Sustainable Power &
Renewable Energy
INTegration

AC Capacitor Dynamics-Based Synchronous Control for Grid-Following Operations

Zehua Tang

King's College London

Publication:

Zehua Tang, Hao Zou, and Grazia Todeschini, "Ac capacitor dynamics-based synchronous control for grid-following operations," *IEEE Trans. Industrial Electronics*, early access, Aug. 12, 2025.

Personal Information

- SPRINT team & me

Sustainable Power & Renewable energy Integration (SPRINT). SPRINT was funded in Oct. 2020 with the aim of supporting the development of the future power system. To achieve this aim, we are working on these key areas:

- Advanced modelling of power system equipment
- Development of controls to facilitate integration of power electronics-based resources into the electricity grid.
- Applications of machine learning to electricity demand and generation forecasting.

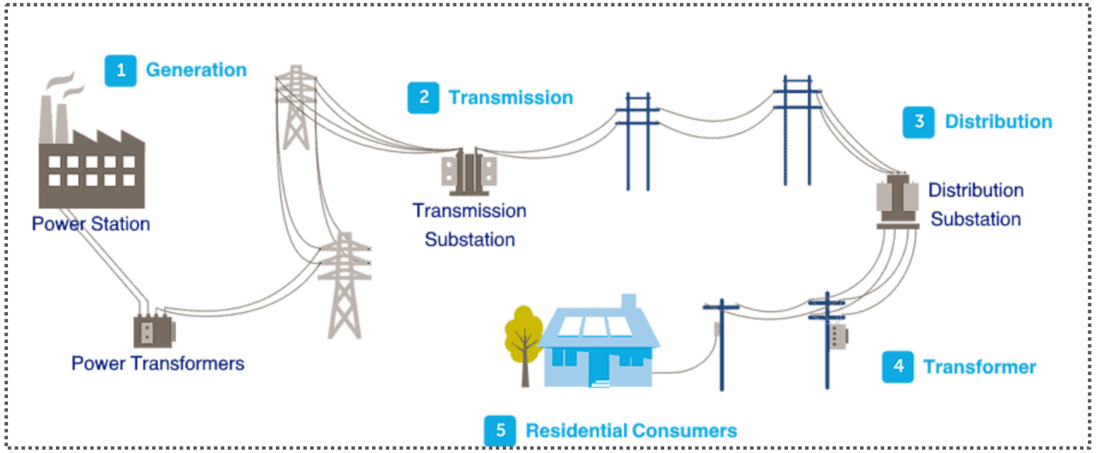
sprintresearch.co.uk/

PhD candidate. I received the B.Eng. and M.Phil. degrees in electrical engineering, China University of Mining & Technology, Xuzhou, China, in 2019 and 2022, respectively. I am currently working toward a Ph.D. degree with the Department of Engineering, King's College London, London, U.K. My major field of study is the control, modeling, and analysis of high-proportioned power electronics-penetrated ac power systems.

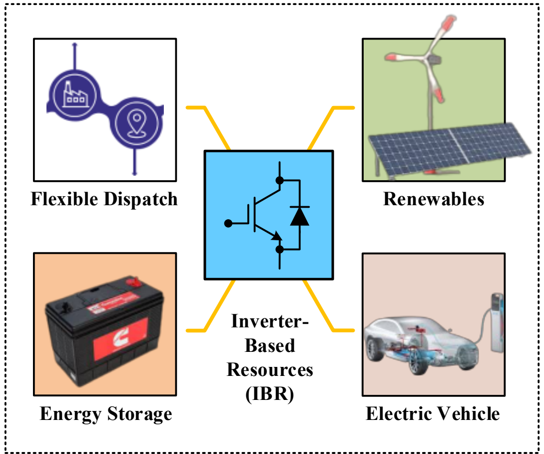
Zehua TANG

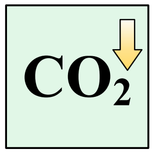
Motivations

- Background

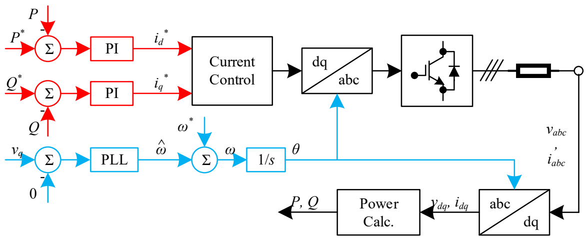


Net Zero 2050



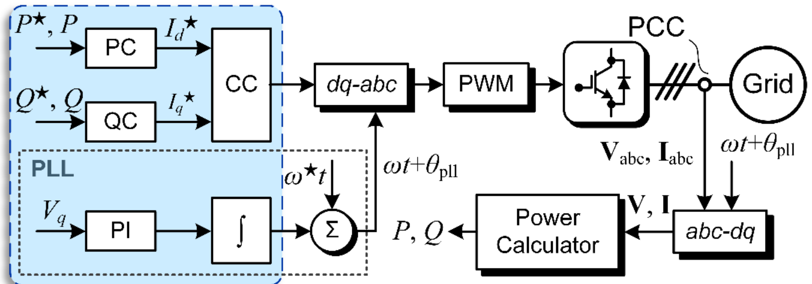


Net-Zero Economy



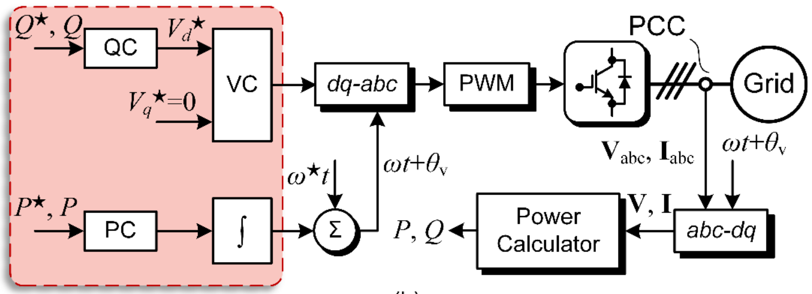
Motivations

- Question
  - Traditionally, grid-tied inverters widely rely on a PLL to align frequency with the grid, hence named grid-following (GFL)-IBRs. But,…
    - PLLs -> de-stabilizers.
    - PLL dynamics -> implicit inertial and damping coefficients.
  - To overcome the limitations, grid-forming (GFM)-IBRs have emerged. But,…
    - may not always be the optimal choice:
      - a) resonances.
      - b) hinder MPPT and require energy storage.
  - Stable current-source behaved GFL-IBRs are not often subject to these GFM-IBR issues and will likely remain the dominant strategy for the foreseeable future due to industry trends.



(a)

Grid-Following (GFL)-IBR



(b)

Grid-Forming (GFM)-IBR

Motivations

- Literature review
  - The above considerations have gained renewed interest in refining GFL controls. A promising direction is to explore PLL-free approaches [13].
  - Early efforts focused on direct power control (DPC). Yet, it lacks current controls to limit over currents [16].
  - Voltage-modulated DPC [17] was proposed to address these issues. However, subsequent studies proved its vulnerability to grid frequency deviations.
  - Drawing inspiration from GFM-IBRs, researchers explored active power-synchronized (PSC) GFL-IBRs [19-21]. But, the intrinsic ω-P coupling remains a challenge.

[13] Li, Y. Gu, and T. C. Green, "Revisiting grid-forming and grid-following inverters: A duality theory," *IEEE Trans. Power Syst*, Nov. 2022.

