



清華大學
Tsinghua University



IECON 2021

47th Annual Conference of the
IEEE Industrial Electronics Society
OCTOBER 13 - 16, 2021 | VIRTUAL CONFERENCE

Transient stability of power electronics-dominated power networks: principle and application

Hua GENG,
PhD, FIEEE, FIET

Dept. of Automation, Tsinghua University,
Beijing, China 100084

Xiuqiang He,
PhD, MIEEE

→ Automatic Control Laboratory (IfA), ETH
Zürich, Switzerland

2021.10.15 IEEE IECON 2021

About me



Xiuqiang He

Education

- **Ph.D. in Control Science and Engineering**
Tsinghua University, China, Aug. 2016 – Jun. 2021
- **B.S. in Automatic Control**
Tsinghua University, China, Aug. 2012 – Jun. 2016

Working experience

- Nov. 2021 – , Automatic Control Laboratory (IfA), ETH Zürich, Switzerland

Research interests

- Synchronization of power systems comprising heterogeneous devices
- Large-disturbance stability of power electronics-dominated power systems
- Generic modeling of inverter-based generation for power system simulations

PART II: Transient Stability

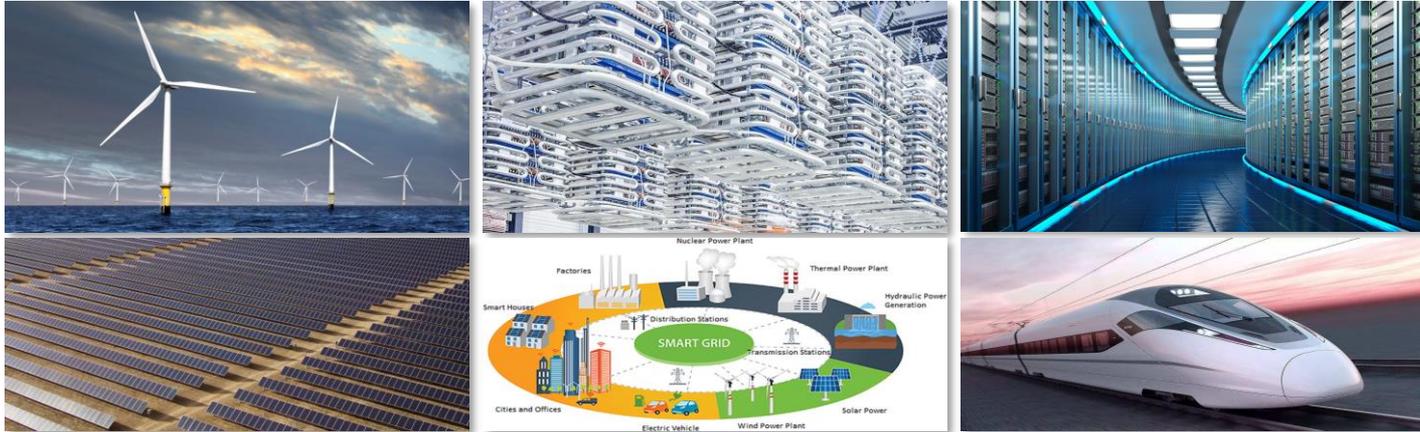
- **Synchronization approaches: principles and classifications**
- **Transient stability of grid-connected converters**
- **Transient stability of power systems with converters / generators**
- **Stability improvements and grid code specifications**

PART II: Transient Stability

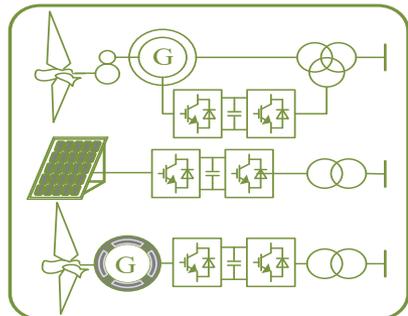
- **Synchronization approaches: principles and classifications**
- **Transient stability of grid-connected converters**
- **Transient stability of power systems with converters / generators**
- **Stability improvements and grid code specifications**

High-penetration of power electronics

- Power systems are facing a trend of a high penetration of power electronics on the generation/transmission/distribution side.

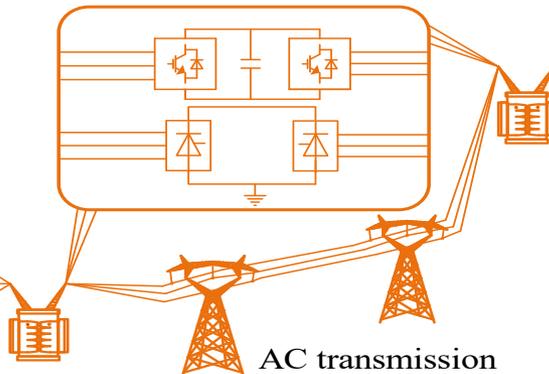


Converter-based generation



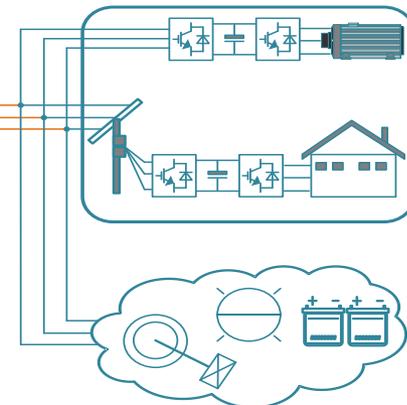
Thermal power generation

Converter-based transmission



AC transmission

Converter-based distribution



Traditional electric loads

Definition of transient stability

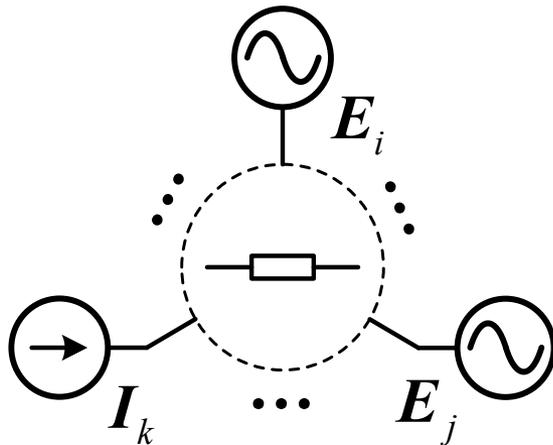
The ability of synchronous generators to remain in synchronism when subjected to disturbances.

**Conventional
power systems**



The ability of synchronous generators **and/or converters** to remain in synchronism when subjected to disturbances.

**Future
power systems**

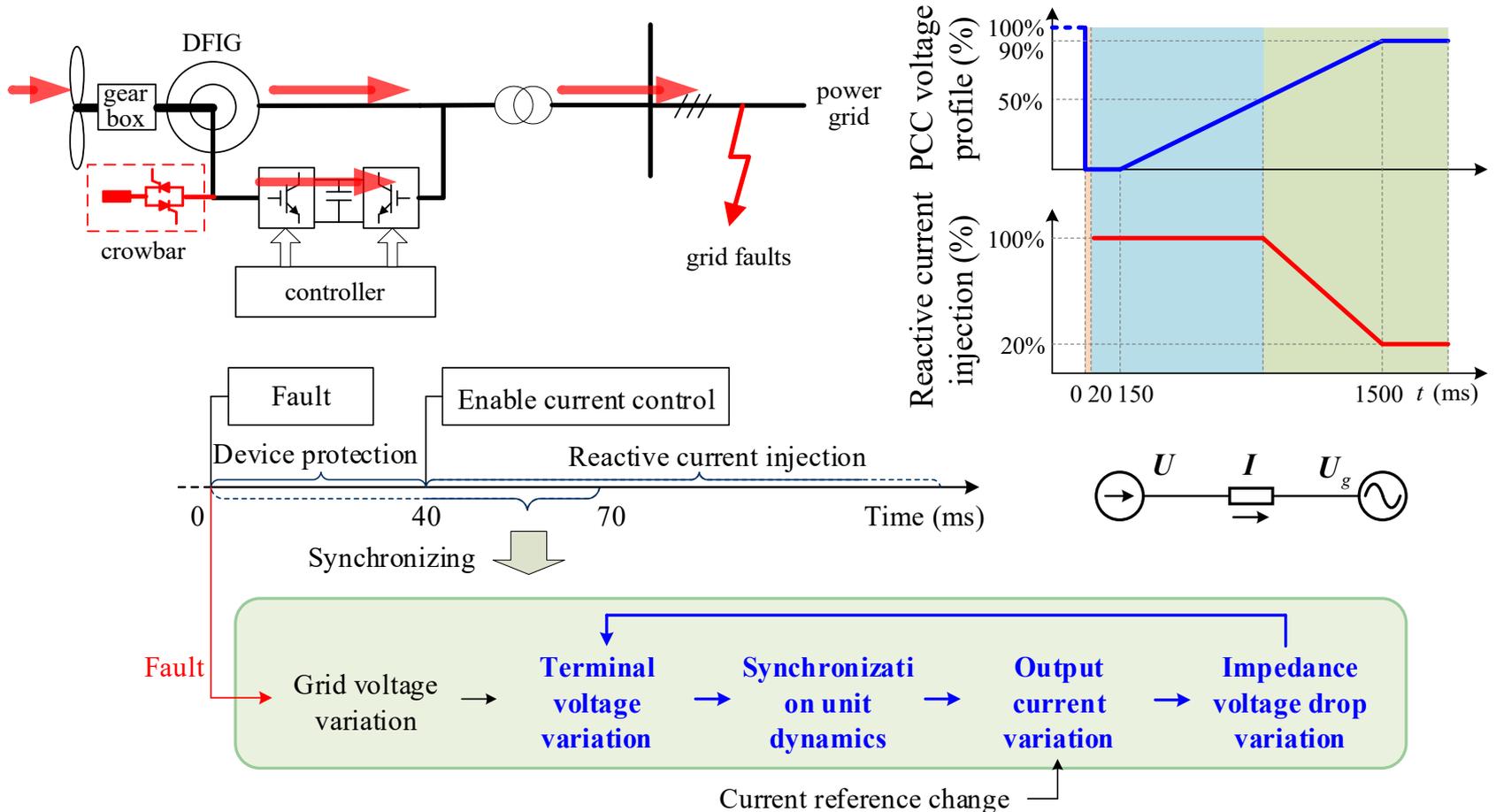


$$t \rightarrow \infty,$$
$$\dot{\theta}_1 \rightarrow \dot{\theta}_2 \rightarrow \dots \rightarrow \dot{\theta}_N \rightarrow \omega_{sync} \in \mathbb{R} [1]$$

[1] Dörfler F, Bullo F. Synchronization in complex networks of phase oscillators: A survey[J]. Automatica, 2014, 50(6): 1539-1564.

Real cases of loss of synchronism (LOS)

■ LOS under grid faults of PV resources in Southern California [2,3]



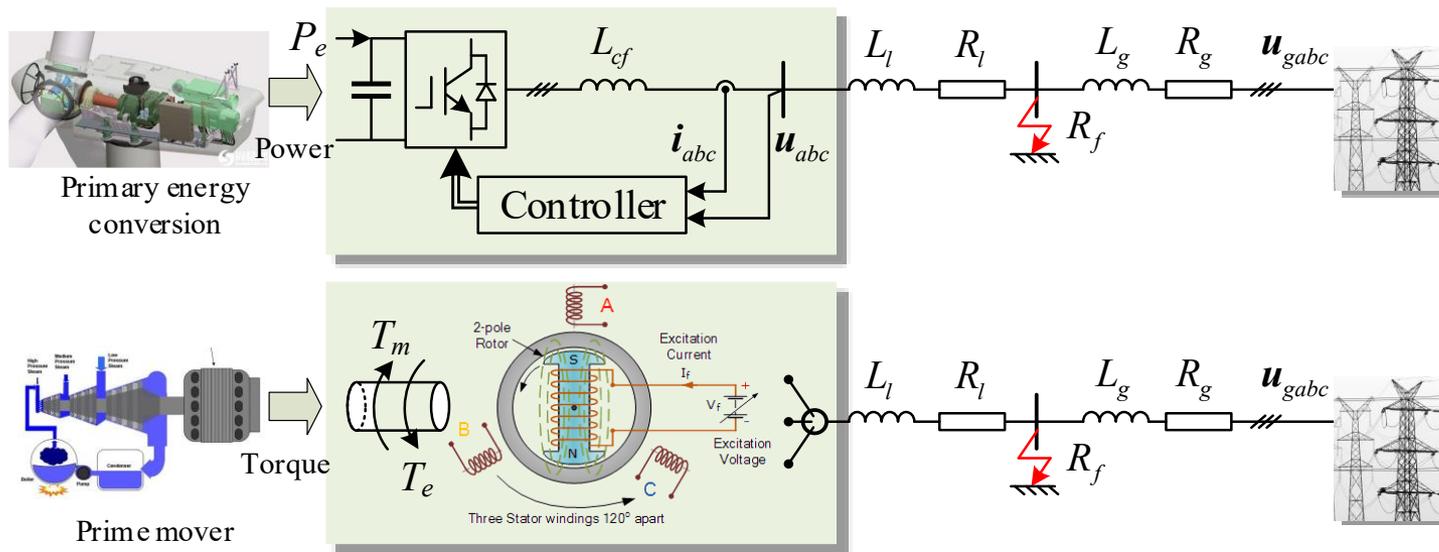
[2] NERC/WECC Inverter Task Force. 1200 MW fault induced solar photovoltaic resource interruption disturbance report[R]. Atlanta: North American Electric Reliability Corporation (NERC), 2017.

