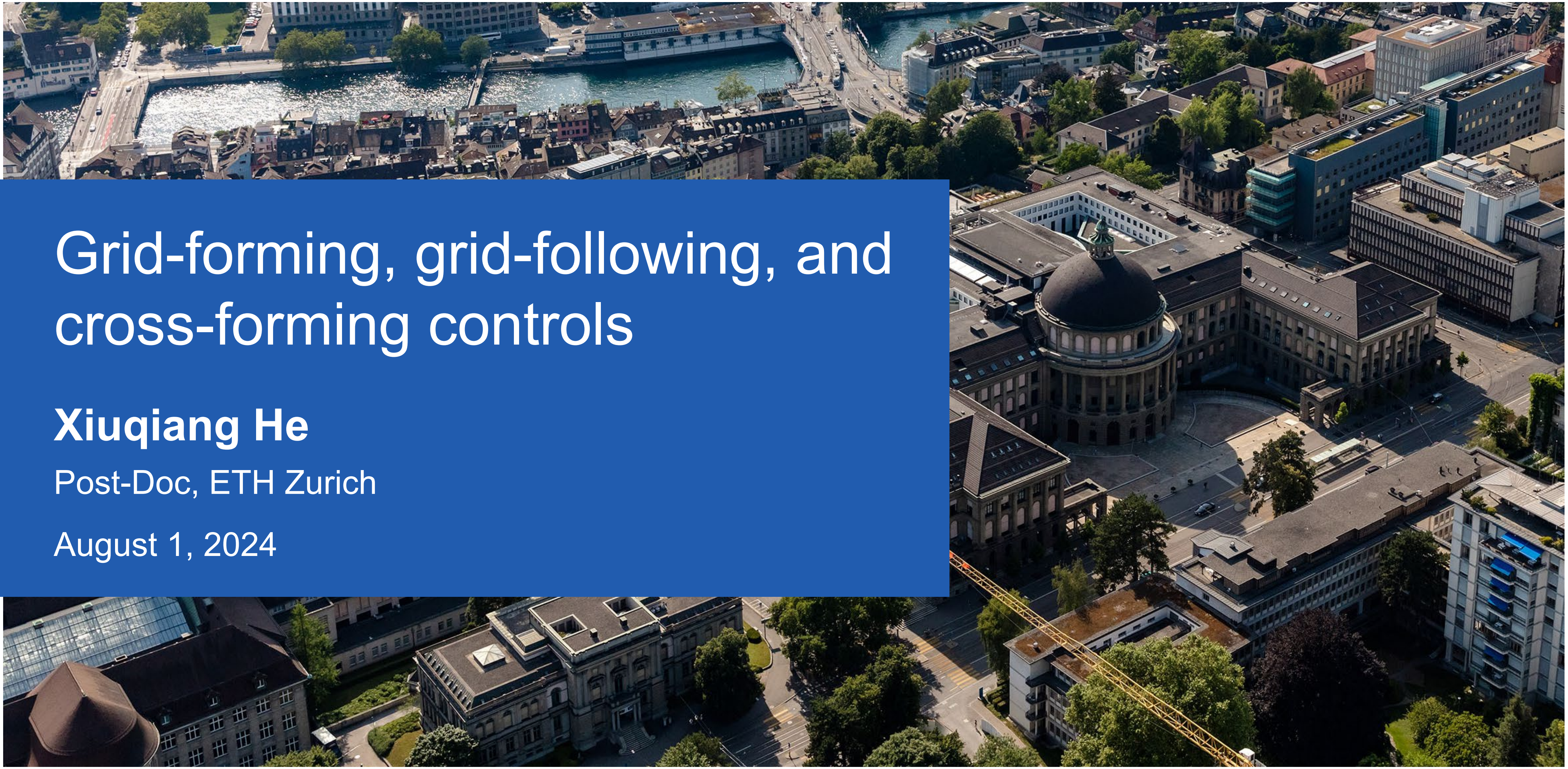

Grid-forming, grid-following, and cross-forming controls

Xiuqiang He

Post-Doc, ETH Zurich

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About me

Xiuqiang He

Postdoc

Personal web page

Education and appointment

- Postdoc — ETH Zurich, Switzerland — 2021 - Present
  Supervisor: Prof. Florian Dörfler
- PhD — Tsinghua University, China — 2016 - 2021
  Supervisor: Prof. Hua Geng
- B.S. degree — Tsinghua University, China — 2012 - 2016

