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High-Frequency Resonance and Damping in Grid-Forming Wind Power Generation

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UKRI Postdoctoral Individual Fellow (MSCA PF Guarantee Grant)

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Division F Conference 07/10/2025

Engineering and Physical Sciences Research Council

Acknowledgement

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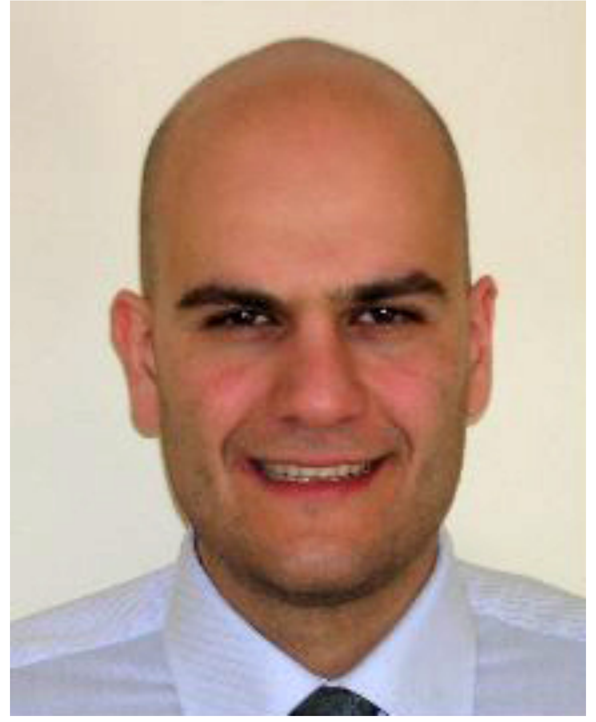

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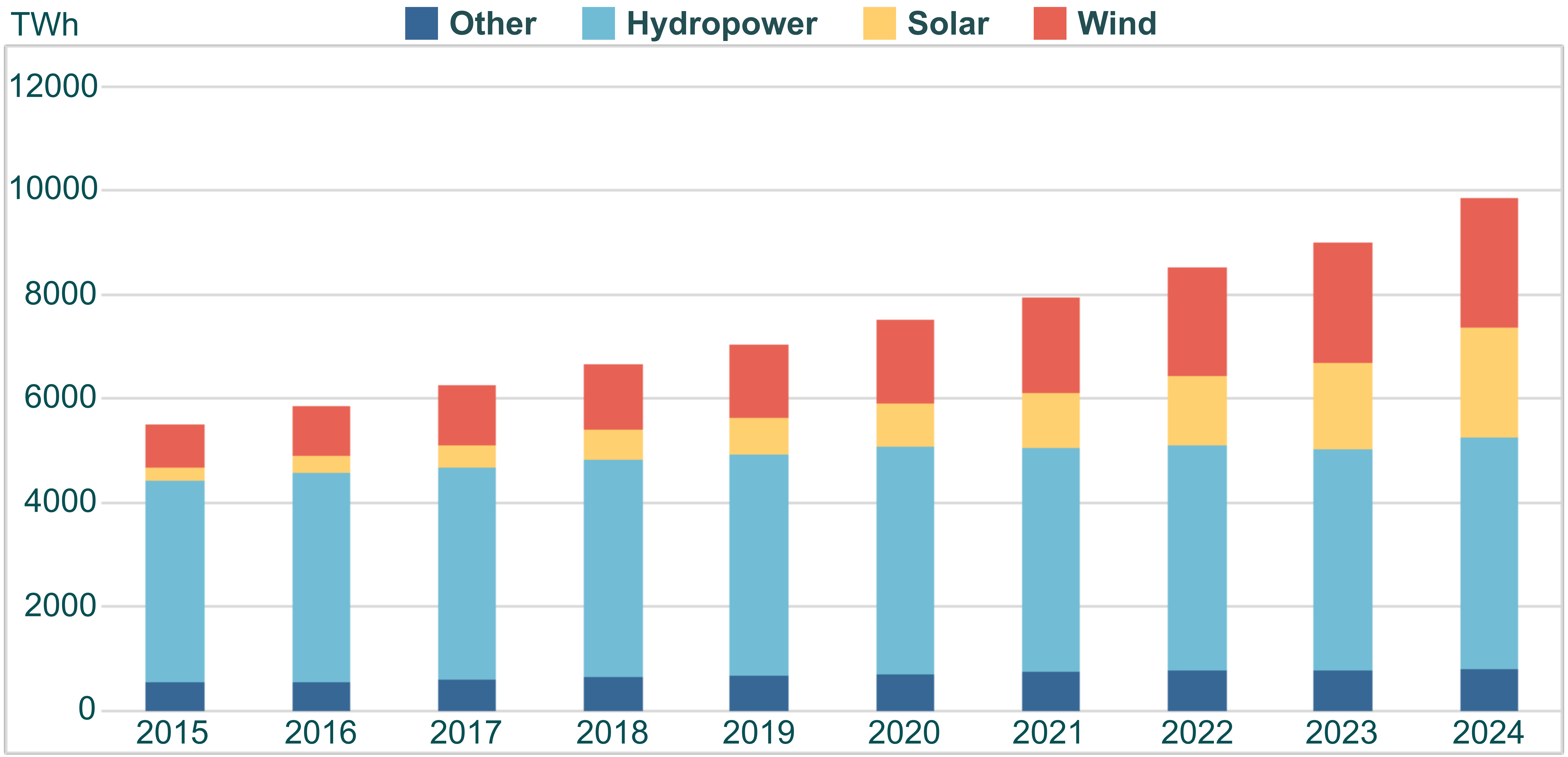
Development of renewable energy