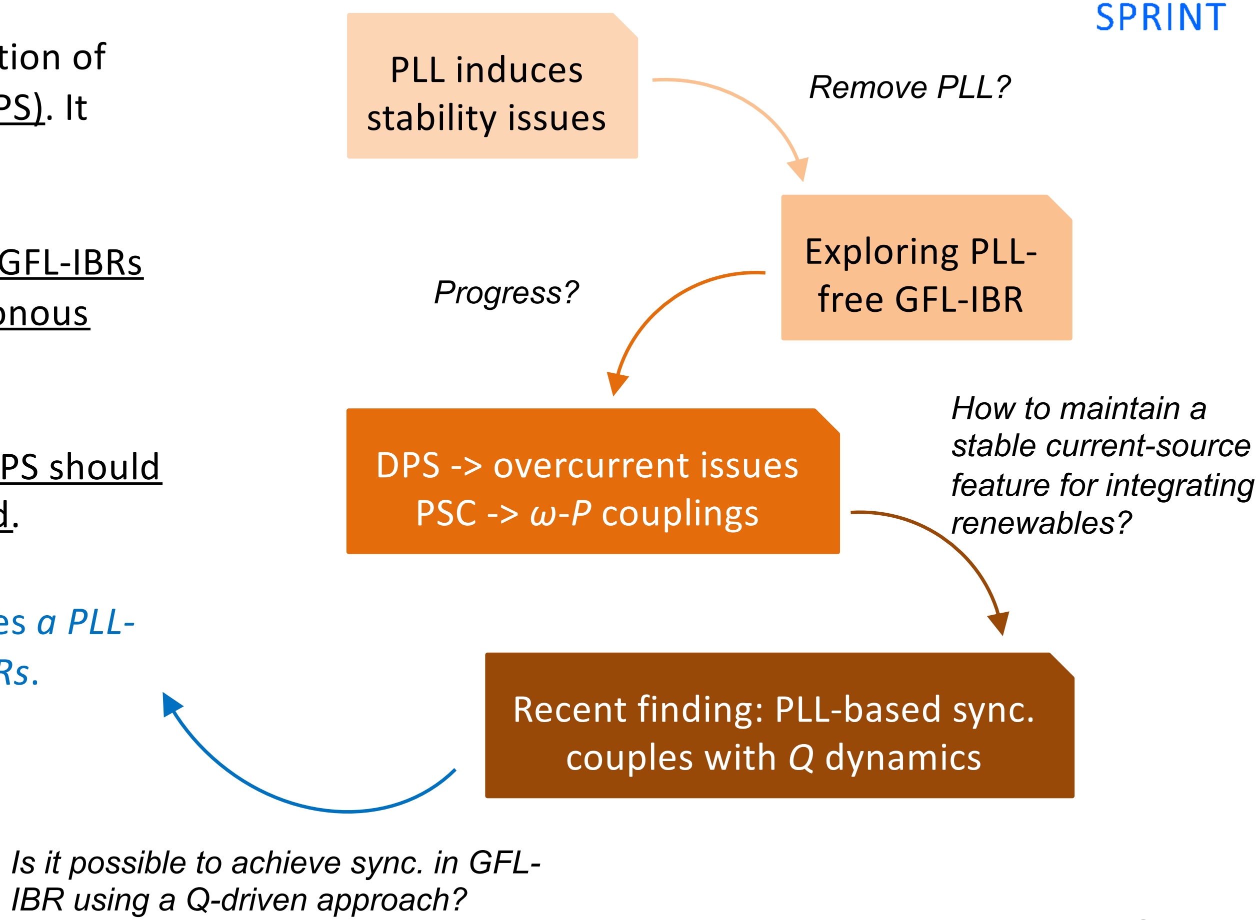
[16] S. Vazquez, *et al.*, "Predictive optimal switching sequence direct power control for grid-connected power converters," *IEEE Trans. Ind. Electron*, Apr.2015

[17] Y. Gui, X. Wang, H. Wu, and F. Blaabjerg, "Voltage-modulated direct power control for a weak grid-connected voltage source inverters," *IEEE Trans. Power Electron.*, Nov. 2019.

[21] N. Mohammed, W. Zhou, and B. Bahrani, "Double-synchronous-reference-frame-based power-synchronized PLL-less grid-following inverters for unbalanced grid faults," *IEEE Open J. Power Electron.*, Jun. 2023.

Motivations

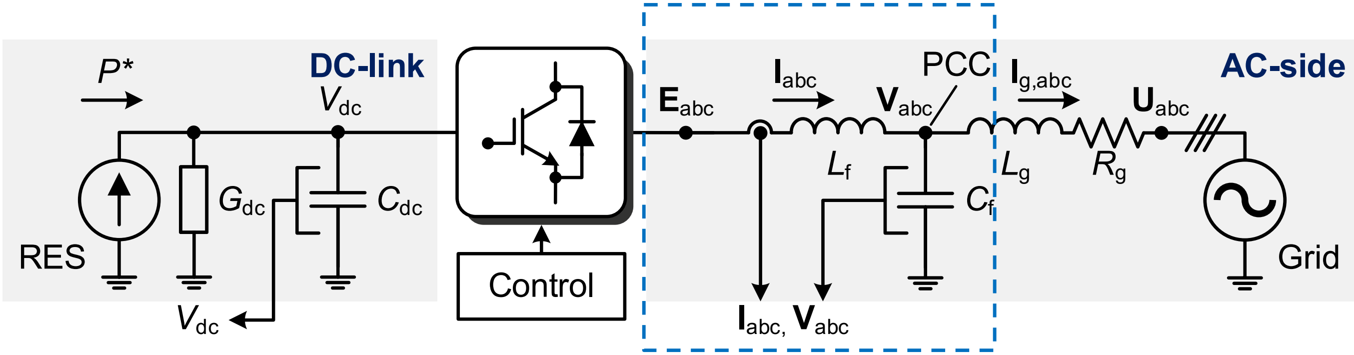
- Literature review
  - The ω-P coupling led to the early exploration of reactive power-based synchronization (RPS). It firstly used in formulate GFM-IBRs.
  - Yet, recent studies clarify that PLL-based GFL-IBRs also exhibit inherent Q-dominant synchronous dynamics [13].
  - This raises the question of whether the RPS should be exclusively classified as a GFM method.
  - Based on these ideas, this work introduces *a PLL-free synchronization approach for GFL-IBRs*.



AC Capacitor-Based Synchronization

- What is the mechanism of the method?

IBR power stage:



– The voltage across ac filter capacitor C_f in s-domain is:

$$(sC_f + G_f + j\omega C_f)\,\mathbf{V}(s) = \mathbf{I}(s) - \mathbf{I}_g(s) \qquad (1)$$

$$\mathbf{V} = Ve^{j\theta_v}$$

– After substitution:
  - The superscript ^{r} denotes the rotation in dq-frame.

$$(sC_f + G_f + j\omega C_f)\,V = (\mathbf{I} - \mathbf{I}_g)\,e^{-j\theta_v} =: \mathbf{I}^r - \mathbf{I}_g^r \qquad (2)$$

AC Capacitor-Based Synchronization

- What is the mechanism of the method?
  - The coupling between operating frequency and its reactive power output (*ω-Q*) in GFL-IBR is [7]:
    - The subscript $_{\mathrm{b}}$ denotes the signal base value.
    - The symbol ~ denotes small-signal dynamics.
    - ϑ_{i}: phase angle of output current vector.
    - $K_{\omega Q}(s)$: transfer function from Q to ω.
    - $K_{\omega V}(s)$: transfer function from V to ω.
    - n: *Q-V* droop coefficient.

$$\tilde{\omega} = s\tilde{\theta}_{\mathrm{i}} = \omega_{\mathrm{b}} K_{\omega\mathrm{Q}}(s)\tilde{Q} \quad (3)$$

Q-V droop: $\tilde{V} = -n\tilde{Q}$

$$\tilde{\omega} = s\tilde{\theta}_{\mathrm{i}} = \omega_{\mathrm{b}} K_{\omega\mathrm{V}}(s)\tilde{V} \quad (4)$$

$$(sC_{\mathrm{f}} + G_{\mathrm{f}} + j\omega C_{\mathrm{f}})\,V = (\mathbf{I} - \mathbf{I}_{\mathrm{g}})\,e^{-j\theta_{\mathrm{v}}} =: \mathbf{I}^{\mathrm{r}} - \mathbf{I}_{\mathrm{g}}^{\mathrm{r}} \quad (2)$$

$$\boxed{\frac{C_{\mathrm{f}}}{\omega_{\mathrm{b}} K_{\omega\mathrm{V}}(s)} s^2\tilde{\theta}_{\mathrm{i}} + \frac{G_{\mathrm{f}} + j\omega C_{\mathrm{f}}}{\omega_{\mathrm{b}} K_{\omega\mathrm{V}}(s)} s\tilde{\theta}_{\mathrm{i}} = \tilde{\mathbf{I}}^{\mathrm{r}} - \tilde{\mathbf{I}}_{\mathrm{g}}^{\mathrm{r}} \quad (5)}$$

Reference:

[7] Y. Gu and T. C. Green, "Power system stability with a high penetration of inverter-based resources," *Proceedings of IEEE*, Jul. 2023.