[3] Joint NERC and WECC Staff. 900 MW fault induced solar photovoltaic resource interruption disturbance report[R]. Atlanta: North American Electric Reliability Corporation (NERC), 2018.

Difference between generators and converters

- Central
- Large rotational inertia
- Self-synchronization
- Mainly electromechanical
- Large short-circuit current
- Slow actuation & control

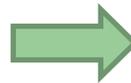
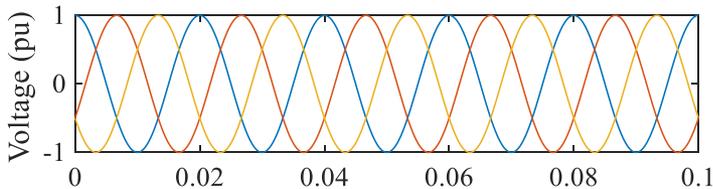
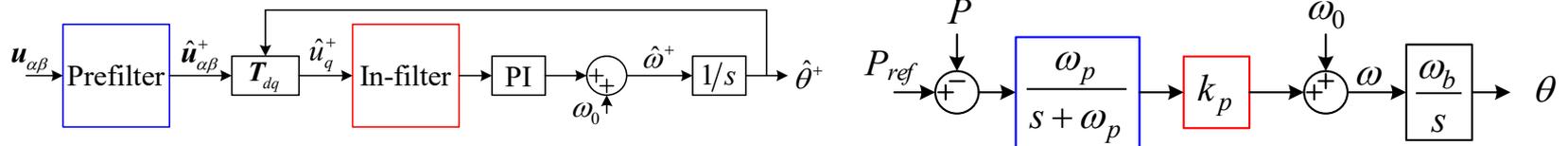
- Distributed, massive
- Almost no energy storage
- No inherent self-synchronization
- Multi-timescale
- Limited short-circuit current
- Fast/flexible control



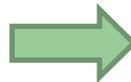
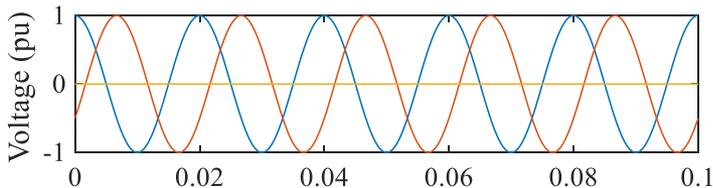
Synchronization approaches

- Classifications of synchronization approaches

	Grid-following (GFL)	Grid-forming (GFM)
Schemes	PLL, FLL	Droop, VSM, matching, VOC, etc.
Domains	Positive- and negative-sequence	Positive-sequence



Positive-sequence synchronization

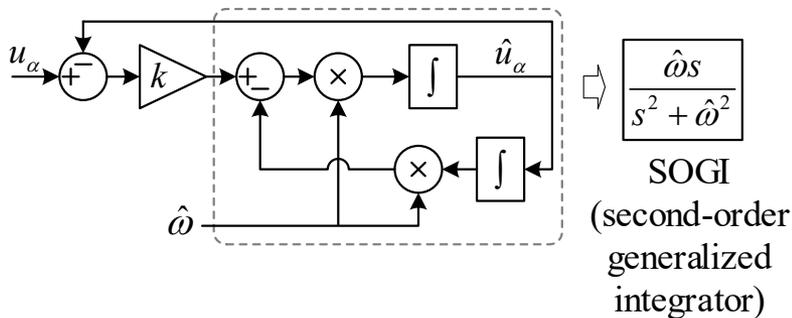


Dual sequence synchronization

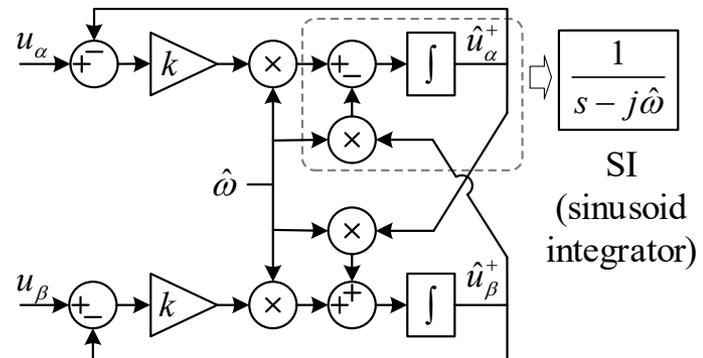
Synchronization approaches

- GFL approaches

Existing PLLs	Existing FLLs
Notch filters: ANF, SOGI-QSG, AQSG, SF, CBF, ROR, ROGI, AVF, etc. (eight options)	Notch filters: ANF, SOGI-QSG, AQSG, SF, CBF, ROR, ROGI, AVF, etc. (eight options)
Types of regulator: P-type, I-type, PI-type (three options)	Types of regulator: P-type, I-type, PI-type (three options)
In-filters: LPF, MAF, Lead-lag, etc. (three options)	Adaptive parameters: frequency, quasi-frequency (two options)
	Dimensions of FD: single, two (two options)

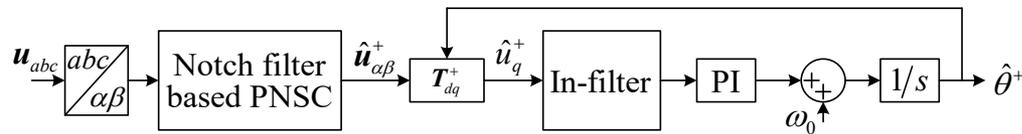


Notch filters: RCF \uparrow and CCF \rightarrow

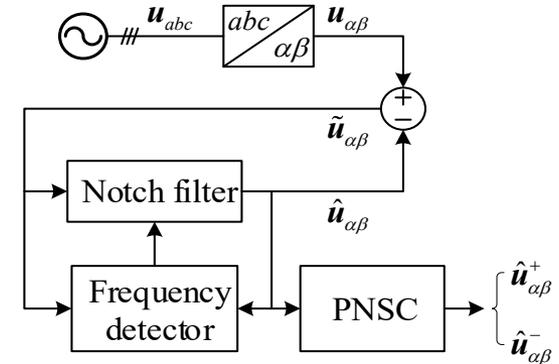


Synchronization approaches

- Generalized GFL approaches (PLLs/FLLs)



Framework of PLLs \uparrow and FLLs \rightarrow

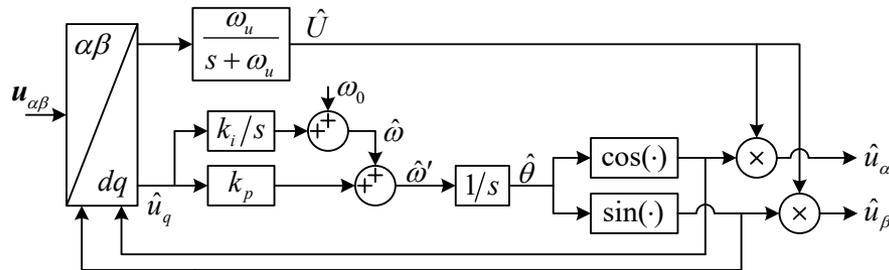


- Method:** the model reference adaptive control (MRAC) method.
- Result:**
 - ✓ PLLs/FLLs are essentially the same
 - ✓ PLLs/FLLs can be represented by a unified prototype in studies of synchronization stability.

[4] He X, Geng H, Yang G. A generalized design framework of notch filter based frequency-locked loop for three-phase grid voltage[J]. IEEE Transactions on Industrial Electronics, 2017, 65(9): 7072-7084.

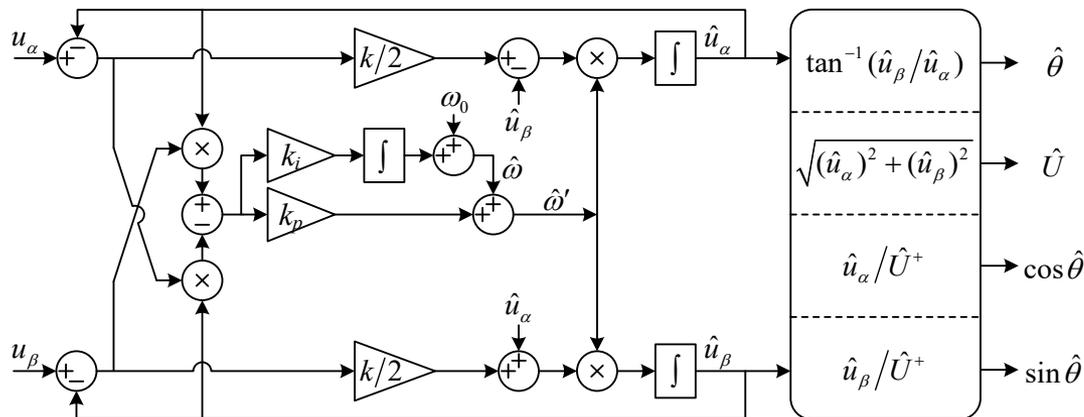
Synchronization approaches

- A unified prototype of PLL/FLLs (balanced conditions)



$$\begin{cases} \dot{\hat{\theta}} = \hat{\omega} + k_{p\text{PLL}} (-u_\alpha \sin \hat{\theta} + u_\beta \cos \hat{\theta}) \\ \dot{\hat{\omega}} = k_{i\text{PLL}} (-u_\alpha \sin \hat{\theta} + u_\beta \cos \hat{\theta}) \\ \dot{\hat{U}} = \omega_u (u_\alpha \cos \hat{\theta} + u_\beta \sin \hat{\theta} - \hat{U}) \end{cases}$$

Mathematically equivalent



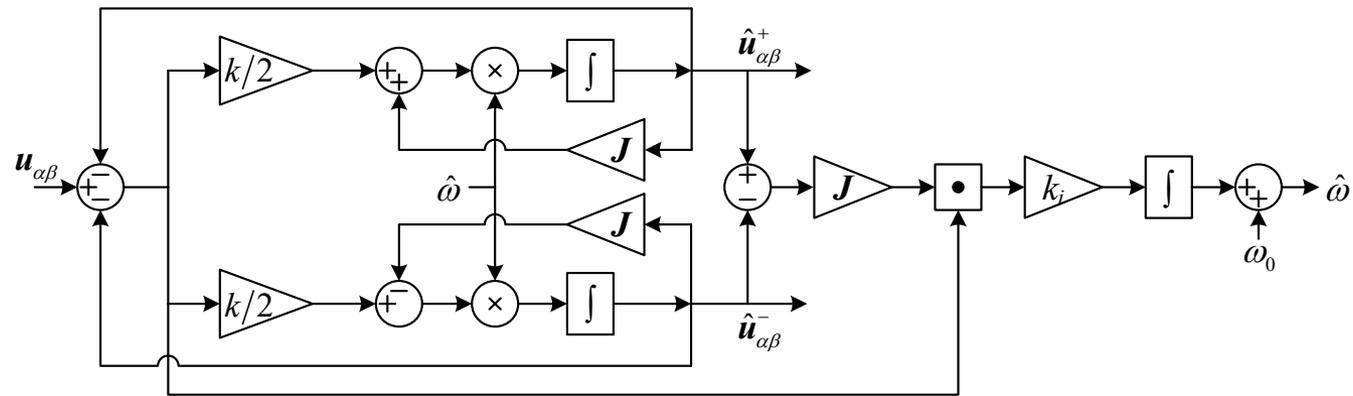
$$\begin{cases} \dot{\hat{\theta}} = \hat{\omega} + \left(k_{p\text{FLL}} \hat{U} + \frac{k \hat{\omega}'}{2 \hat{U}} \right) (-u_\alpha \sin \hat{\theta} + u_\beta \cos \hat{\theta}) \\ \dot{\hat{\omega}} = k_{i\text{FLL}} \hat{U} (-u_\alpha \sin \hat{\theta} + u_\beta \cos \hat{\theta}) \\ \dot{\hat{U}} = \frac{k \hat{\omega}'}{2} (u_\alpha \cos \hat{\theta} + u_\beta \sin \hat{\theta} - \hat{U}) \end{cases}$$

A unified prototype of PLLs/FLLs under balanced conditions

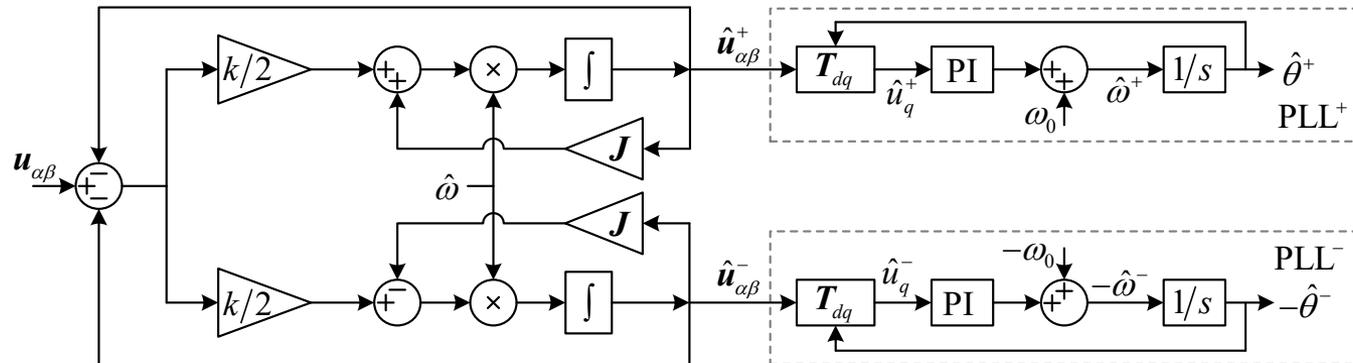
[5] Golestan S, Guerrero J M, Rawa M J H, et al. FLLs in electrical power energy systems: Equivalent or different to PLLs?[J/OL]. IEEE Industrial Electronics Magazine, 2021: 0-0. DOI: 10.1109/MIE.2021.3054580.