Development of global renewable energy generation in the past 10 years

Source: Energy Institute. Statistical review of world energy. Tech. Rep. (2025)

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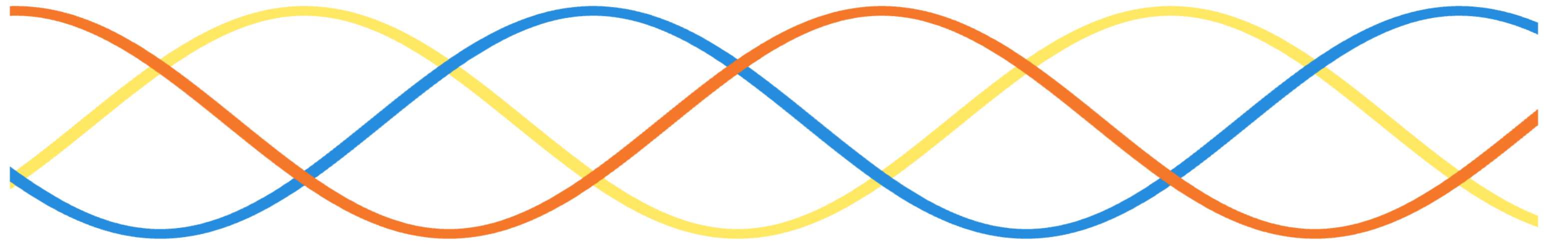
Conventional power system operation —— SG-dominated system