AC Capacitor-Based Synchronization

- What is the mechanism of the method?

$$\boxed{\frac{C_\mathrm{f}}{\omega_\mathrm{b} K_{\omega \mathrm{V}}(s)} s^2 \tilde{\theta}_\mathrm{i}} + \boxed{\frac{G_\mathrm{f} + j\omega C_\mathrm{f}}{\omega_\mathrm{b} K_{\omega \mathrm{V}}(s)} s \tilde{\theta}_\mathrm{i}} = \tilde{\mathbf{I}}^\mathrm{r} - \tilde{\mathbf{I}}^\mathrm{r}_\mathrm{g} \qquad (5)$$

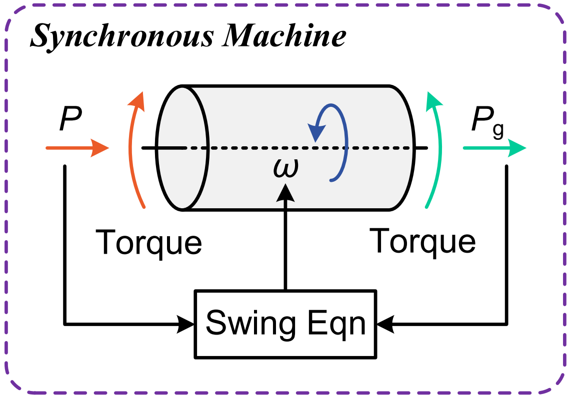
Inertia term

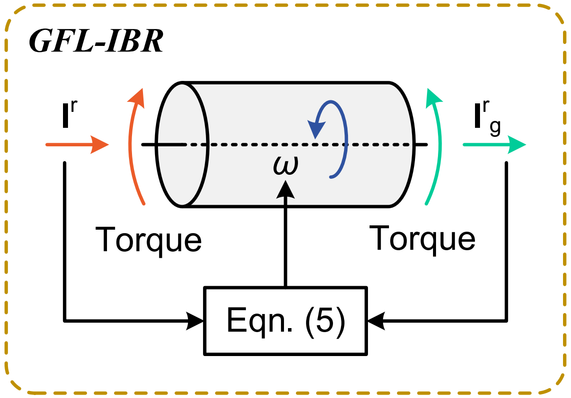
$$\frac{k_\mathrm{J}}{\omega_\mathrm{b}} s^2 \tilde{\theta}_\mathrm{i}$$

Damping term

$$\frac{k_\mathrm{D}}{\omega_\mathrm{b}} s \tilde{\theta}_\mathrm{i}$$

resembles





– Hence, by ignoring the coupling term $j\omega C_\mathrm{f}$ for its minimal influence, an expression for $K_{\omega \mathrm{V}}(s)$ can be:

$$\frac{C_\mathrm{f}}{\omega_\mathrm{b} K_{\omega \mathrm{V}}(s)} s^2 \tilde{\theta}_\mathrm{i} + \frac{G_\mathrm{f}}{\omega_\mathrm{b} K_{\omega \mathrm{V}}(s)} s \tilde{\theta}_\mathrm{i} = \frac{k_\mathrm{J}}{\omega_\mathrm{b}} s^2 \tilde{\theta}_\mathrm{i} + \frac{k_\mathrm{D}}{\omega_\mathrm{b}} s \tilde{\theta}_\mathrm{i}$$

$$\Rightarrow \quad K_{\omega \mathrm{V}}(s) = (sC_\mathrm{f} + G_\mathrm{f})/(sk_\mathrm{J} + k_\mathrm{D}) \qquad (7)$$

AC Capacitor-Based Synchronization

- What is the method mechanism?

$$\tilde{\omega} = s\tilde{\theta}_{\mathrm{i}} = \omega_{\mathrm{b}} K_{\omega \mathrm{V}}(s)\tilde{V} \quad (4)$$

$$K_{\omega \mathrm{V}}(s) = (sC_{\mathrm{f}} + G_{\mathrm{f}})/(sk_{\mathrm{J}} + k_{\mathrm{D}}) \quad (7)$$

$$\begin{aligned} \tilde{\theta}_{\mathrm{i}} = \frac{\tilde{\omega}}{s} &= \frac{\omega_{\mathrm{b}} K_{\omega \mathrm{V}}(s)}{s}\tilde{V} \\ &= \frac{\omega_{\mathrm{b}}}{sk_{\mathrm{J}} + k_{\mathrm{D}}}\left(C_{\mathrm{f}} + \frac{k_{\mathrm{G}}}{s}\right)\tilde{V} =: K_{\mathrm{SYN}}(s)\tilde{V} \end{aligned} \quad (8)$$

– Eqn. (8) defines *a synchronous controller for GFL-IBR based on the ac capacitor dynamics*.

– k_{J} (inertial coef.), k_{D} (damping coef.), and k_{G} (virtual conductance) are variable parameters to configure synchronous behaviors.

How is the controller designed?

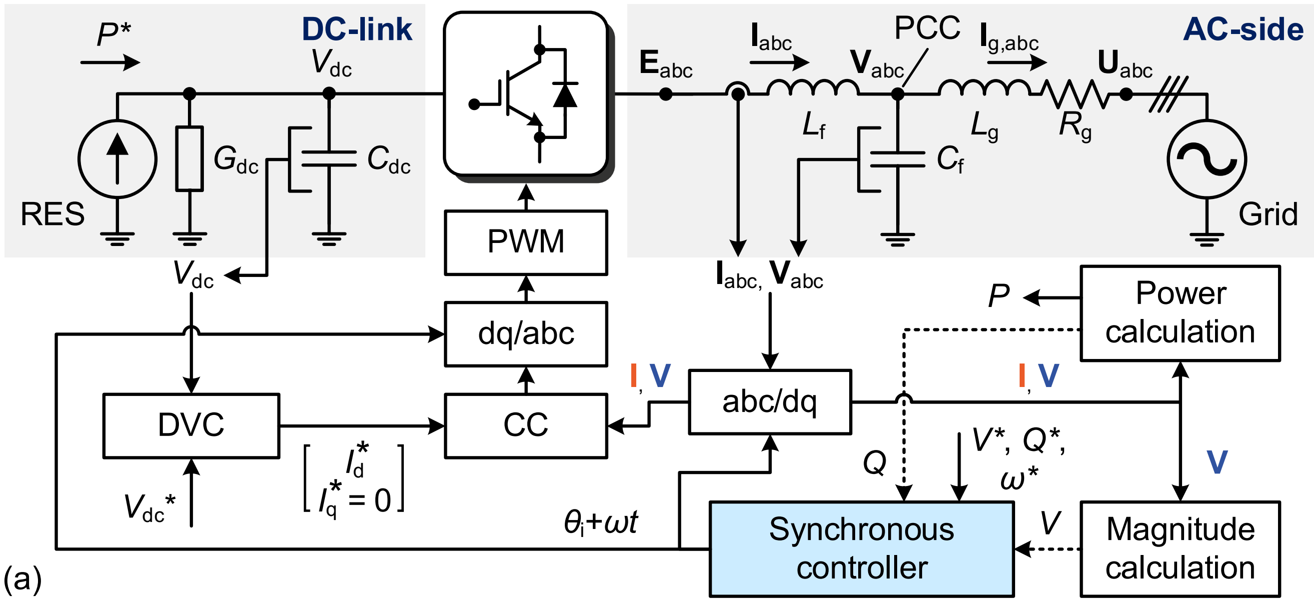
GFL-IBR Control Design and Analysis

- What is the control design?