Research interests

- Control of renewable energy generation systems
- Dynamics and stability of future power systems
- Grid ancillary services and dynamic virtual power plants (DVPPs)
- Generic modeling of converter-based generation for power system simulations

Services

- Secretary of IEC SC 8A WG 8 (Generic simulation modeling of RE)

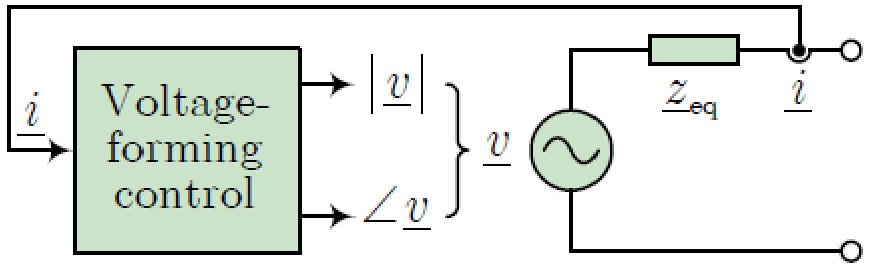
Agenda

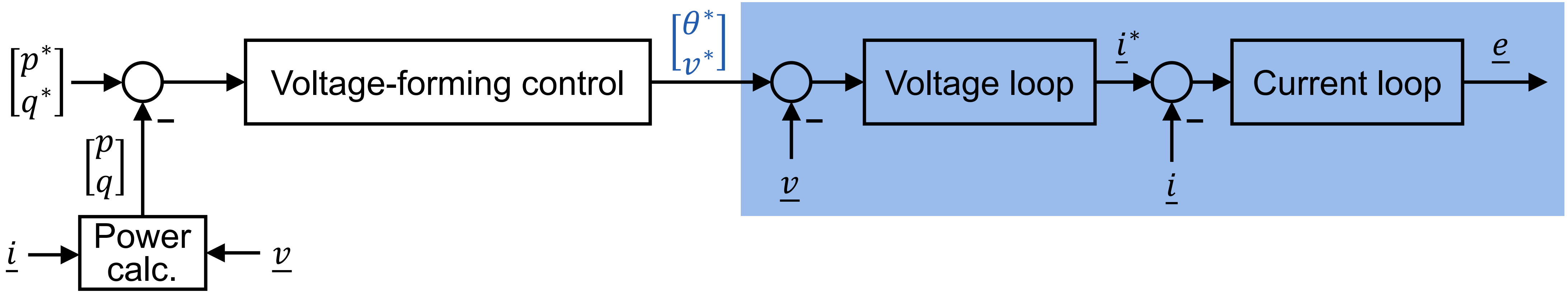
- TPSP Introduction (5 mins)
- Presentation (30-45 mins)
  - Introduction to existing control strategies (Voltage vs Current Forming)
  - Limitations of existing strategies (from Table 1 in the paper https://arxiv.org/pdf/2404.13376)
  - Novel control strategy proposed in the paper (Cross Forming Control)
  - Limitations of cross-forming and future scope (Table 1 and 2 in the paper)
- Brief discussion or questions

Grid-forming (Voltage-forming)

- **Definition of GFM [NERC, AEMO, UNIFI, ESIG, etc.]**
  GFM IBR controls maintain *an internal voltage phasor* that is *constant or nearly constant* in the *sub-transient to transient time frame*

  – Droop Control
  – Virtual Synchronous Machine (VSM)
  – Dispatchable virtual oscillator control (complex droop control)