Synchronization approaches

- A unified prototype of PLL/FLLs (unbalanced conditions)



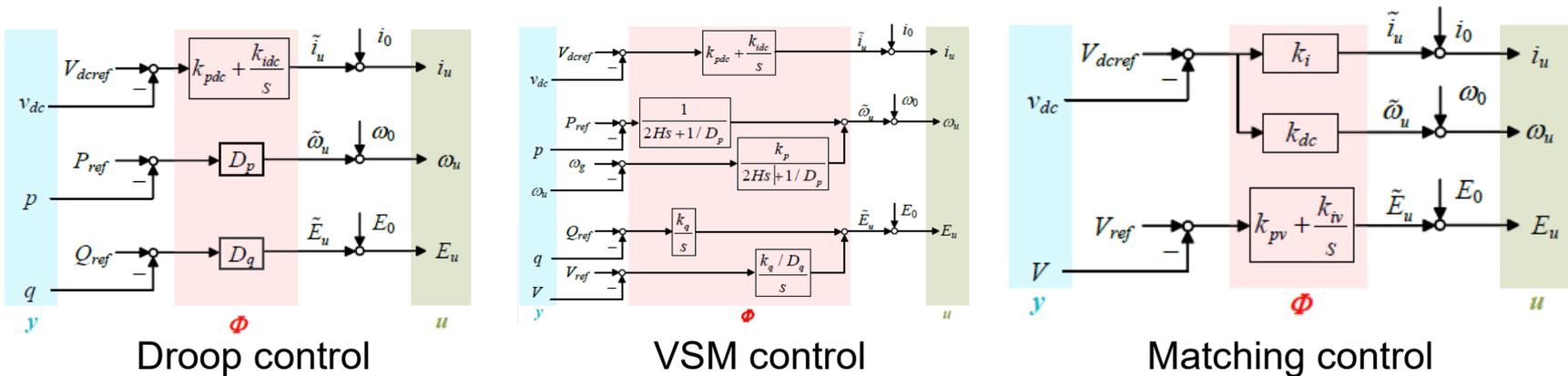
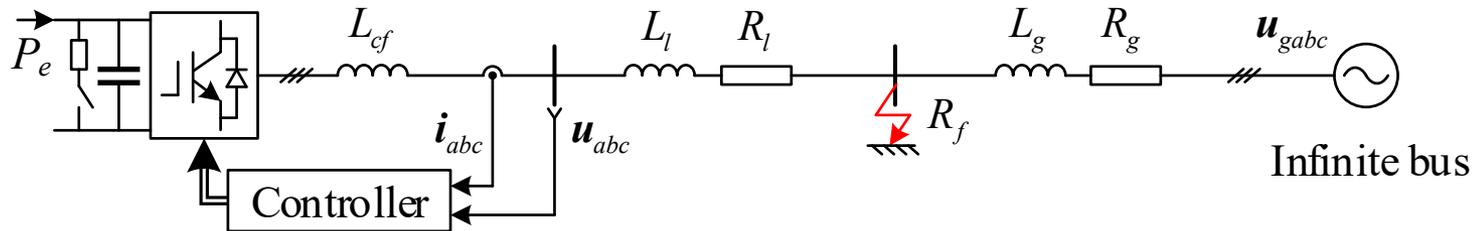
Not equivalent



Unified prototypes of PLLs and FLLs under unbalanced conditions

Synchronization approaches

- GFM approaches

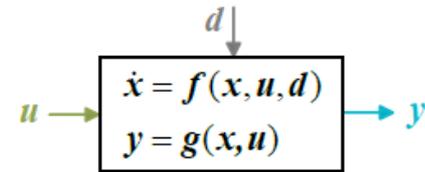
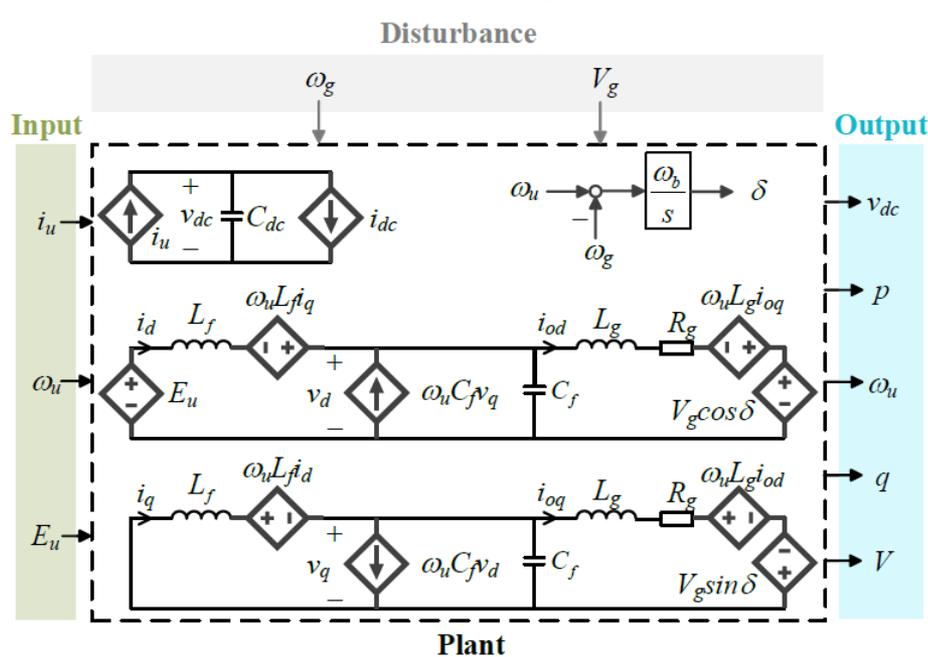


- Droop control is often inertialess.
- VSM and matching control is inertial.

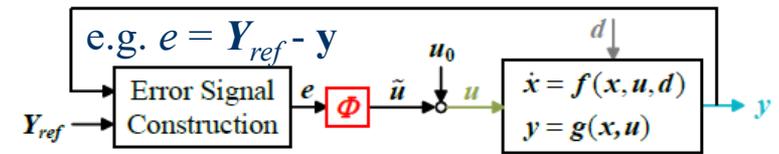
[6] Chen M, Zhou D, Tayyebi A, et al. Generalized multivariable grid-forming control design for power converters[J]. arXiv preprint arXiv:2109.06982, 2021.

Synchronization approaches

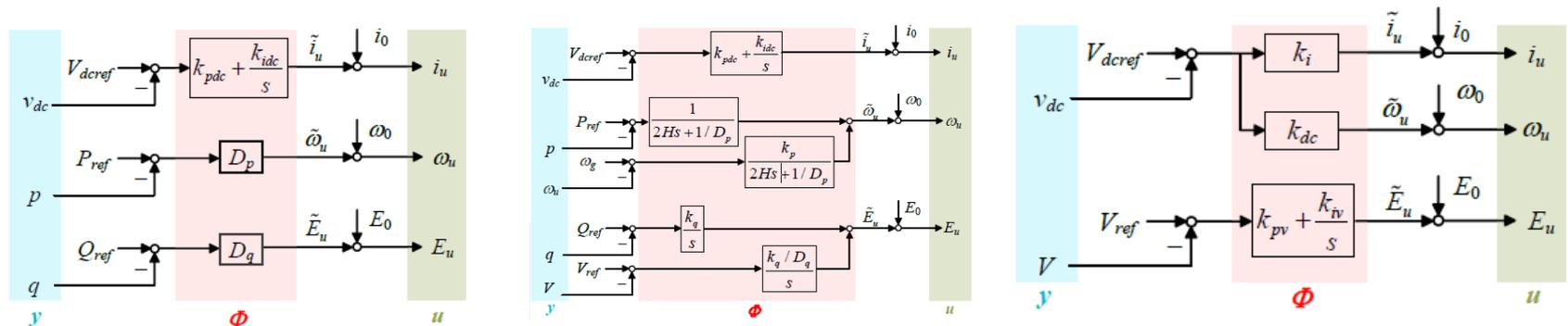
- Generalized GFM approaches



Plant model of GFM converters



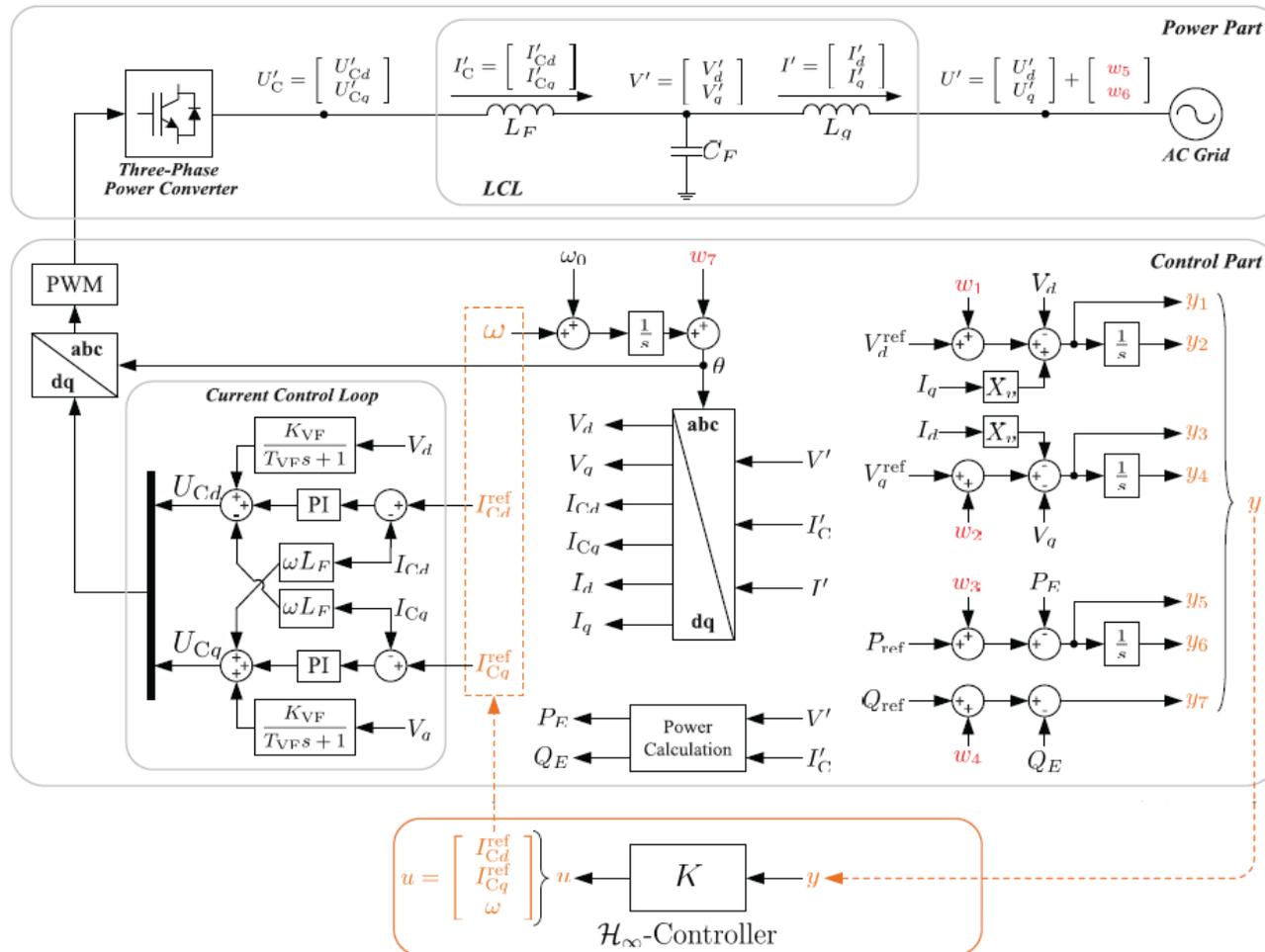
General MIMO close-loop feedback control framework for GFM converters



[6] Chen M, Zhou D, Tayyebi A, et al. Generalized multivariable grid-forming control design for power converters[J]. arXiv preprint arXiv:2109.06982, 2021.