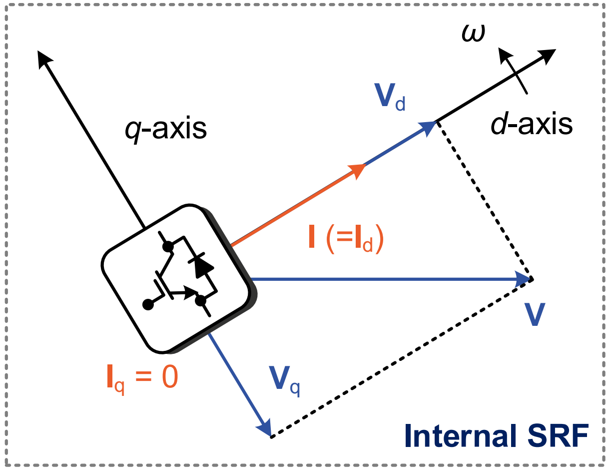
Synchronous controller

$$\tilde{\theta}_{\mathrm{i}} = \frac{\tilde{\omega}}{s} = \frac{\omega_{\mathrm{b}} K_{\omega\mathrm{V}}(s)}{s}\tilde{V} = \frac{\omega_{\mathrm{b}}}{s k_{\mathrm{J}} + k_{\mathrm{D}}}\left(C_{\mathrm{f}} + \frac{k_{\mathrm{G}}}{s}\right)\tilde{V} =: K_{\mathrm{SYN}}(s)\tilde{V} \quad (8)$$

Termed *ac capacitor dynamics-synchronized (CacDS)* *GFL-IBR*.



(a)



(b) Synchronous reference frame (SRF)

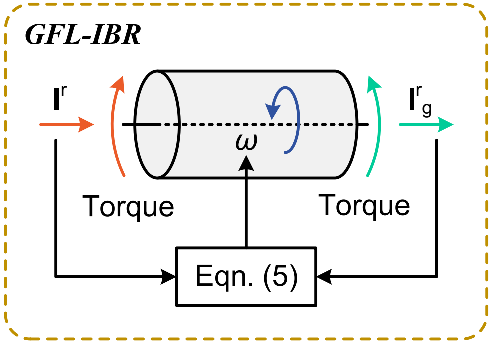
GFL-IBR Control Design and Analysis

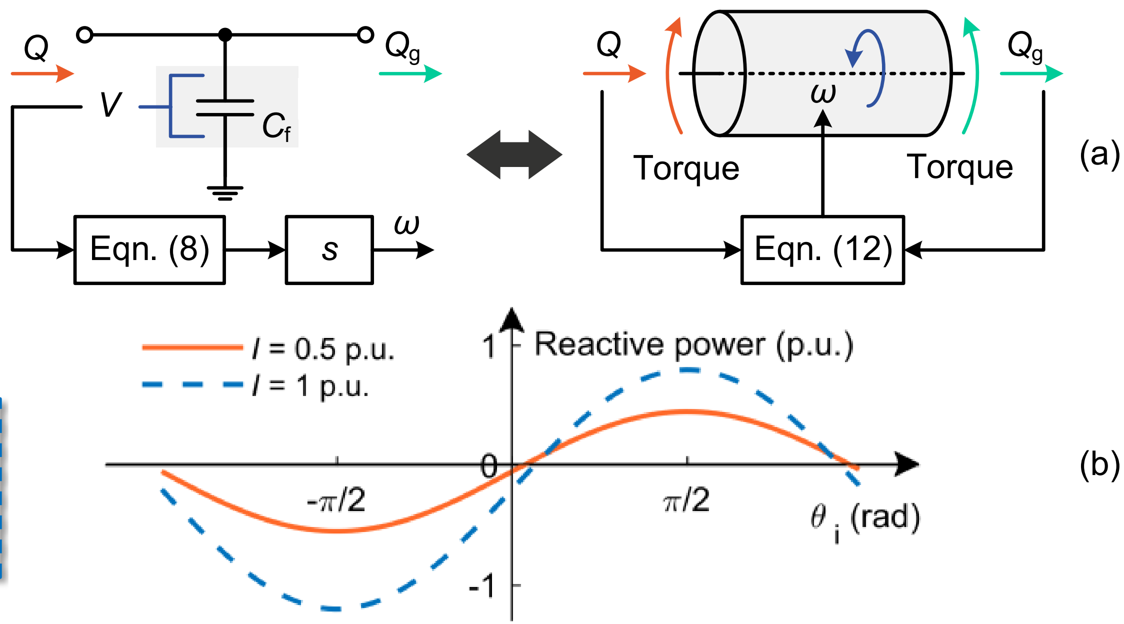
- Does the CacDS control synchronize by balancing Q?
  - From Eqn. (8), the CacDS control regulates V to achieve synchronization, reflecting a reactive power synchronization (RPS)-based essence.
  - Reformulate the dynamics in Eqn. (5) into Eqn. (9) with reference to the rotor-swing equation:

$$\frac{C_\mathrm{f}}{\omega_\mathrm{b} K_{\omega\mathrm{V}}(s)} s^2\tilde{\theta}_\mathrm{i} + \frac{G_\mathrm{f} + j\omega C_\mathrm{f}}{\omega_\mathrm{b} K_{\omega\mathrm{V}}(s)} s\tilde{\theta}_\mathrm{i} = \tilde{\mathbf{I}}^\mathrm{r} - \tilde{\mathbf{I}}^\mathrm{r}_\mathrm{g} \quad (5)$$

Showing a reactive power sync. (RPS)-based method

$$\frac{k_\mathrm{J}}{\omega_\mathrm{b}} s\Delta\omega + \frac{k_\mathrm{D}}{\omega_\mathrm{b}} \Delta\omega = Q - Q_\mathrm{g} \quad (9)$$





GFL-IBR Control Design and Analysis

- Why is the RPS a method for the GFL-IBR?
  - When the current vector serves as the SRF phase reference, it leads to the power equations:

$$P := UI\cos\theta_{\mathrm{i}}, \quad Q := UI\sin\theta_{\mathrm{i}} - X_{\mathrm{g}} I^2 \qquad (10)$$

$$\frac{k_{\mathrm{J}}}{\omega_{\mathrm{b}}} s\Delta\omega + \frac{k_{\mathrm{D}}}{\omega_{\mathrm{b}}}\Delta\omega = Q - Q_{\mathrm{g}} \qquad (9)$$

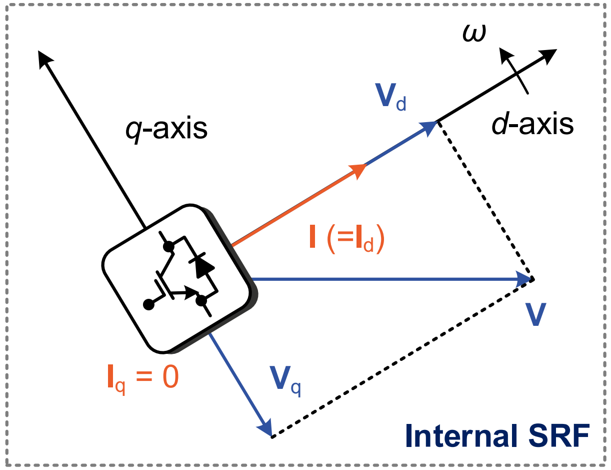
$$+$$

$$X_{\mathrm{g}} = \omega L_{\mathrm{g}}$$

After linearization

$$\frac{k_{\mathrm{J}}}{\omega_{\mathrm{b}}} s\tilde{\omega} + \frac{k_{\mathrm{D}}}{\omega_{\mathrm{b}}}\tilde{\omega} = \tilde{Q}_{\mathrm{g}} - U_0 I_0 \cos\theta_{\mathrm{i}0}\tilde{\theta}_{\mathrm{i}} + L_{\mathrm{g}} I_0^2 \tilde{\omega} \qquad (11)$$

$$\Leftrightarrow \frac{k_{\mathrm{J}}}{\omega_{\mathrm{b}}} s\tilde{\omega} + \left(\frac{k_{\mathrm{D}}}{\omega_{\mathrm{b}}} \boxed{- L_{\mathrm{g}} I_0^2}\right)\tilde{\omega} = \tilde{Q}_{\mathrm{g}} - U_0 I_0 \cos\theta_{\mathrm{i}0}\tilde{\theta}_{\mathrm{i}}$$