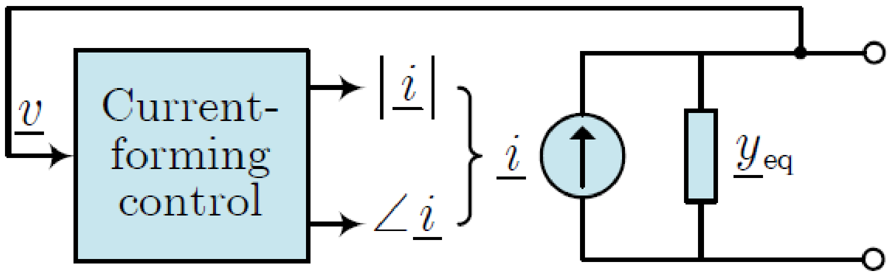


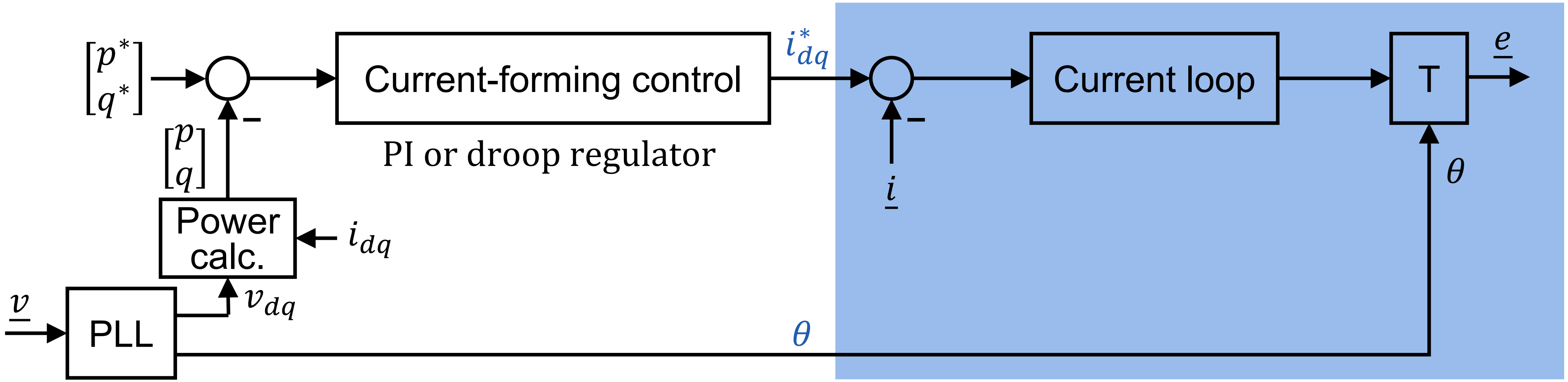


Grid-following (Current-forming)

- **Definition of grid-following**
  GFL IBR controls maintain *an output current phasor* that is *constant or nearly constant* in the *sub-transient to transient time frame*

  - PLL-based control (slow)
  - Dual counterparts of voltage-forming controls (e.g., dual synchronous generator [Xin 2021])