Synchronization approaches

- Generalized GFM/GFL approaches



General MIMO
close-loop
feedback control
framework for
GFL/GFM
converters



Select the gain
matrix K



Optimal
synchronization
characteristics

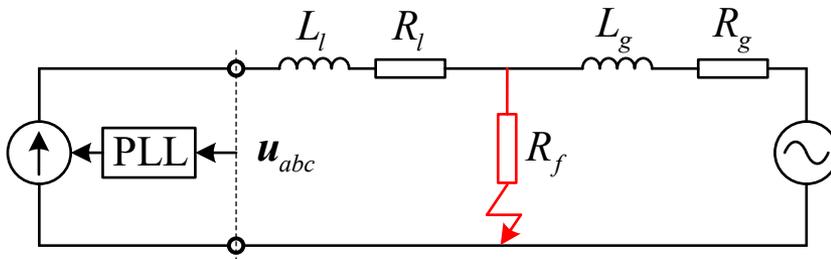
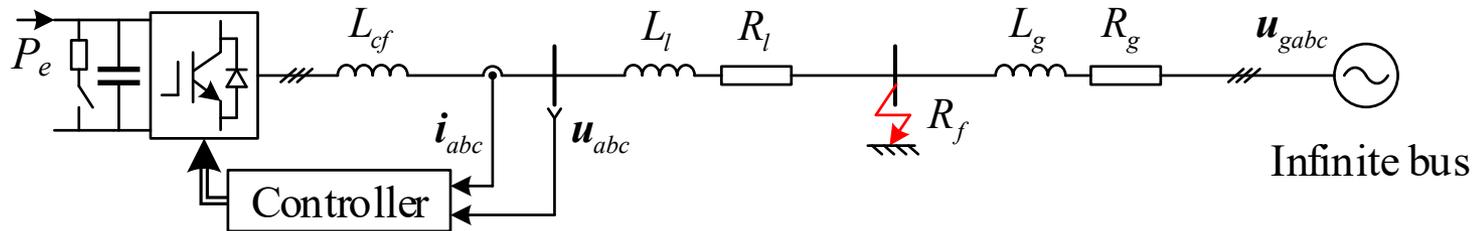
[7] Huang L, Xin H, Dörfler F. \mathcal{H}_∞ -control of grid-connected converters: design, objectives and decentralized stability certificates[J]. IEEE Transactions on Smart Grid, 2020, 11(5): 3805-3816.

PART II: Transient Stability

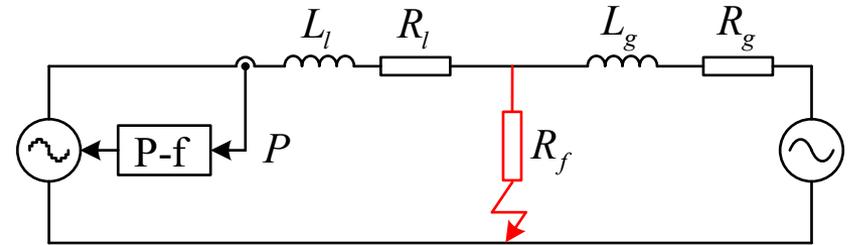
- Synchronization approaches: principles and classifications
- Transient stability of grid-connected converters
- Transient stability of power systems with converters / generators
- Stability improvements and grid code specifications

Transient stability of grid-connected converters

- Different controls, different stability performance



Grid-following converter

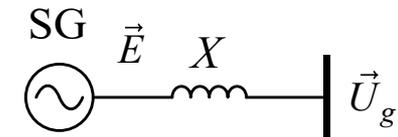
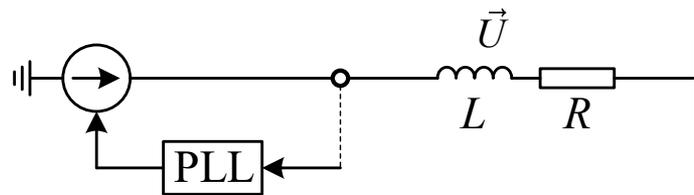
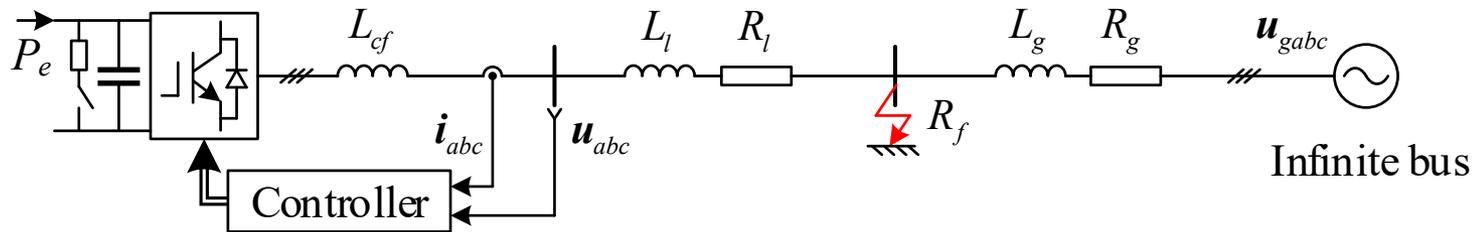


Grid-forming converter

	GFL control	GFM control
Disturbances	Symmetrical faults Asymmetrical faults	Symmetrical faults
Problems	Synchronization stability of GFL devices	Synchronization stability of GFM devices

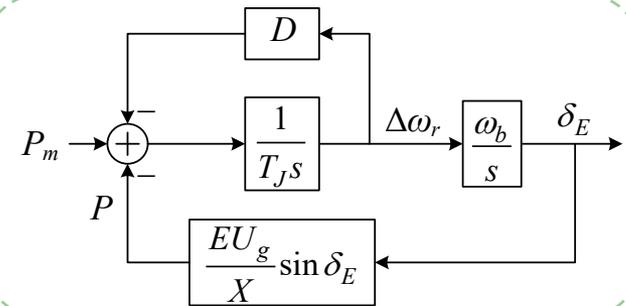
Transient stability of GFL converters

- Problem description



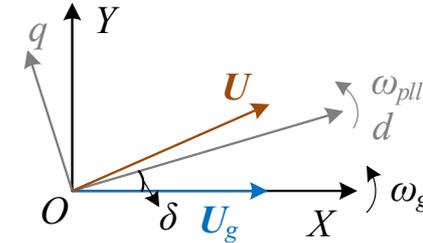
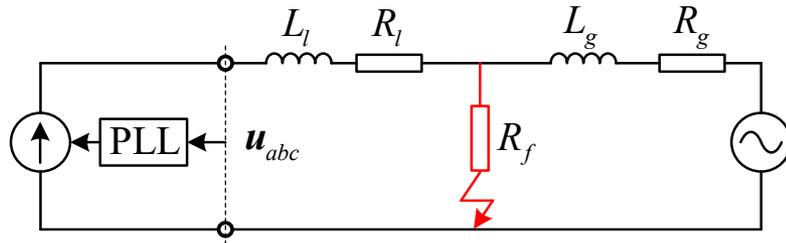
**Modeling, analysis
and control for GFL
converters?**

Similar
Approaches?

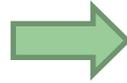


Transient stability of GFL converters

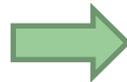
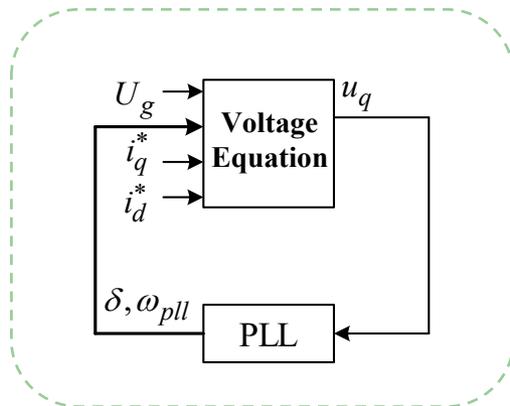
- Transient stability of GFL converters (symmetrical grid faults)



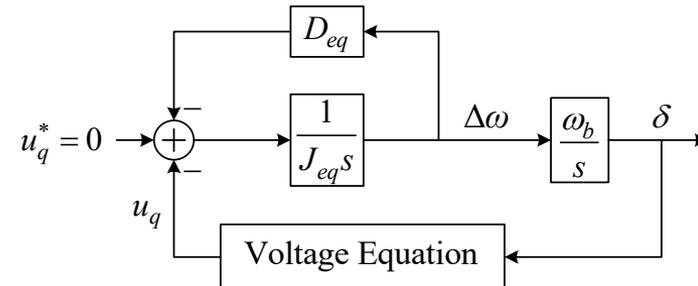
$$\begin{cases} d\Delta\omega/dt = k_p du_q/dt + k_i u_q \\ d\delta/dt = \Delta\omega \\ u_q = IZ_g \sin(\theta_l + \theta_z) - U_g \sin \delta \end{cases}$$



$$\begin{cases} J_{eq} d\Delta\omega/dt = u_q - D_{eq} \Delta\omega \\ d\delta/dt = \Delta\omega \\ u_q = IZ_g \sin(\theta_l + \theta_z) - U_g \sin \delta \end{cases}$$



$$J_{eq} = (1 - k_p L_g i_d) / k_i \approx 1/k_i \quad D_{eq} = k_p U_g \cos \delta / k_i$$



- Approaches from conventional power systems can be applied to GFL devices.

Transient stability of GFL converters

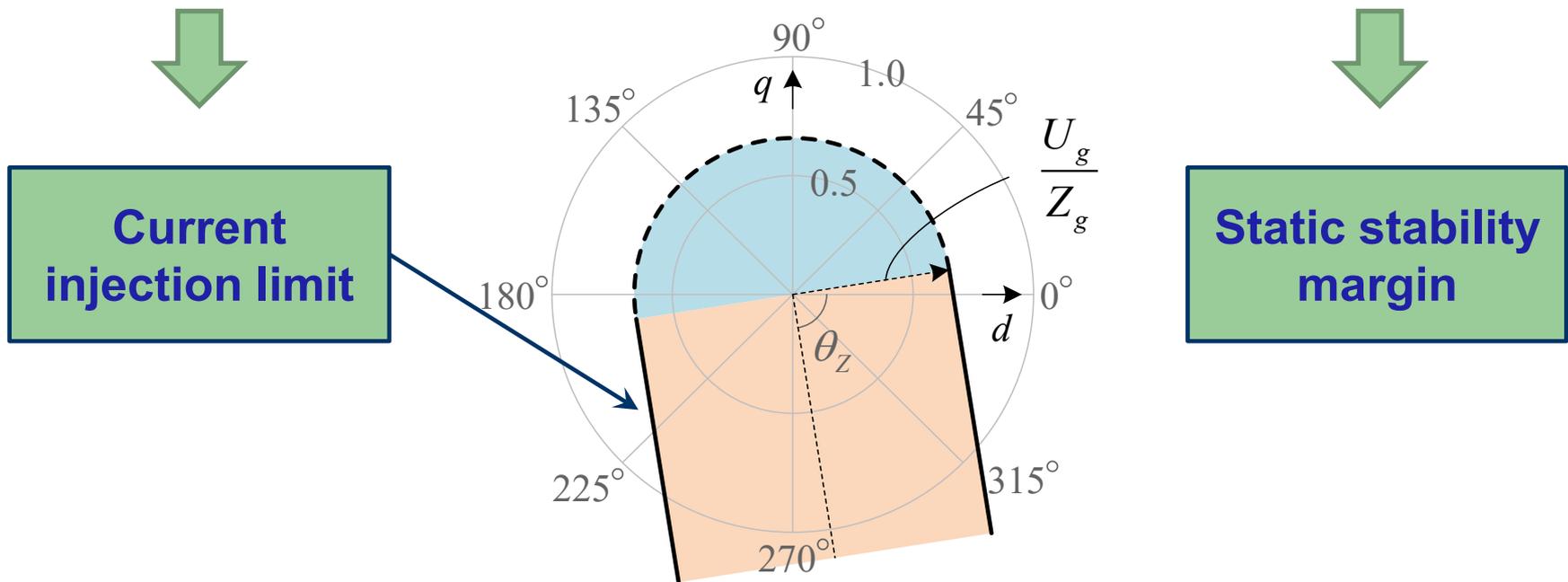
- Transient stability of GFL converters (symmetrical grid faults)