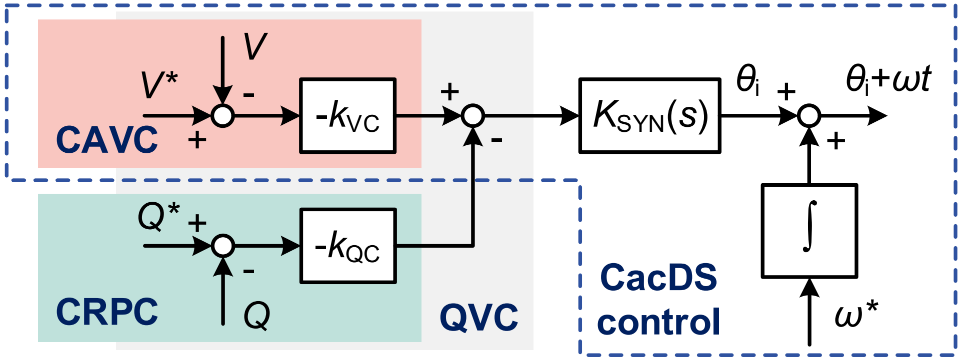
(b) Synchronous reference frame (SRF)

- Eqn. (11) reveals a negative damping adversely impacts IBRs' damping when grid weakens (i.e., L_g grows).
- The RPS-based IBR behaves more likely a GFL-IBR rather than a GFM-IBR in weak grids, confirming a GFL design.

GFL-IBR Control Design and Analysis

- Can the CacDS control be extended?
  - Under the CacDS control, the constant ac voltage control (CAVC) is used for sync..
  - In practice, often three reactive-power controls (RPCs) are used in IBRs:
    - CAVC,
    - constant reactive power control (CRPC), and
    - *Q-V* droop control (QVC).
  - Thus, by adding them into the CacDS controller, it formulates the unified PLL-free synchronization method (Eqn. (12)).

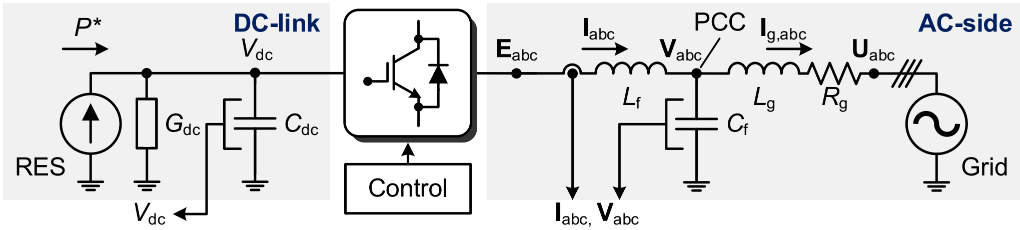
$$\theta_\mathrm{i} = -K_\mathrm{SYN}(s)\left(k_\mathrm{VC}\Delta V - k_\mathrm{QC}\Delta Q\right) \quad (12)$$



k_{VC} and k_{QC} are constants:
- If $k_{VC} \neq 0$ and $k_{QC} = 0$, it corresponds to the original CacDS control.
- If $k_{VC} = 0$ and $k_{QC} \neq 0$, the CRPC strategy is applied.
- If $k_{VC} \neq 0$ and $k_{QC} = n$ (*Q-V* droop coefficient), the QVC strategy is applied.

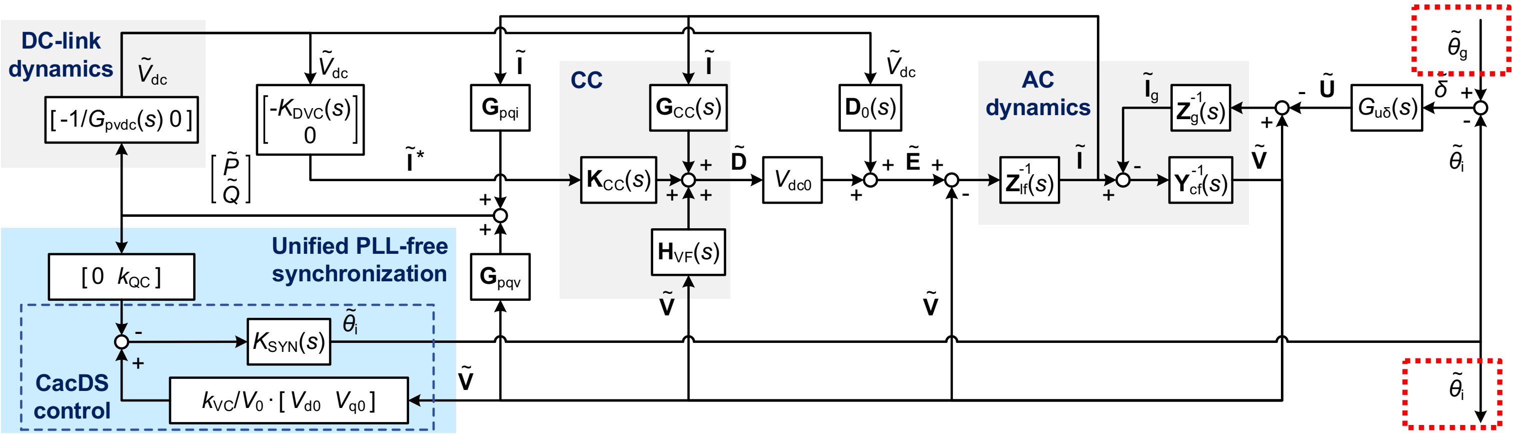
SISO Model of the GFL-IBR System

- Further analysis?
  - An SISO model for the proposed unified PLL-free GFL-IBR framework is derived.
  - It illustrates how the angle generated by the CacDS control tracks variations of the infinite-bus angle.