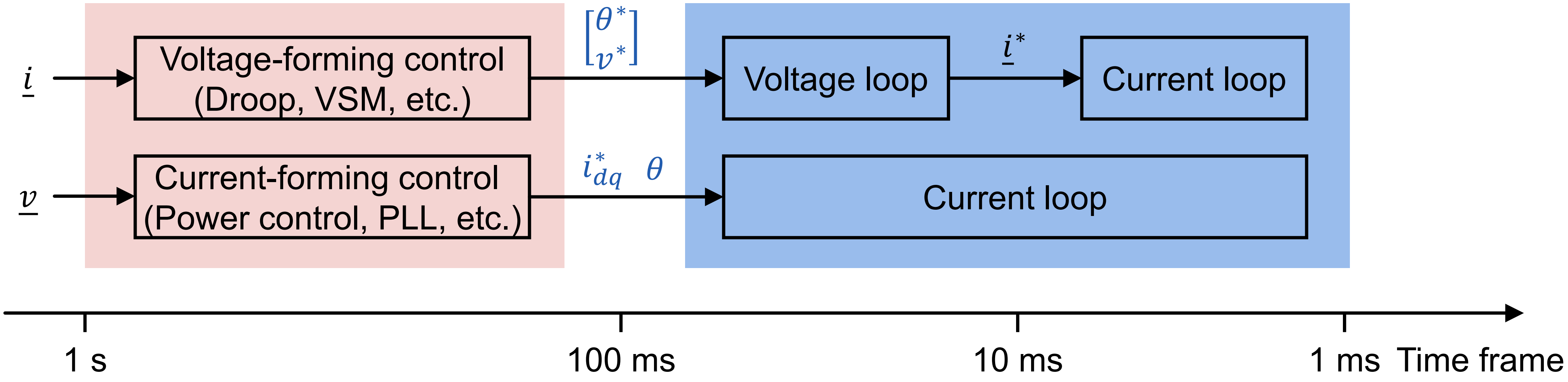




Contrast between voltage-forming and current-forming

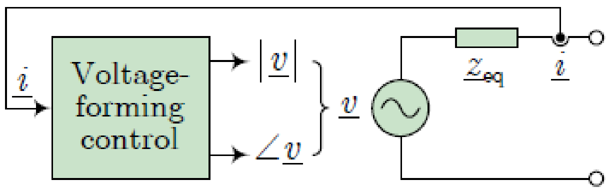
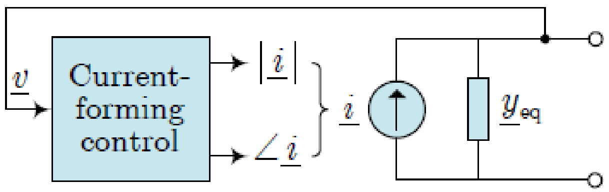
- Longer time frames (100 ms to steady state).
- Control objectives can be the same or different: Sync., power sharing/dispatching, frequency and voltage regulation, islanding operation, black start, LFO damping, etc.

- Sub-transient to transient time frame (0 to 100 ms)
- Different control objectives
  - GFM: Constant voltage phasor
  - GFL: Constant current phasor
- Same control objectives: Sink for imbalances/harmonics, small-signal stability improvement / passivity, etc.



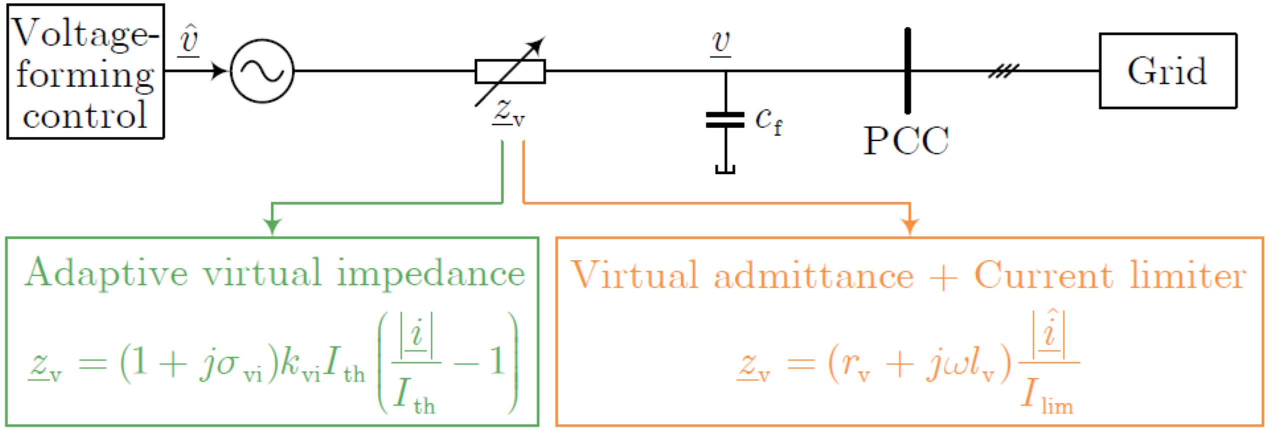
Limitations of voltage-forming and current-forming