$$I_{\text{lim}} = \frac{U_g}{Z_g \sin(\theta_I + \theta_Z)}$$

$$u_q = IZ_g \sin(\theta_I + \theta_Z) - U_g \sin \delta$$

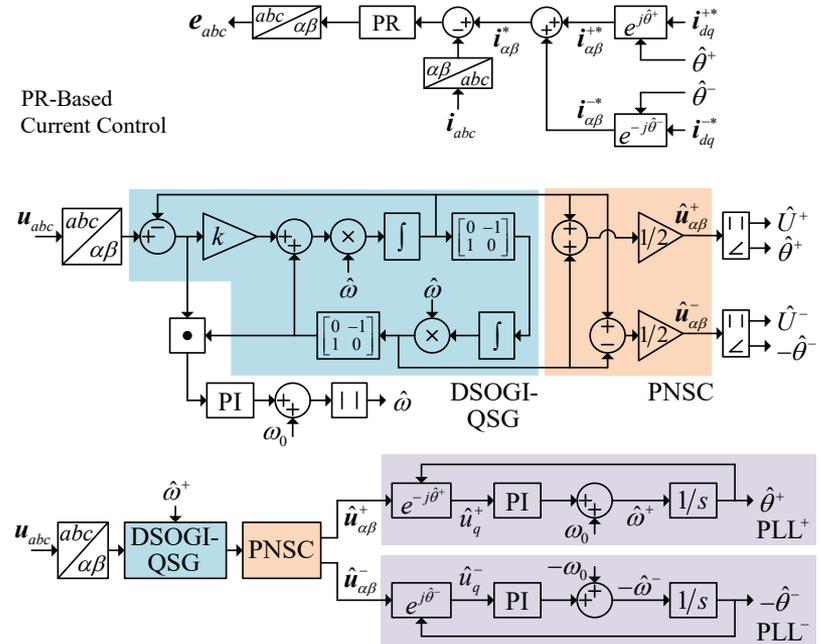
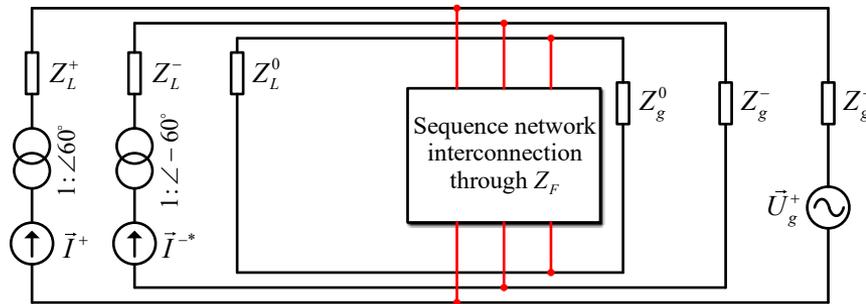
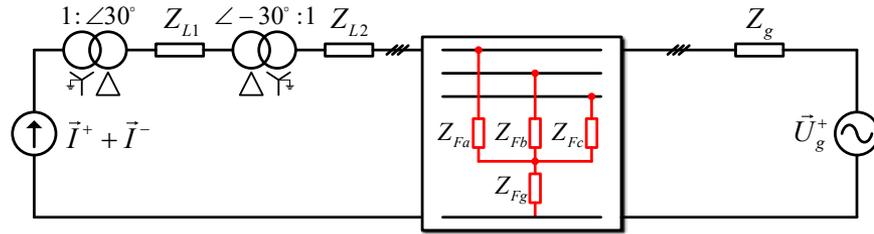
$$\Rightarrow \underbrace{IZ_g \sin(\theta_I + \theta_Z)}_a \leq U_g$$

$$\lambda = \frac{U_g - |a|}{U_g}$$



Transient stability of GFL converters

- Transient stability of GFL converters (asymmetrical grid faults)



Positive-sequence synchronization stability analysis

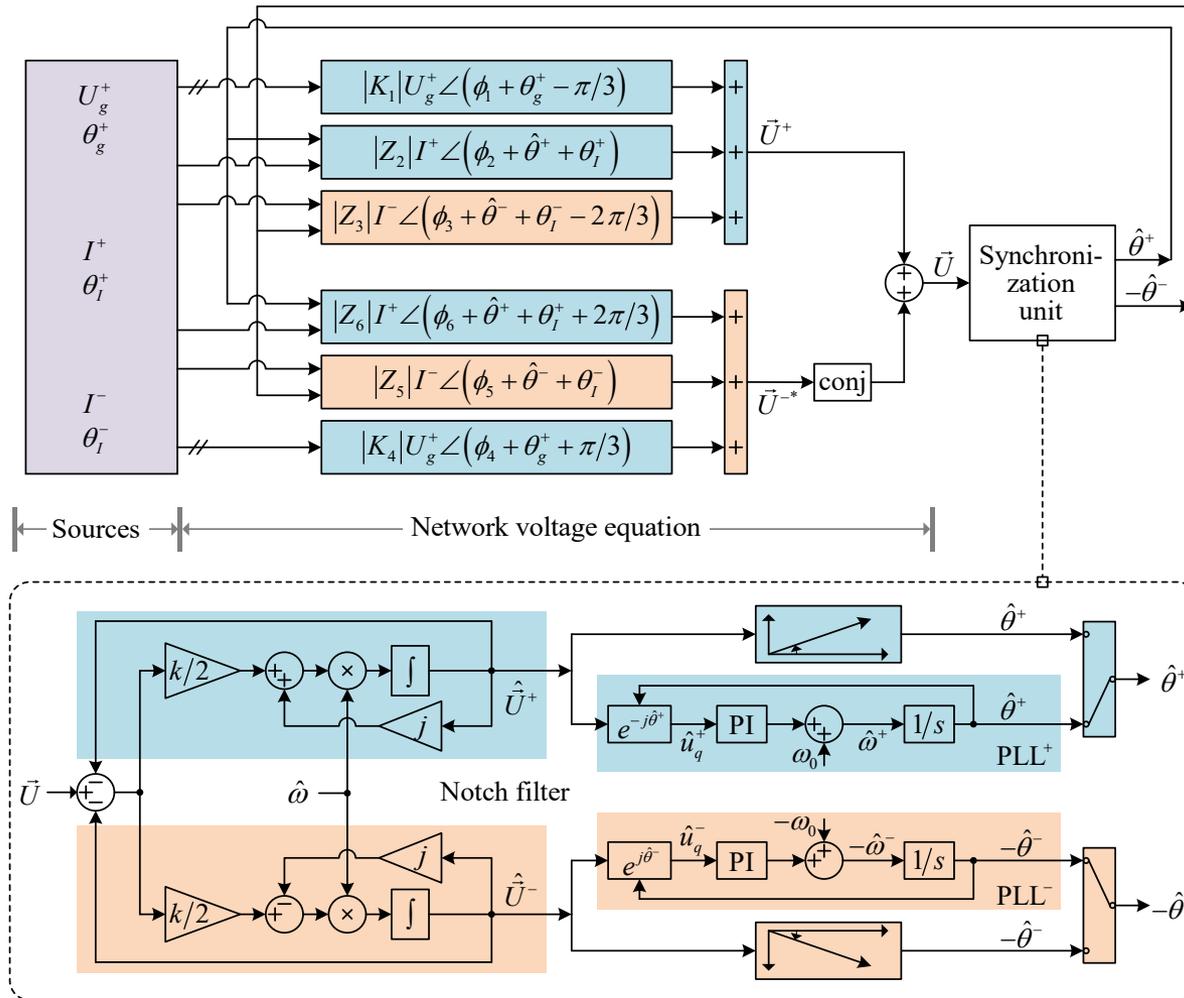


Dual-sequence synchronization stability analysis?

- The inter-sequence coupling makes things different and difficult.

Transient stability of GFL converters

- Transient stability of GFL converters (asymmetrical grid faults)

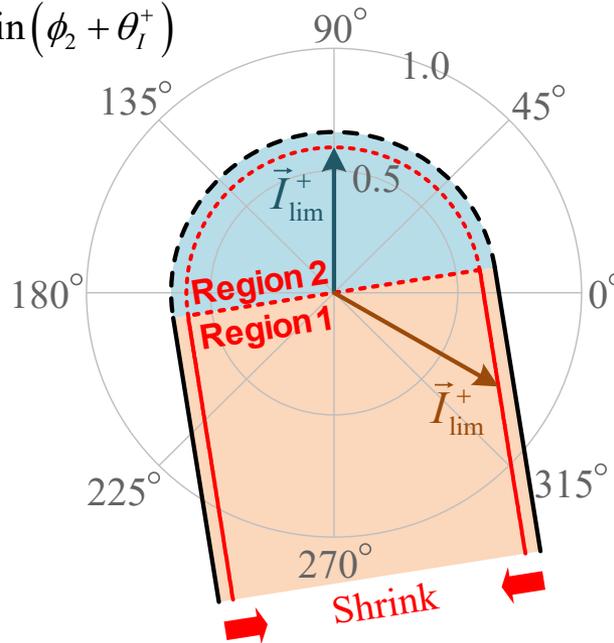


Transient stability of GFL converters

- **Transient stability of GFL converters (asymmetrical grid faults)**
 - Positive-sequence dominated instability
 - Negative-sequence dominated instability

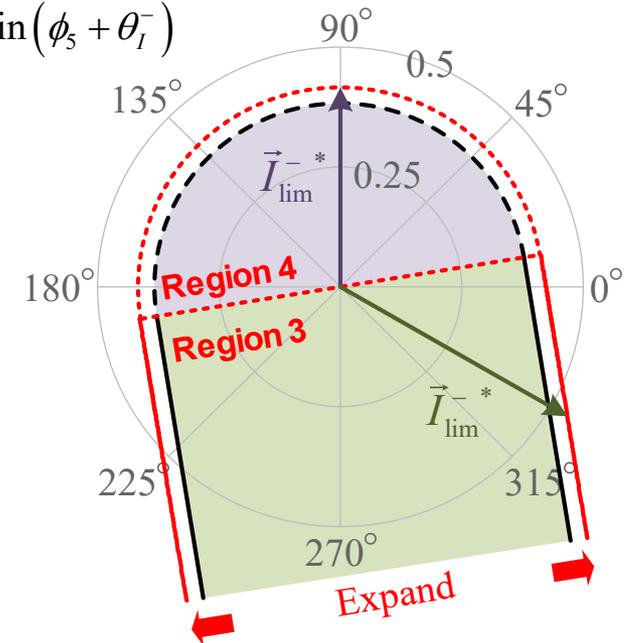
$$u_q^+ = |K_1|U_g^+ \sin(\phi_1 - \delta^+) + |Z_2|I^+ \sin(\phi_2 + \theta_I^+) + |Z_3|I^- \sin(\phi_3 + \theta_I^- - \delta^+ + \delta^-) = 0$$

$$I^+ \leq \frac{|K_1|U_g^+}{|Z_2|\sin(\phi_2 + \theta_I^+)}$$



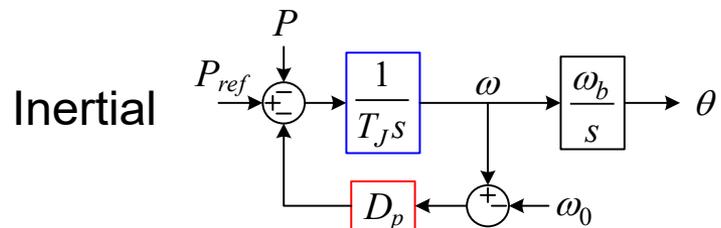
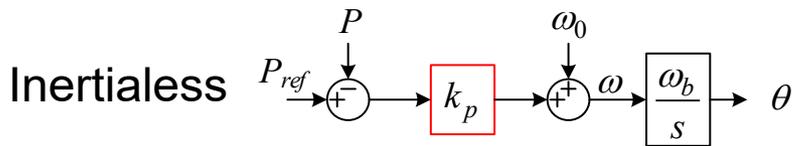
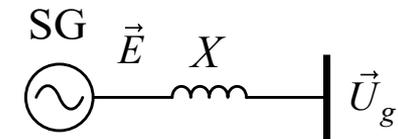
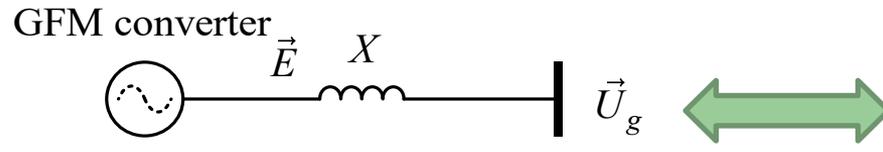
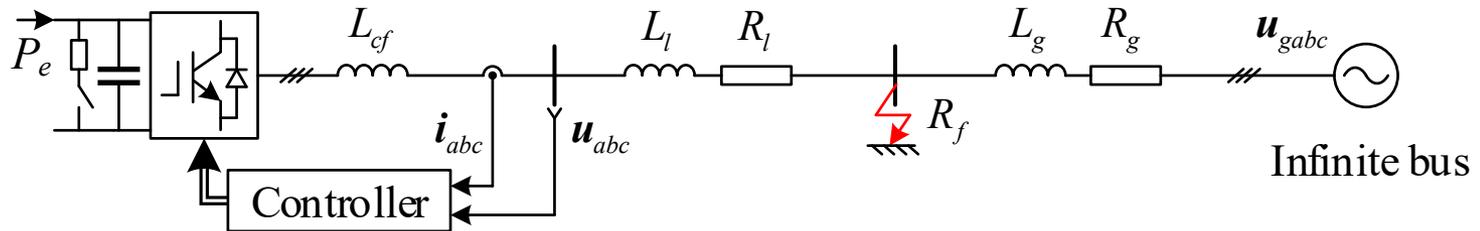
$$u_q^- = |K_4|U_g^+ \sin(\phi_4 - \delta^-) + |Z_5|I^- \sin(\phi_5 + \theta_I^-) + |Z_6|I^+ \sin(\phi_6 + \theta_I^+ + \delta^+ - \delta^-) = 0$$

$$I^- \leq \frac{|K_4|U_g^+}{|Z_5|\sin(\phi_5 + \theta_I^-)}$$

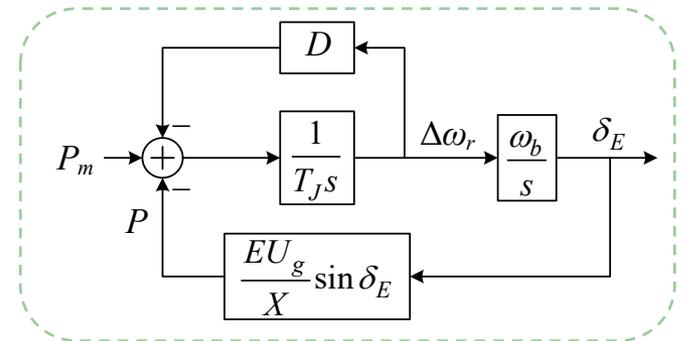


Transient stability of GFM converters

- Problem description

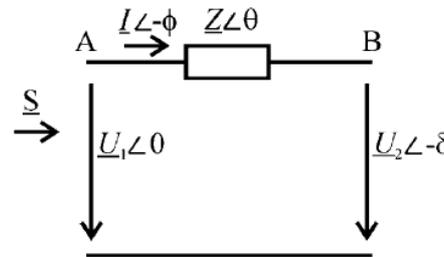
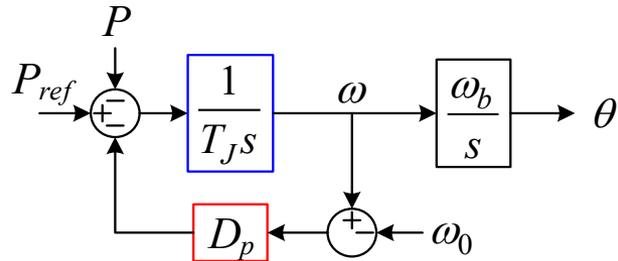


Similar approaches?