small-signal modeling

infinite-bus angle dynamics



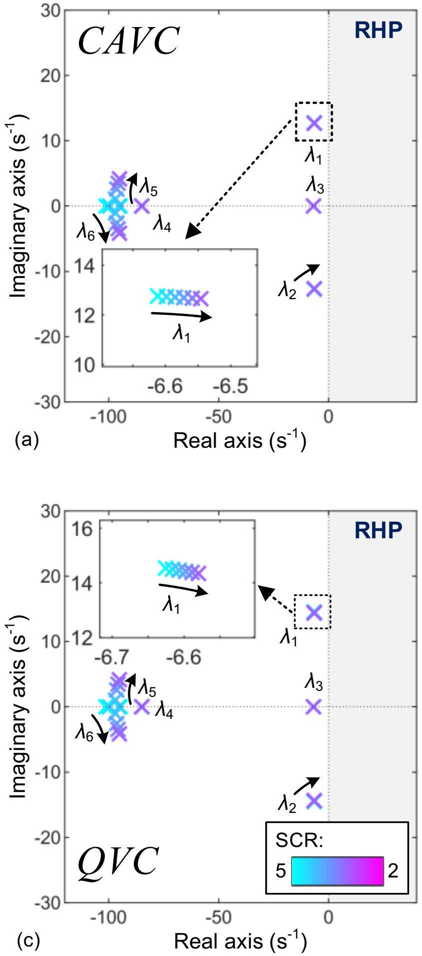
control generated angle dynamics

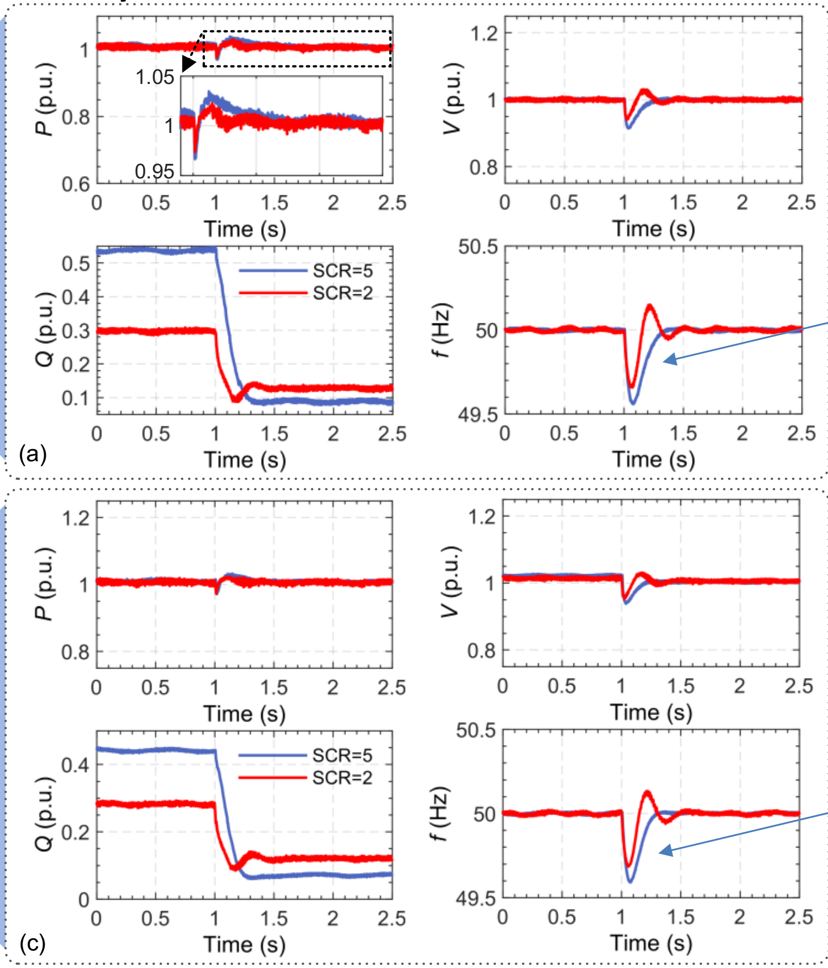
Method validation?