- For voltage-forming: **Current limitation issue**
- For current-forming: **Need fast current setpoint adjustment** for providing voltage-source-like behavior

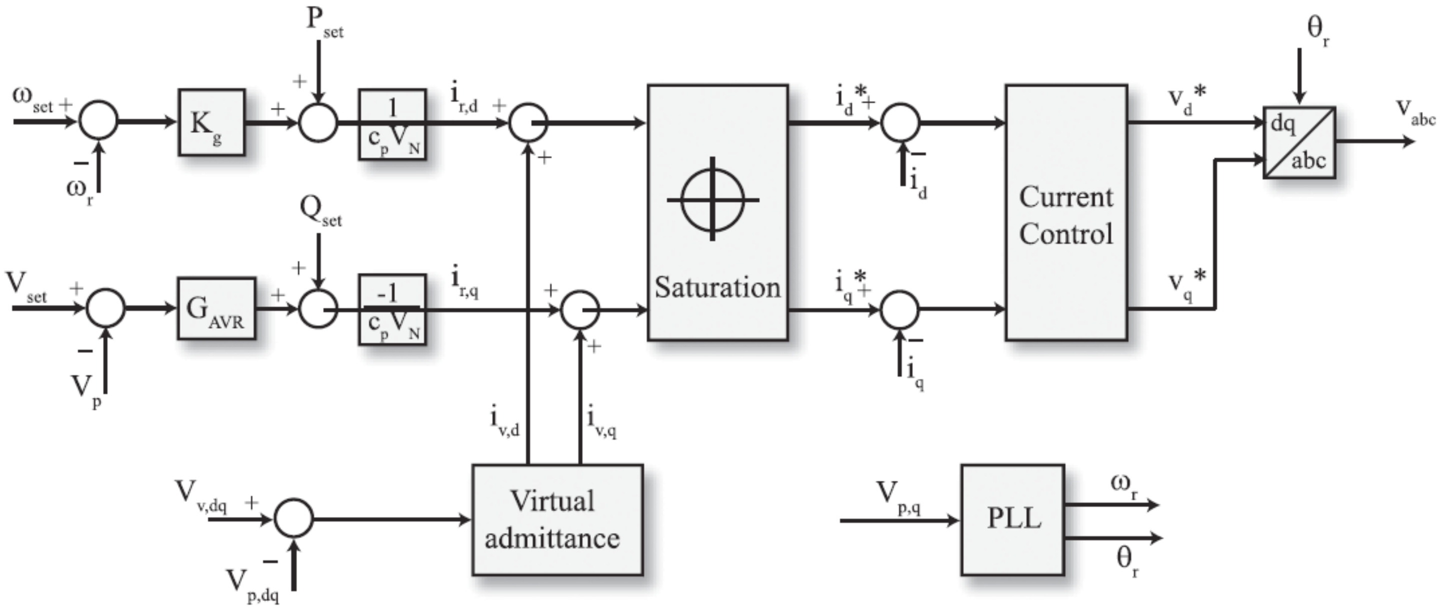
	Voltage-forming mode	Current-forming mode
Illustrations		
Examples	Droop, VSM, dVOC, complex droop control, SM-matching, and dual-port control[1]	PLL-based current control, and the dual counterparts of voltage forming controls
References	[6], [8]	[16], [32]
Voltage behavior	Angle and magnitude forming	Angle and magnitude following
Current behavior	Angle and magnitude following	Angle and magnitude forming
Synchronization	Voltage angular frequency	Current angular frequency
Fault current injection	Yes, natural response	Yes, but need setpoint adjust
Phase jump power delivery	Yes, natural response	Yes, but need setpoint adjust
Negative-sequence services[2]	Yes, flexible	Yes, flexible
Current limiting	No, additional remedies required[3]	Yes, inherent

How to overcome the limitations?