Transient stability of GFM converters

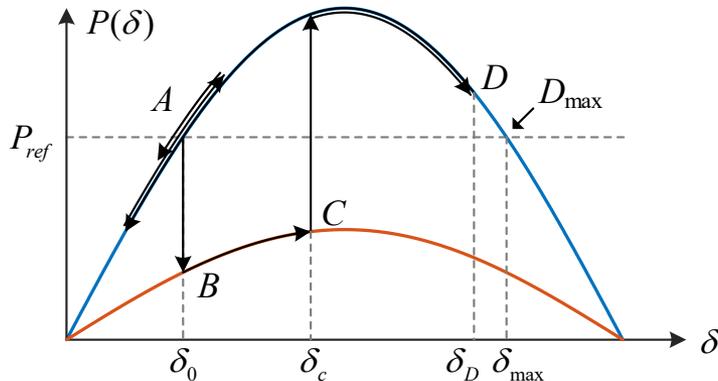
- Transient stability of inertial GFM converters (VSG)



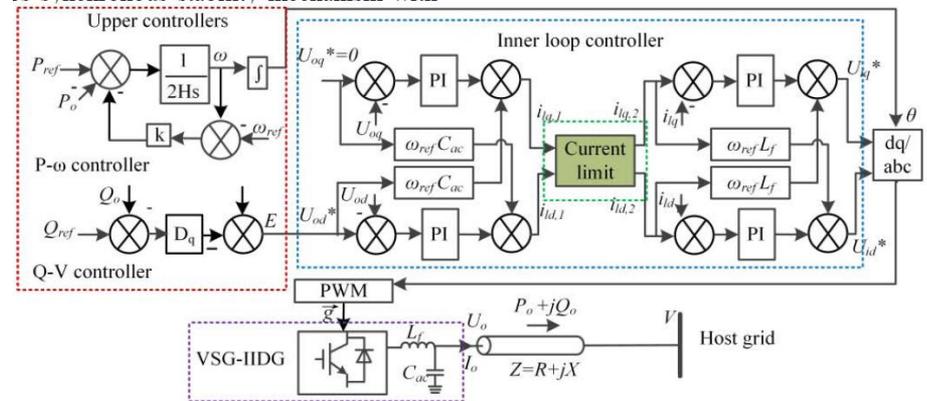
$$P = \frac{U_1^2}{Z} \cos \theta - \frac{U_1 U_2}{Z} \cos(\theta + \delta)$$

$$Q = \frac{U_1^2}{Z} \sin \theta - \frac{U_1 U_2}{Z} \sin(\theta + \delta).$$

P-Q coupling in networks



Basic stability characteristics



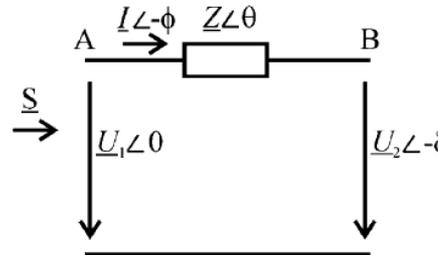
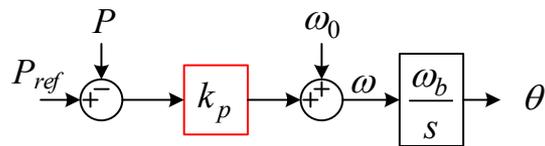
Current saturation nonlinear

[10] De Brabandere K, Bolsens B, Van den Keybus J, et al. A voltage and frequency droop control method for parallel inverters[J]. IEEE Transactions on power electronics, 2007, 22(4): 1107-1115..

[11] Li M, Huang W, Tai N, et al. Transient behavior analysis of VSG-IIDG during disturbances considering the current limit unit[C]//2019 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2019: 1-5.

Transient stability of GFM converters

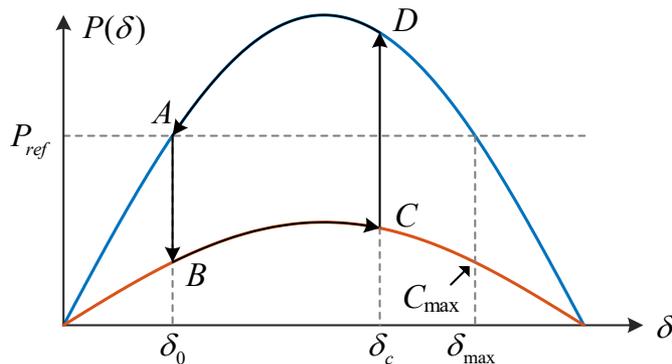
- Transient stability of inertialess GFM converters (droop)



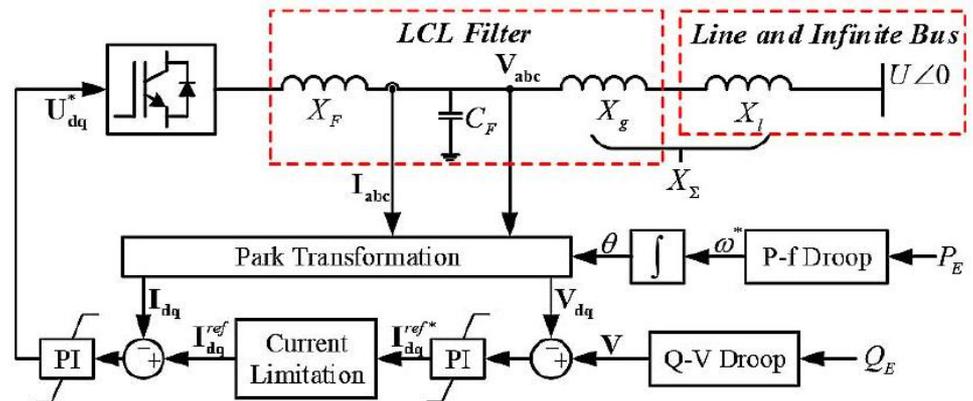
$$P = \frac{U_1^2}{Z} \cos \theta - \frac{U_1 U_2}{Z} \cos(\theta + \delta)$$

$$Q = \frac{U_1^2}{Z} \sin \theta - \frac{U_1 U_2}{Z} \sin(\theta + \delta).$$

P-Q coupling in networks



Basic stability characteristics



Current saturation nonlinear

[12] Xin H, Huang L, Zhang L, et al. Synchronous instability mechanism of P-f droop-controlled voltage source converter caused by current saturation[J]. IEEE Transactions on Power Systems, 2016, 31(6): 5206-5207.

PART II: Transient Stability

- **Synchronization approaches: principles and classifications**
- **Transient stability of grid-connected converters**
- **Transient stability of power systems with converters / generators**
- **Stability improvements and grid code specifications**

Transient stability of power systems with converters / generators

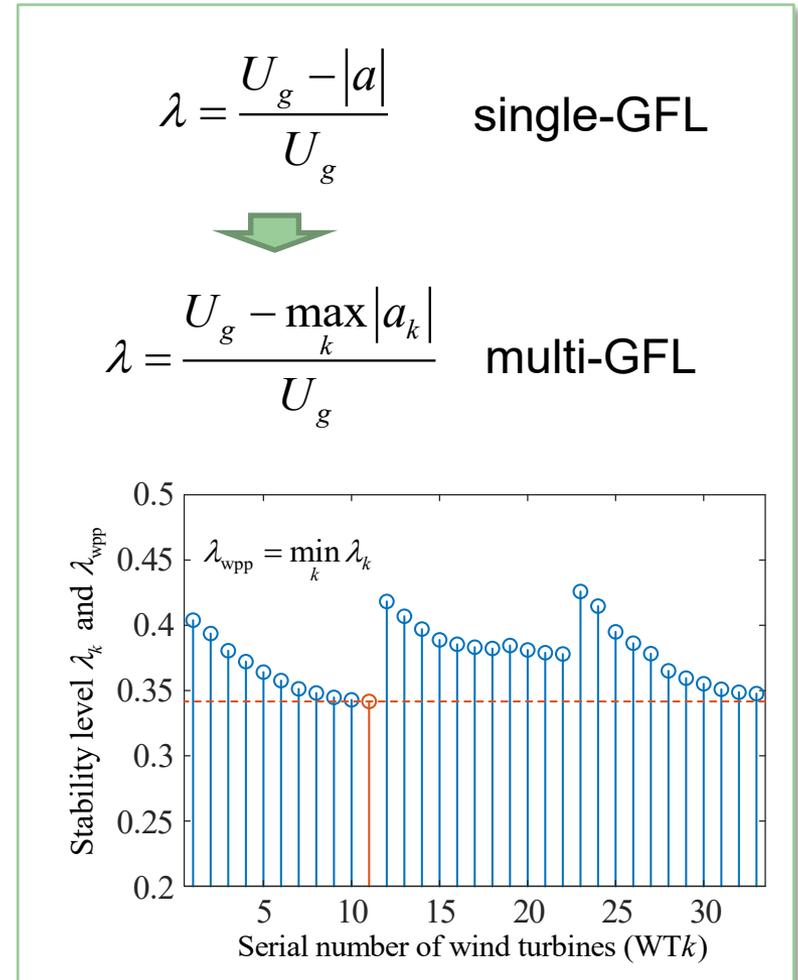
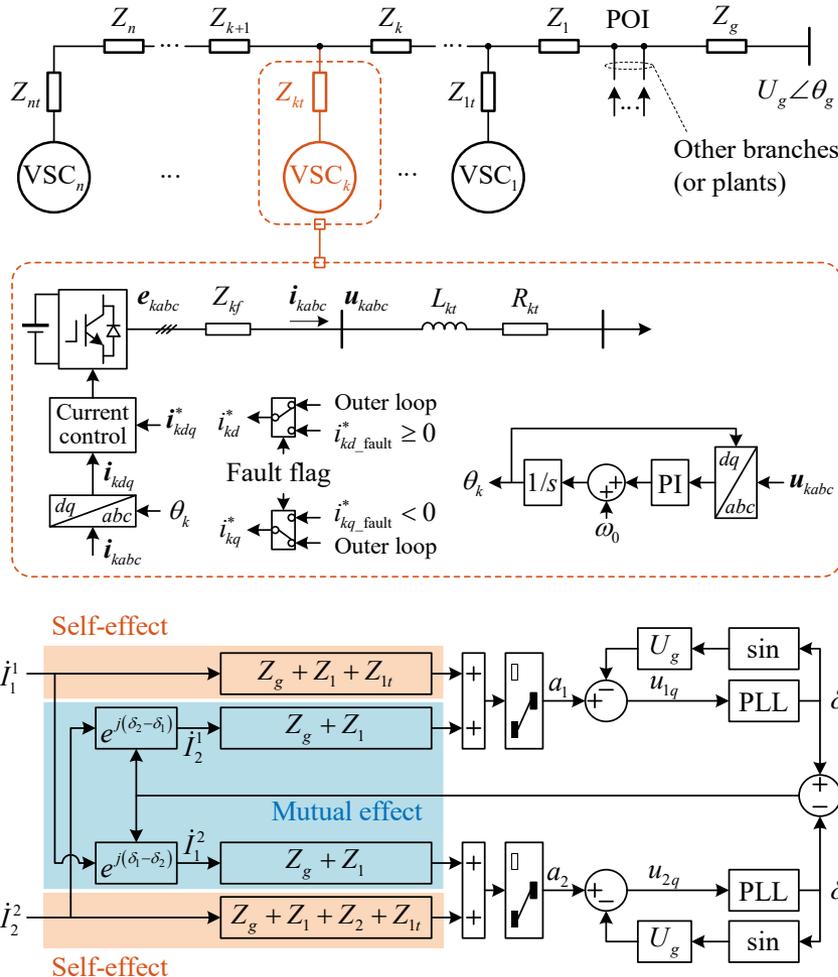
- **Classifications**

- Types of devices: {GFL, inertial GFM (GFM1), inertialess GFM (GFM2)}
- System composition: single type × single device (3), single type × multiple devices (3), multiple types × single device (4), multiple types × multiple devices (4)

single type × single device	single type × multiple devices	multiple types × single device	multiple types × multiple devices
single-GFL infinite-bus syst.	multi-GFL infinite-bus syst.	single-GFL// single-GFM1	multi-GFL// multi-GFM1
single-GFM1 infinite-bus syst.	multi-GFM1 syst.	single-GFL// single-GFM2	multi-GFL// multi-GFM2
single-GFM2 infinite-bus syst.	multi-GFM2 syst.	single-GFM1// single-GFM2	multi-GFM1// multi-GFM2
		single-GFL// single-GFM1// single-GFM2	multi-GFL// multi-GFM1// multi-GFM2