Validation

- Impact of grid strength on unified PLL-free synchronization

Simulations



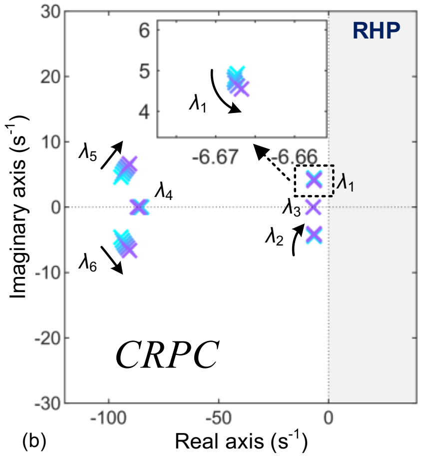


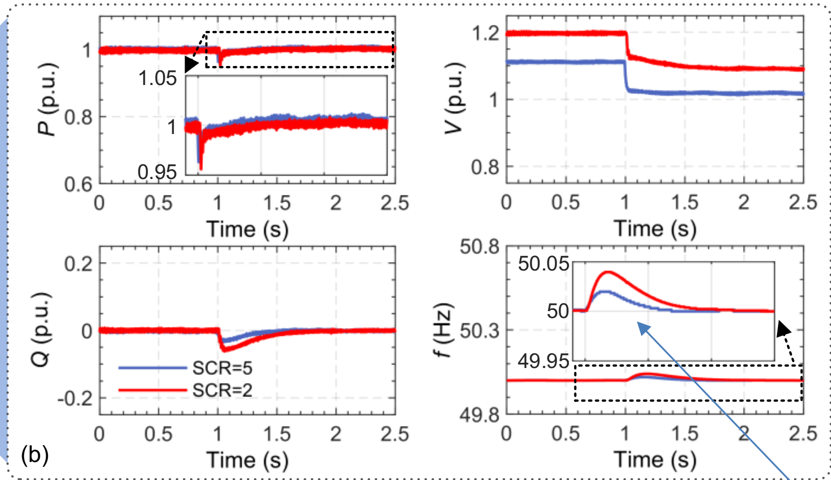
HiL tests
10% grid voltage sag applied

Validation

- Impact of grid strength on unified PLL-free synchronization

Simulations

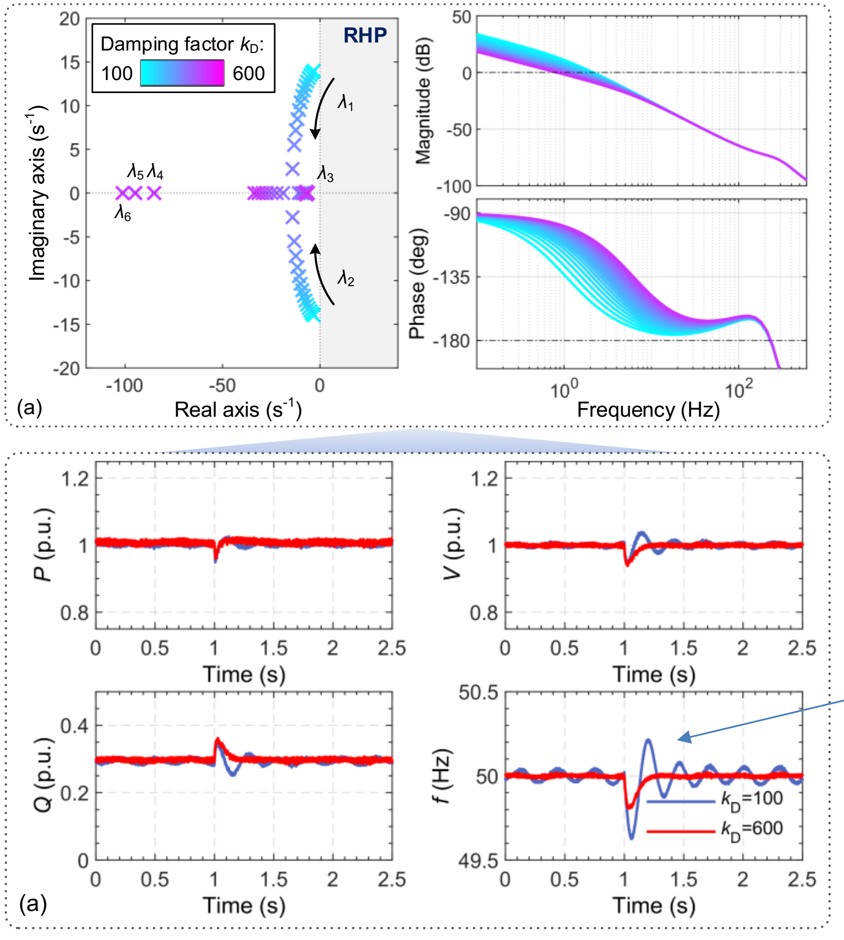




HiL tests
10% grid voltage sag applied

Validation

- Impact of synchronization parameters: k_D

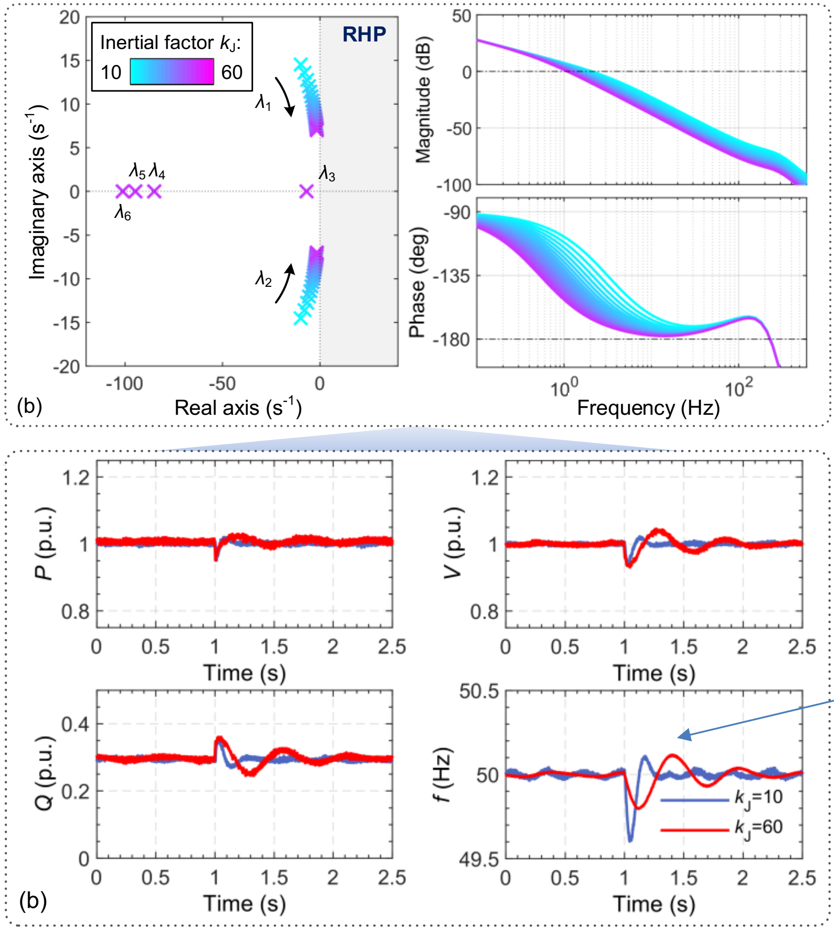


Simulations

HiL tests
5% V^* change applied

Validation

- Impact of synchronization parameters: k_J

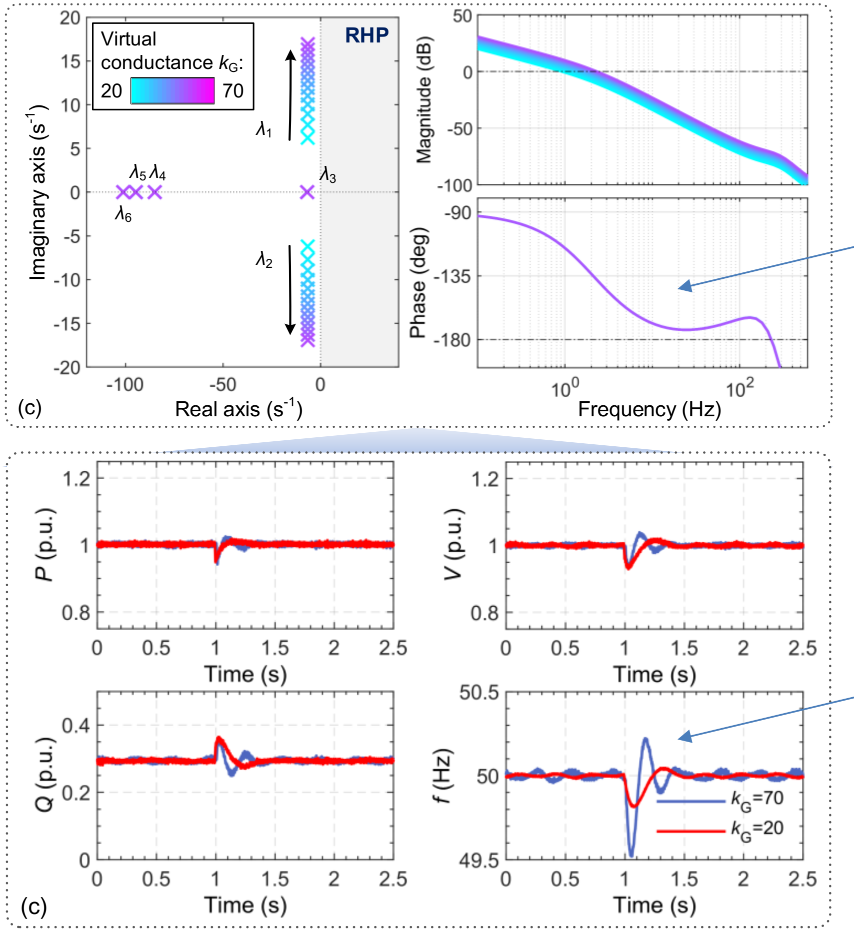


Simulations

HiL tests
5% V^* change applied

Validation

- Impact of synchronization parameters: k_G



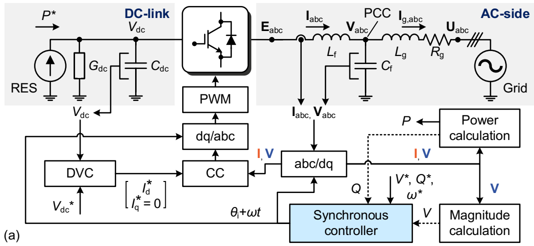
Simulations

HiL tests
5% V^* change applied

Conclusion

- This work proposed a synchronous control strategy for grid-tied GFL-IBRs based on the ac-side capacitor dynamics, named *CacDS GFL-IBR*.

Control Diagram:



- It enables synchronization independent of the active power control and PLL, offering explicit synchronous inertia and damping coefficients.

Inertia term: $\frac{k_{\mathrm{J}}}{\omega_{\mathrm{b}}} s^2 \tilde{\theta}_{\mathrm{i}}$ + Damping term: $\frac{k_{\mathrm{D}}}{\omega_{\mathrm{b}}} s \tilde{\theta}_{\mathrm{i}}$

- The analysis study further confirms that reactive power synchronization (RPS)-based designs manifests GFL-IBR behaviors, not GFM ones.

L_g impacts on Q-based sync.:

$$\frac{k_{\mathrm{J}}}{\omega_{\mathrm{b}}} s\tilde{\omega} + \frac{k_{\mathrm{D}}}{\omega_{\mathrm{b}}}\tilde{\omega} = \tilde{Q}_{\mathrm{g}} - U_0 I_0 \cos\theta_{\mathrm{i0}}\tilde{\theta}_{\mathrm{i}} + L_{\mathrm{g}} I_0^2 \tilde{\omega} \qquad (11)$$

$$\Leftrightarrow \frac{k_{\mathrm{J}}}{\omega_{\mathrm{b}}} s\tilde{\omega} + \left(\frac{k_{\mathrm{D}}}{\omega_{\mathrm{b}}} \boxed{- L_{\mathrm{g}} I_0^2}\right)\tilde{\omega} = \tilde{Q}_{\mathrm{g}} - U_0 I_0 \cos\theta_{\mathrm{i0}}\tilde{\theta}_{\mathrm{i}}$$

Thank you!

Zehua Tang

zehua.tang@kcl.ac.uk

Publication:

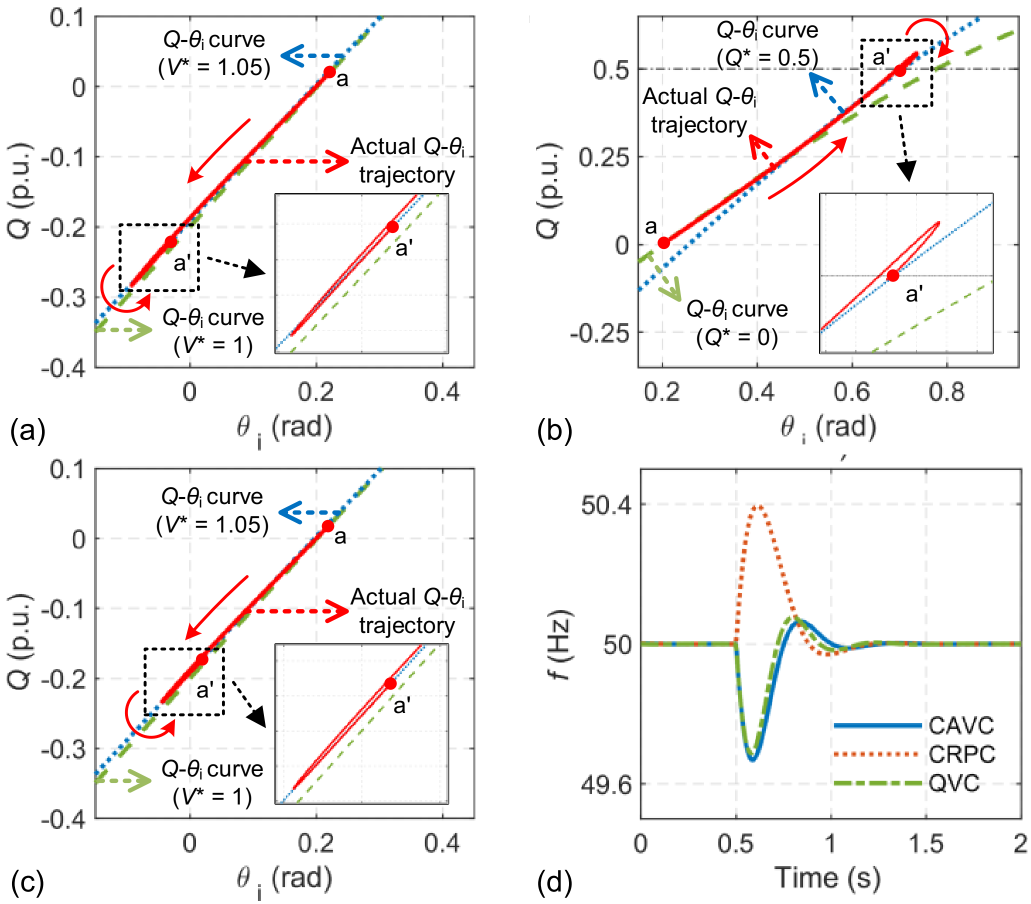
Zehua Tang, Hao Zou, and Grazia Todeschini, "Ac capacitor dynamics-based synchronous control for grid-following operations," *IEEE Trans. Industrial Electronics*, early access, Aug. 12, 2025.