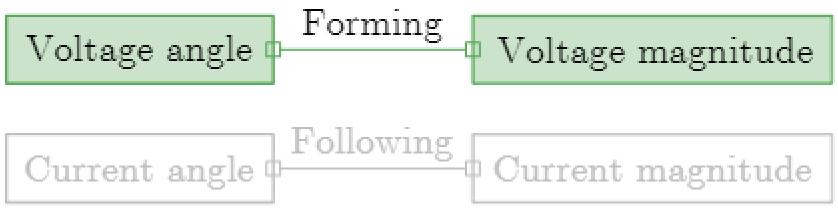
- For voltage-forming: **Current limitation issue**
  - Adaptive virtual impedance
  - Virtual admittance + Current limiter



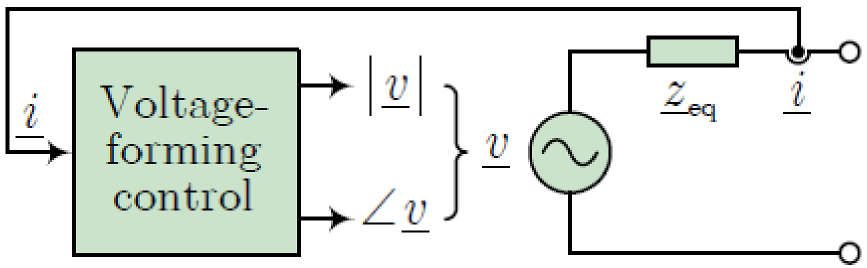
- For current-forming: **Need fast current setpoint adjustment** for providing voltage-source-like behavior
  - GFM vector current control [Lennart Harnefors, 2022]
  - Dual synchronous generator [Xin, 2021]