Three-phase sinusoidal AC voltages

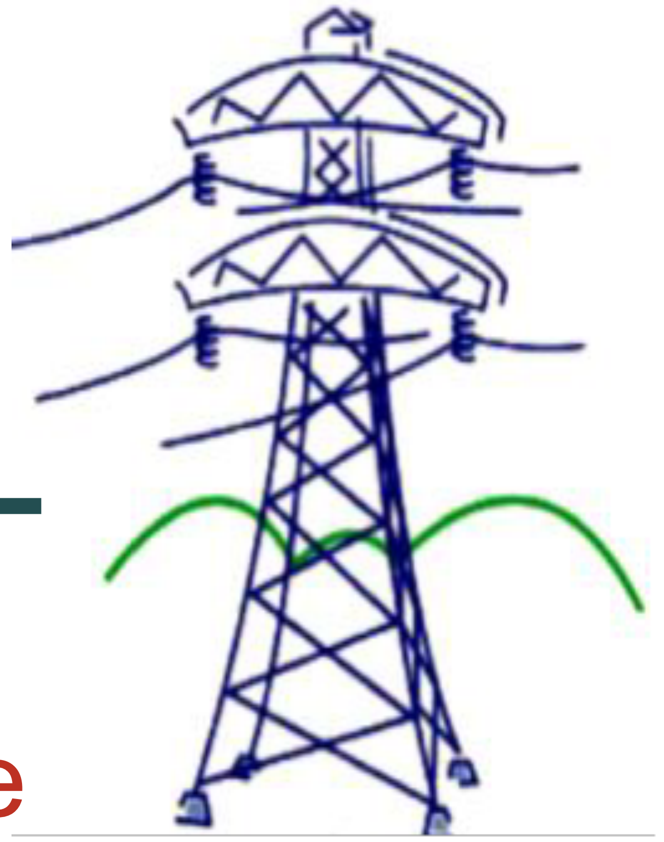
Source: https://researcherstore.com/courses/synchronous-generator/