GFL-IBR Control Design and Analysis

$$Q := UI\sin\theta_{\mathrm{i}} - X_{\mathrm{g}}I^2 \quad (10)$$

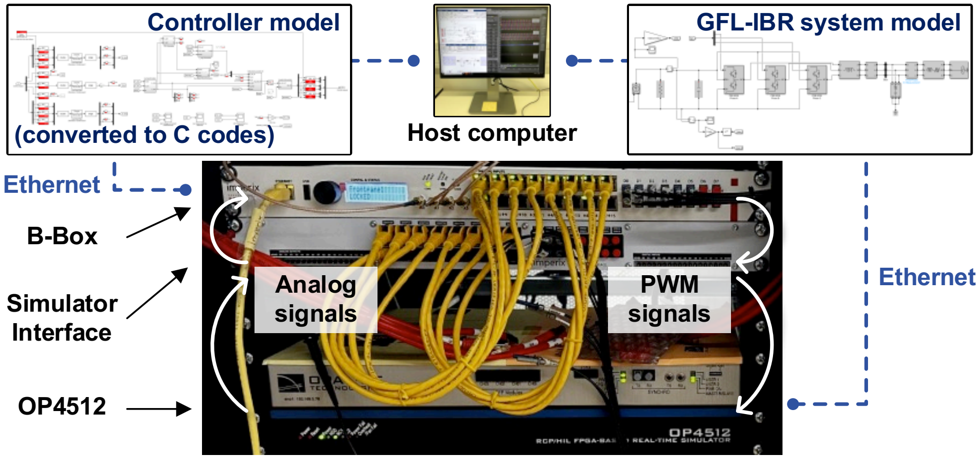
serves as the reference curve

- Numerical tests
  - An EMT simulation is built to exemplify the proposed method.
    - At 0.5 s, V^* steps from 1 to 1.05 p.u. for both the CAVC and QVC, and Q^* steps from 0 to 0.5 p.u. for the CRPC.
  - The inverter begins at ***point a*** on the initial curves and converges to a new equilibrium ***point a'*** on the final curves after swings.
  - Beyond verifying the presented synchronous control, it highlights the tight coupling between the reactive power output Q and the control-dependent angle ϑ_{i} in the GFL-IBR.



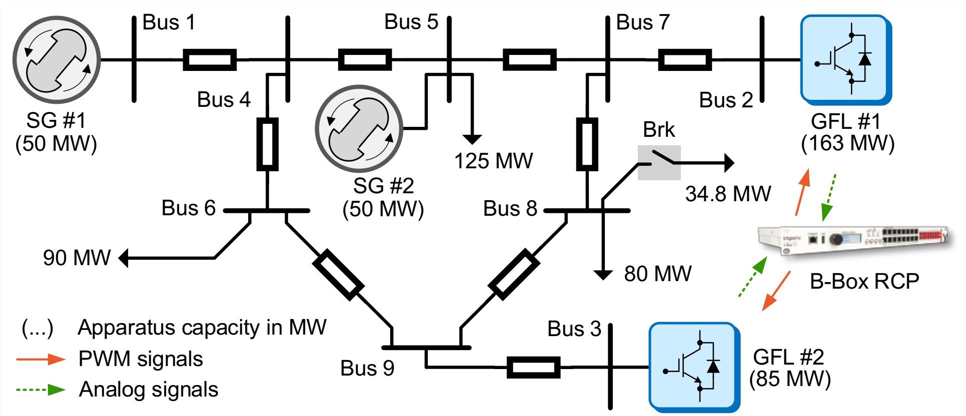
Validation

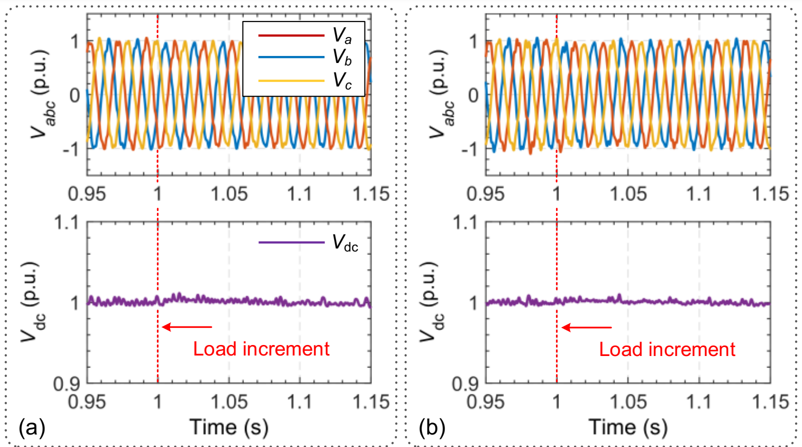
- Experimental setup
  - The experimental study is conducted on the platform in the right figure, which consists of
    - an Imperix B-Box RCP 3.0 for control algorithm implementation (in C codes), and
    - an OPAL-RT OP4512 that emulates the system physical circuits with a simulation time step of 5 us.
    - Signal exchange between the two devices is managed by the Imperix simulator interface, enabling real-time controller hardware-in-the-loop (CHIL) testing.
  - Both the B-Box and OP4512 are linked to a host computer via Ethernet cables for signal recording using the Imperix Cockpit software, as well as for applying associated perturbations.



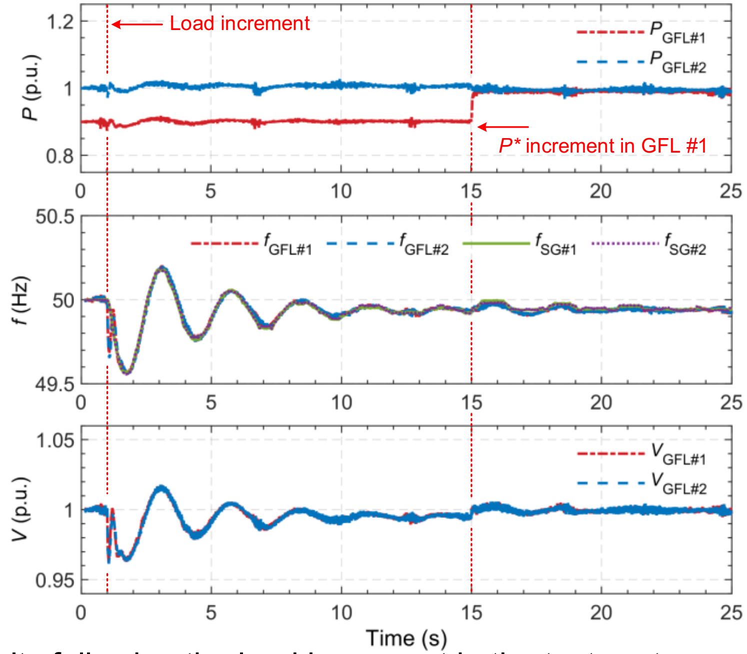
Validation

- Impact of Power Variation in Network Scenario (WSCC 9-bus grid-based)





Voltages following the load increment for (a) GFL #1 and (b) GFL #2.



Results following the load increment in the test system and P^* increment in GFL #1.

– These results demonstrate the compatibility and robust operation of the CacDS GFL-IBR within an ac power system environment.