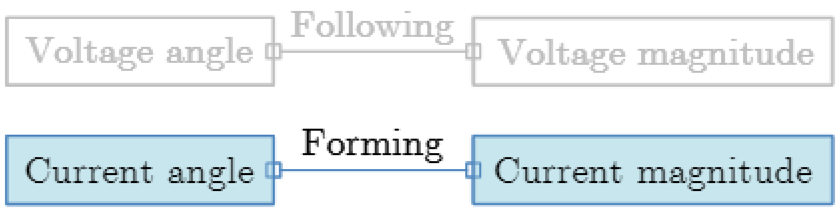


Motivation of cross-forming

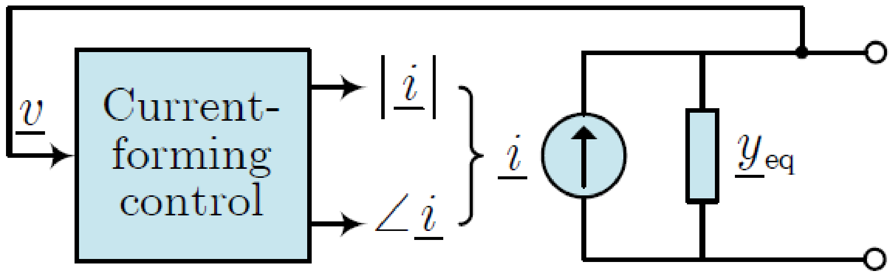


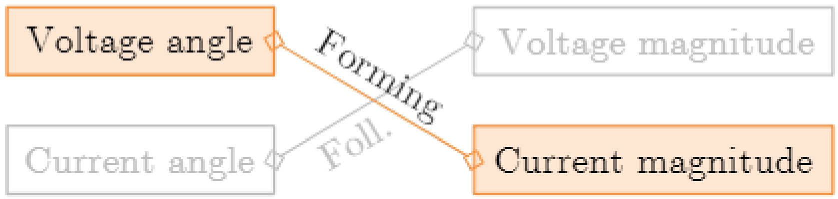
(a) Voltage-forming mode



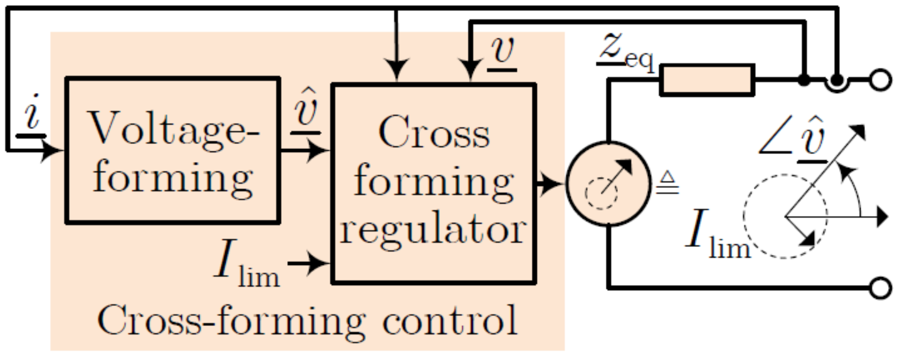


(b) Current-forming mode



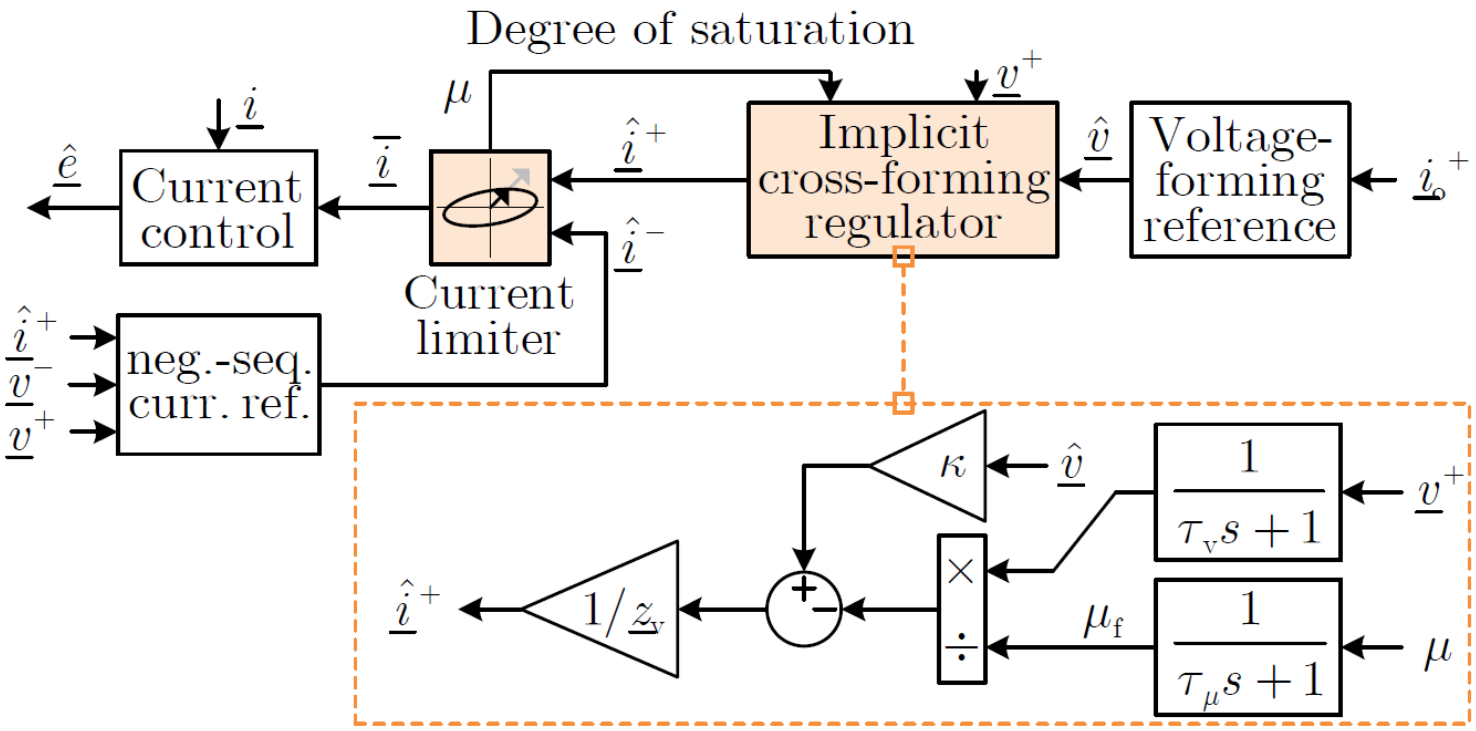


(c) Proposed cross-forming mode



How to achieve cross-forming?

- There are many ways to achieve cross-forming behavior https://arxiv.org/abs/2404.13376



Benefits of cross-forming control

	Voltage-forming strategies	Current-forming strategies	Cross-forming strategies
Current limiting strategies	• Type-A: Adaptive virtual impedance [9], [10] • Type-B: Current limiter with virtual admittance [11]–[15]	Current reference direct specification [16]–[19] or in a drooped way [21], [22]	• Explicit cross-forming • Implicit cross-forming
Forming behaviors	• Internal voltage forming • Current magnitude constrained	• Current forming • Voltage following (undesired)	• Voltage angle forming • Current magnitude forming
Control switching	No switching needed	Yes and incompatible	Yes but compatible
Tuning complexity	• Complicated if using Type-A • Simple if using Type-B	Simple for current limiting, but complicated for FRT services	Simple
Current-limiting speed	• Slow if using Type-A • Fast if using Type-B	Fast	Fast
Overcurrent utilization	• No, for Type-A, limited within $[I_{\mathrm{th}}, I_{\mathrm{lim}}]$ • Yes, for Type-B, limited at I_{lim}	Yes, limited at I_{lim}	Yes, limited at I_{lim}
FRT i_Q provision	i_Q naturally provided, with high priority by reducing $p^\star$	• Adjust $i_Q^\star$ if using PLL, but slow • Reduce $p^\star$ if using frequency droop [16], but i_Q provision may be slow	i_Q naturally provided, with high priority by reducing $p^\star$
Phase jump i_P provision	i_P naturally provided	i_P may not be compliant due to behaving as a current source	i_P naturally provided
Resulting impedance	Current-dependent for both Type-A and -B	NA	Constant