Transient stability of multi-GFL-converters

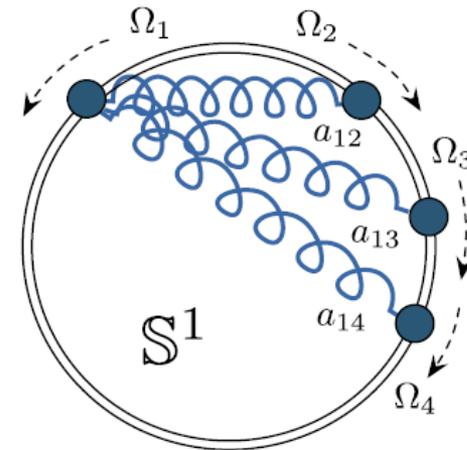
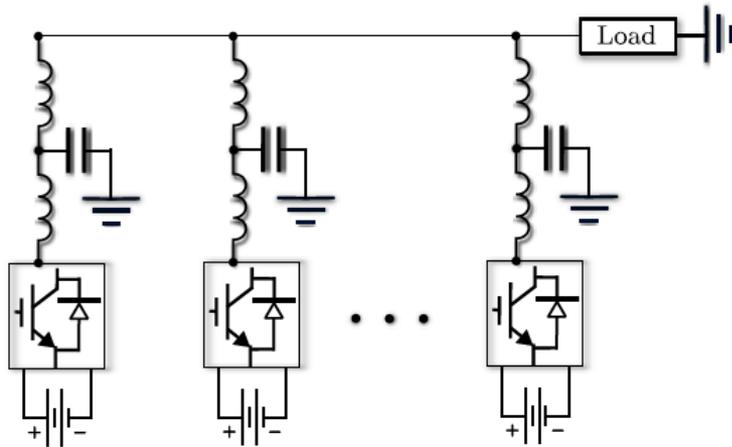
- Multiple GFL converters



[13] He X, Geng H. PLL synchronization stability of grid-connected multi-converter systems[J]. IEEE Transactions on Energy Conversion, in press.

Transient stability of multi-GFM-converters

- Multiple inertial GFM converters → conventional systems
- Multiple inertialess GFM converters



$$\omega_i = \omega^* - n_i(P_{e,i} - P_i^*)$$

$$P_{e,i} = \sum_{j=1}^n E_i E_j |Y_{ij}| \sin(\theta_i - \theta_j)$$

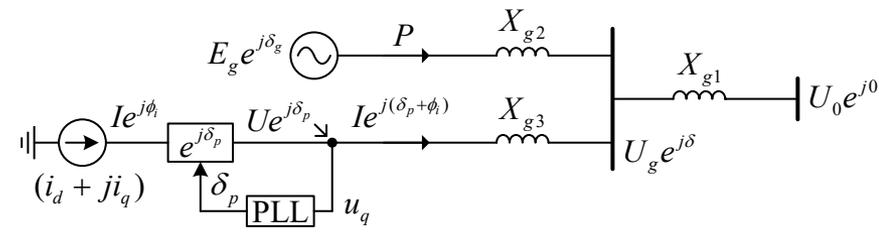
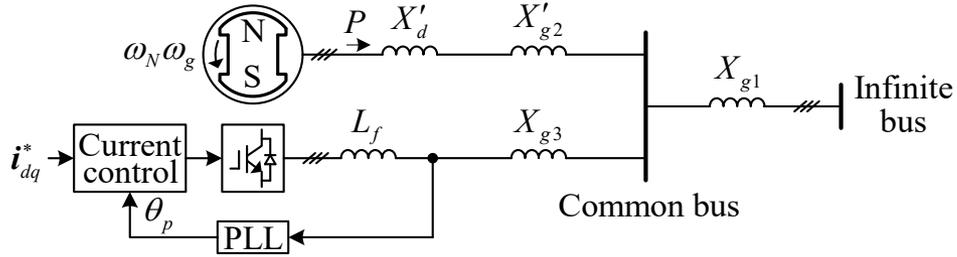
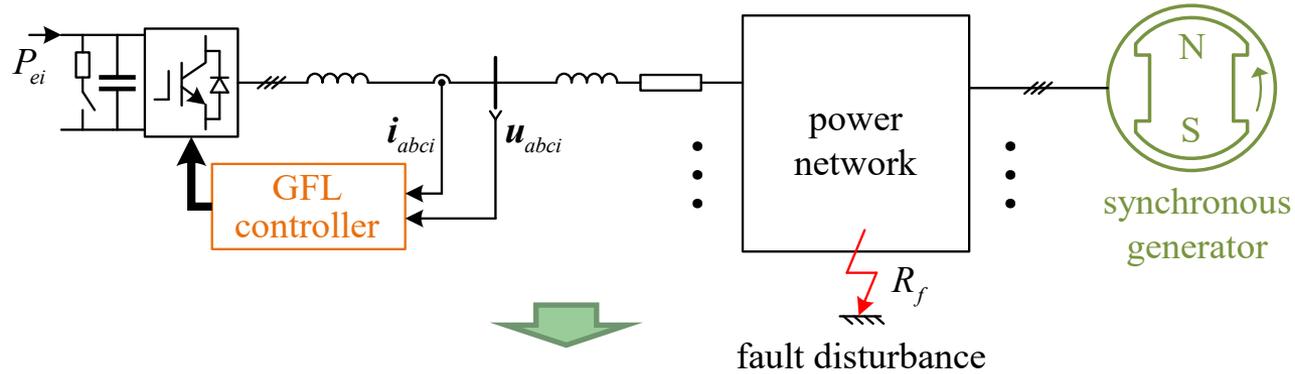
$$D_i \dot{\theta}_i = \Omega_i - \sum_{j=1}^n a_{ij} \sin(\theta_i - \theta_j), \quad i \in \{1, \dots, n\}$$

Kuramoto oscillator

- Synchronization stability condition: the power flow is feasible.
- Droop control → Exponentially stable.

Transient stability of hybrid systems

- GFL-GFM hybrid system**



In electromechanical time scale, improper network voltage angle and amplitude may lead to the singularity of the PLL equation, which is in electromagnetic time scale.

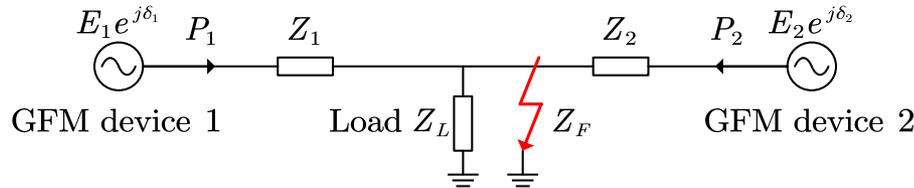
$$u_q = K_1 E_g \sin(\delta_g - \delta_p) - K_2 U_0 \sin \delta_p + X_{g5} i_d = 0$$

Solution exists

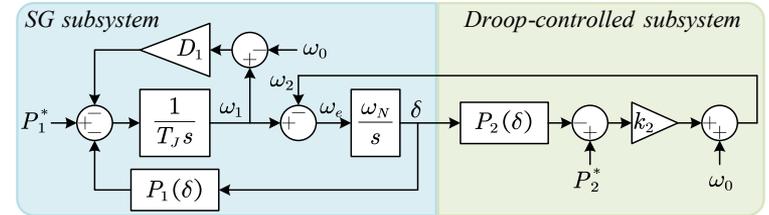
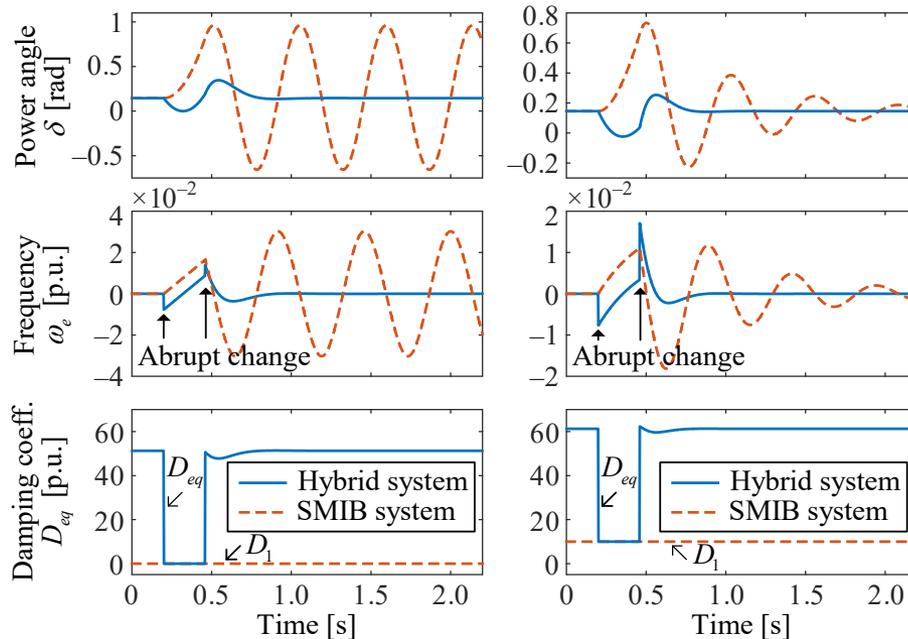
$$\sqrt{(K_1 E_g)^2 + (K_2 U_0)^2 + 2K_1 K_2 E_g U_0 \cos \delta_g} \geq X_{g5} i_d.$$

Transient stability of hybrid systems

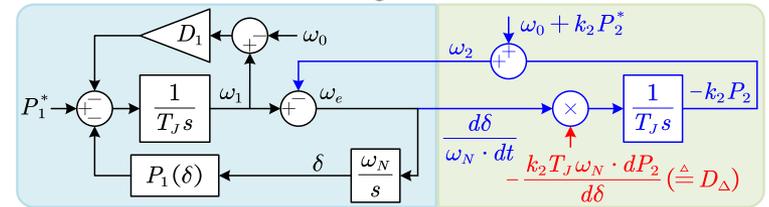
Inertial and Inertialess GFM hybrid system



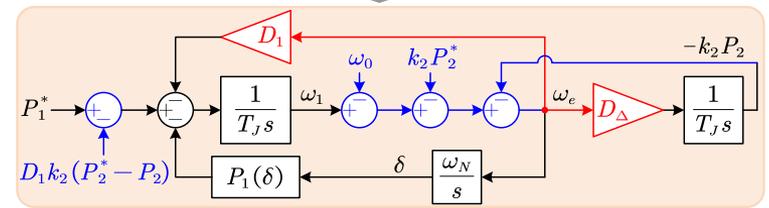
- Damping enhanced by droop control
- Frequency jump due to inertialess



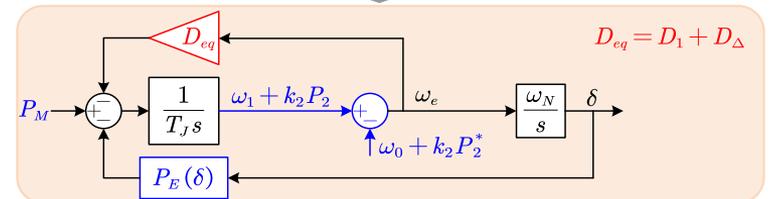
Transforming the right part



Arranging the damping term inputs



Integrating and simplifying

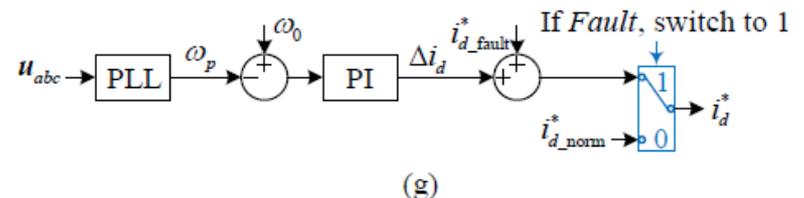
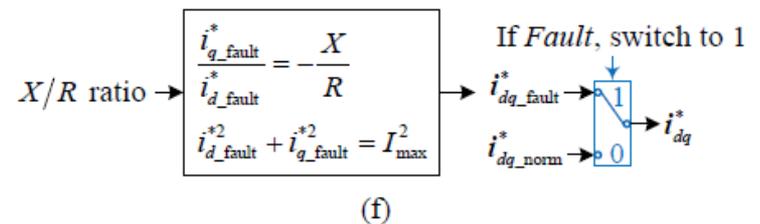
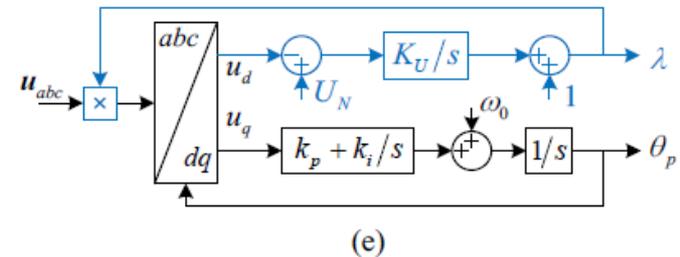
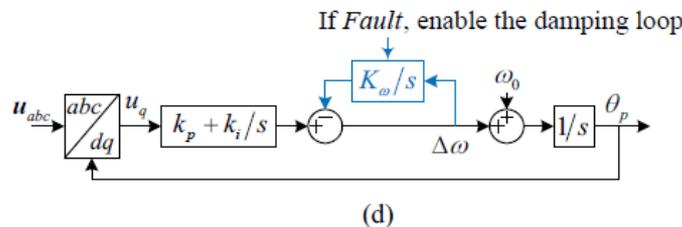
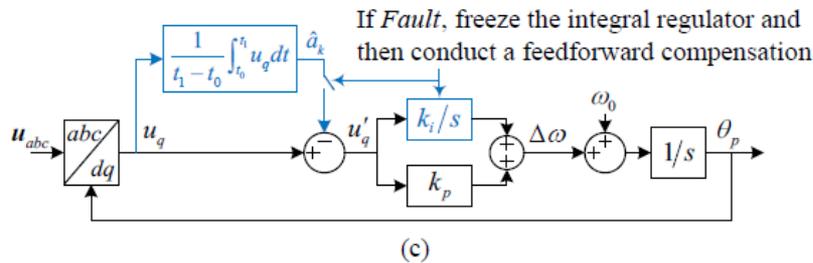
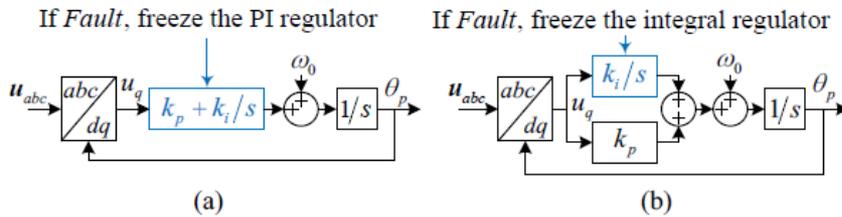


PART II: Transient Stability

- **Synchronization approaches: principles and classifications**
- **Transient stability of grid-connected converters**
- **Transient stability of power systems with converters / generators**
- **Stability improvements and grid code specifications**

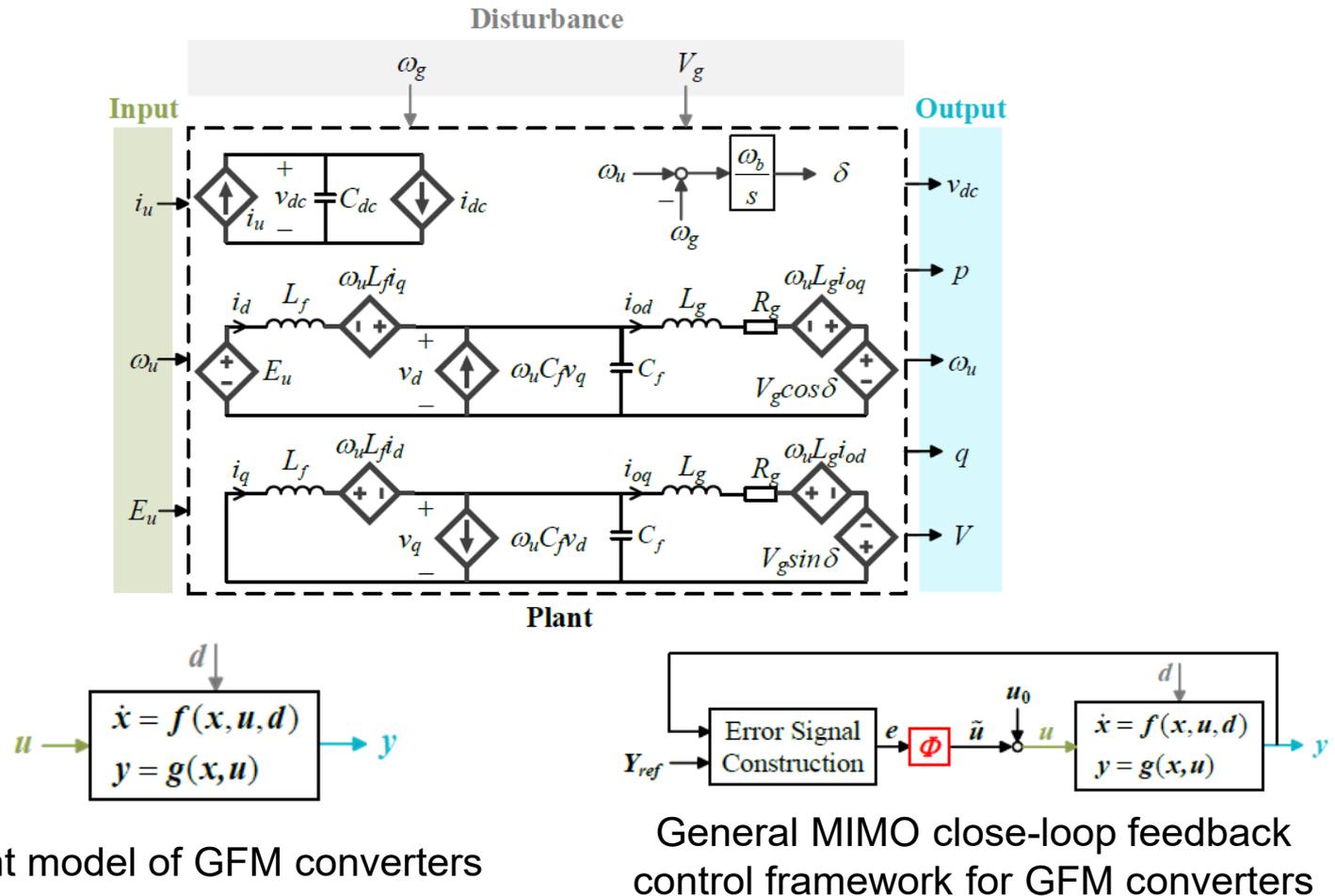
Stability improvements of GFL converters

- (a) PLL frozen
- (b,c) Variable-structure PLL (to first-order PLL)
- (d,e) Enhanced second-order PLL
- (f,g) Adjusting current output references



Stability improvements of GFM converters

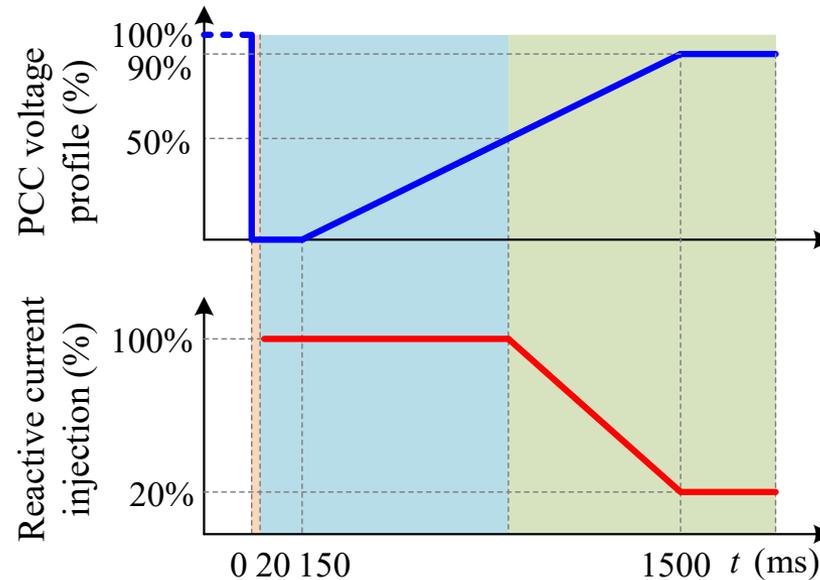
- Stability improvement under generalized GFM framework



[6] Chen M, Zhou D, Tayyebi A, et al. Generalized multivariable grid-forming control design for power converters[J]. arXiv preprint arXiv:2109.06982, 2021.

Grid codes relating to transient stability?

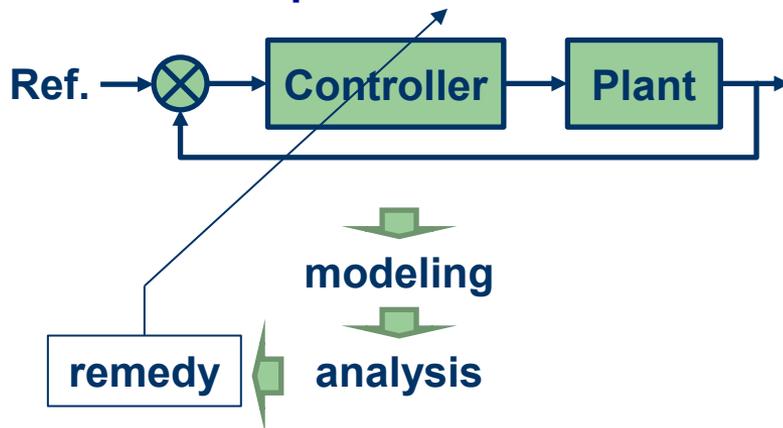
- Existing grid codes (FRT)



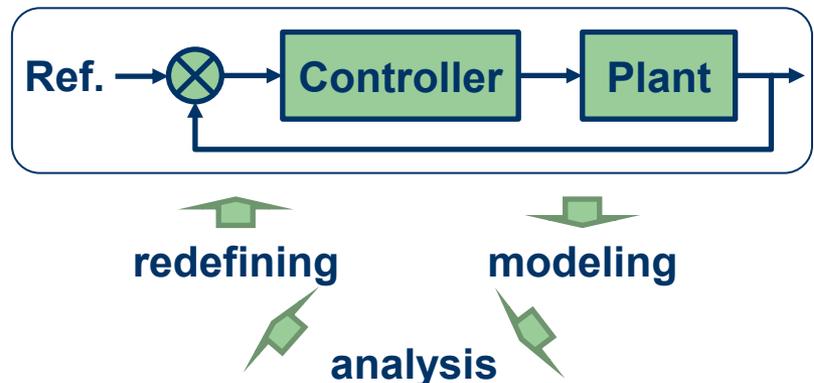
- Without considering synchronization requirement
- Specified only for GFL devices
- Unknown largely regarding negative-sequence provision
- ...

Open issues and future directions

Becoming hybrid systems (inherited from legacy systems), which comprises heterogeneous devices with various performance



Building all-new systems, which comprises consistently specified device performance by agreed protocols



- **Coupling between phase-angle, frequency, and voltage dynamics**
→ **Stability classifications?** → **Modeling and stability analysis approaches?**
- **Interactions between multiple timescales, massive devices**
- **Fragile devices, e.g., addressing current limiting for transient stability in additional to protection...**

Selected publications

1. X. He, C. He, S. Pan, H. Geng, and F. Liu, "Synchronization instability of inverter-based generation during asymmetrical grid faults," *IEEE Trans. Power Syst.*, in press.
2. X. He, S. Pan, and H. Geng, "Transient stability of hybrid power systems dominated by different types of grid-forming devices," *IEEE Trans. Energy Convers.*, in press.
3. X. He, and H. Geng, "PLL synchronization stability of grid-connected multi-converter systems," *IEEE Trans. Ind. Appl.*, in press.
4. X. He and H. Geng, "Transient stability of power systems integrated with inverter-based generation," *IEEE Trans. Power Syst.*, vol. 36, no. 1, pp. 553-556, 2021.
5. X. He, H. Geng, J. Xi, and J. M. Guerrero, "Resynchronization analysis and improvement of grid-connected VSCs during grid faults," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 9, no. 1, pp. 438-450, 2021.
6. X. He, H. Geng, and G. Mu, "Modeling of wind turbine generators for power system stability studies: a review," *Renew. Sust. Energ. Rev.*, vol. 143, pp. 110865, 2021.
7. X. He, H. Geng, R. Li, and B. C. Pal, "Transient stability analysis and enhancement of renewable energy conversion system during LVRT," *IEEE Trans. Sustain. Energy*, vol. 11, no. 3, pp. 1612-1623, 2020.
8. X. He, H. Geng, and S. Ma, "Transient stability analysis of grid-tied converters considering PLL's nonlinearity," *CPSS Trans. Power Electron. Appl.*, vol. 4, no. 1, pp. 40-49, March 2019.
9. X. He, H. Geng, and G. Yang, "A generalized design framework of notch filter based frequency-locked loop for three-phase grid voltage," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7072-7084, 2018.
10. H. Geng, L. Liu, and R. Li, "Synchronization and reactive current support of PMSG-based wind farm during severe grid fault," *IEEE Trans. Sustain. Energy*, vol. 9, no. 4, pp. 1596-1604, 2018.
11. S. Ma, H. Geng, L. Liu, G. Yang, and B. C. Pal, "Grid-synchronization stability improvement of large scale wind farm during severe grid fault," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 216-226, 2018.



清華大學
Tsinghua University



IECON 2021

47th Annual Conference of the
IEEE Industrial Electronics Society
OCTOBER 13 - 16, 2021 | VIRTUAL CONFERENCE

Thanks! Q&A

Transient stability of power electronics-dominated power networks: principle and application

Hua GENG,
PhD, FIEEE, FIET

Dept. of Automation, Tsinghua University,
Beijing, China 100084

Xiuqiang He,
PhD, MIEEE

→ Automatic Control Laboratory (IfA), ETH
Zurich, Switzerland

2021.10.15 IEEE IECON 2021