Transient stability enhancements	Numerous strategies available, e.g., • Virtual-power feedback [12] • Alternating virtual inertia [38] • Mode-adaptive control [39] • Power setpoint adjusting [40] • Transient active power control [41]	• Q-axis voltage feedback [16] • Current reference angle adjusting [17]–[19], but may conflict with FRT services requirements	• Enhanced voltage-forming references
Transient stability analysis	Difficult since the resulting virtual impedance is current-dependent	Relatively difficult due to involving control architecture switching	Equivalent normal forms allow extending existing methods

Open problems

- By detecting what signal should the cross-forming control be activated and deactivated?
  - Terminal voltage?
  - Terminal phase jump?
  - Output current?
- How to quantify the response behavior of grid-forming (current-saturated) converters?
  - How large is the fault current contribution?
  - How large is the active power response?
- How to specify the response of grid-forming (current-saturated) converters more clearly in grid code development?

Conclusion

- GFM and GFL differ from one another in the sub-transient to transient time frame (0 to 100 ms) because the control objectives in this time frame are different.
- GFM and GFL can achieve the same control objectives in longer time frames (100 ms to steady state).
- To ensure the GFM behavior (more specifically, voltage-angle-forming) and current limitation, we proposed the cross-forming control.
- Future work will
  - quantify the response behavior of cross-forming inverters under current saturation,
  - specify the response behavior of grid-forming (current-saturated) converters as grid code requirements, and
  - investigate the capability of the cross-forming inverters to fulfill grid code requirements.

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Thank you!

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Xiuqiang He (何秀强), postdoc

ETH Zurich, Switzerland
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