Synchronous Generator (SG)
+
Control

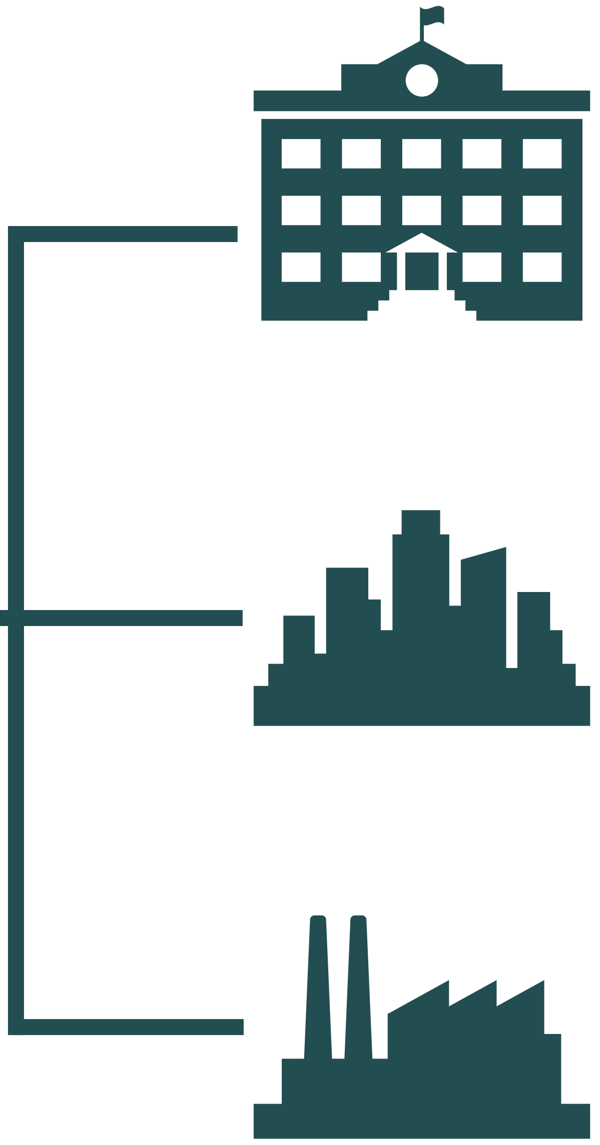


Active power balance → frequency

Reactive power balance → magnitude



Power Grid



Load

Key features of SG for stable operation against disturbances

A Frequency

- Large mechanical inertia
- Governor

B Magnitude

- Automatic voltage control

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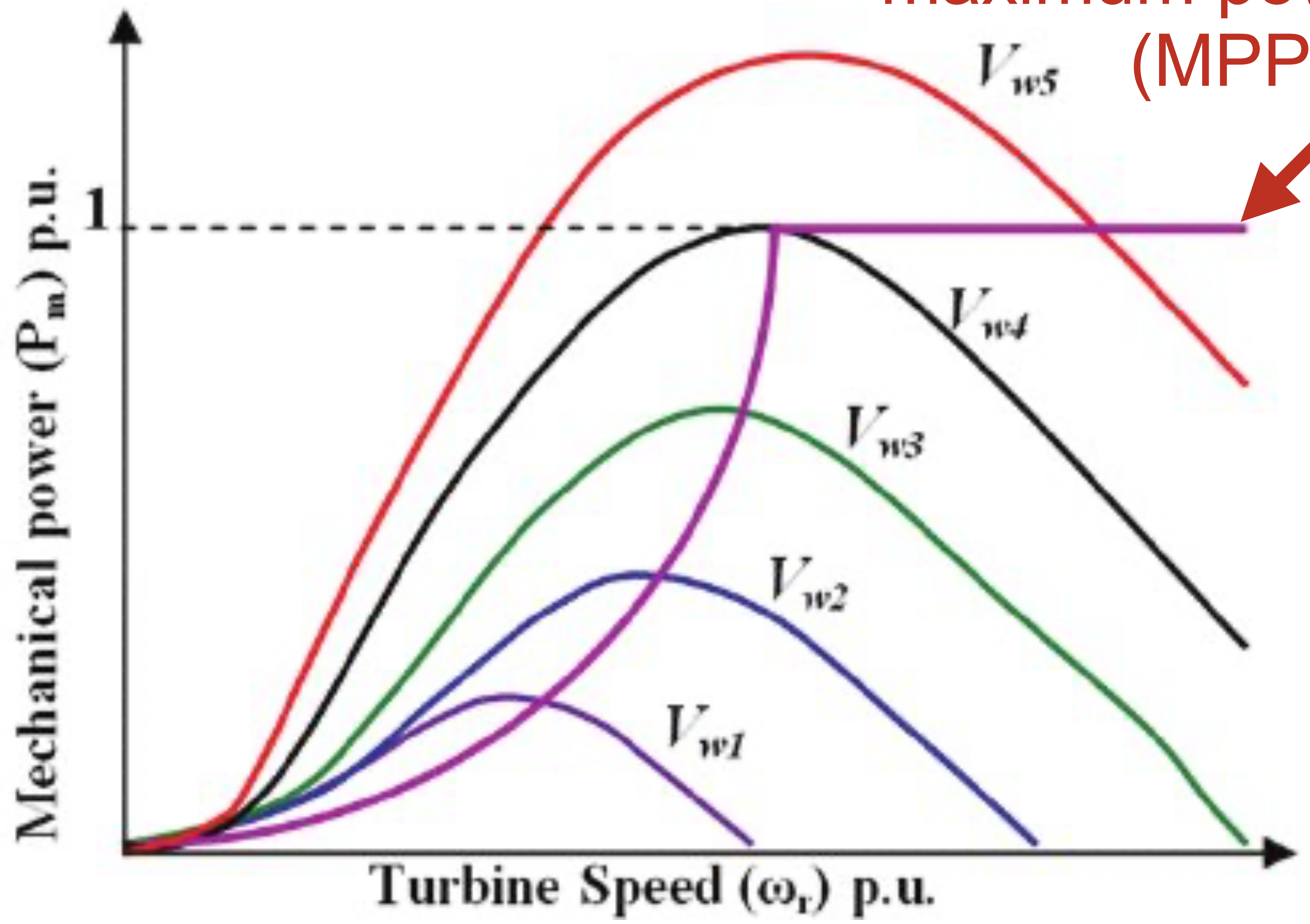
Wind turbine integration - MPPT control

Actual operation curve: maximum power point tracking (MPPT) control



Mechanical power characteristics

- The captured wind power changing into wind turbine mechanical power is related to both wind speed and turbine speed
- MPPT control changes the turbine speed in real time to obtain the maximum power
- **Wind power generators cannot be directly connected to the power system**

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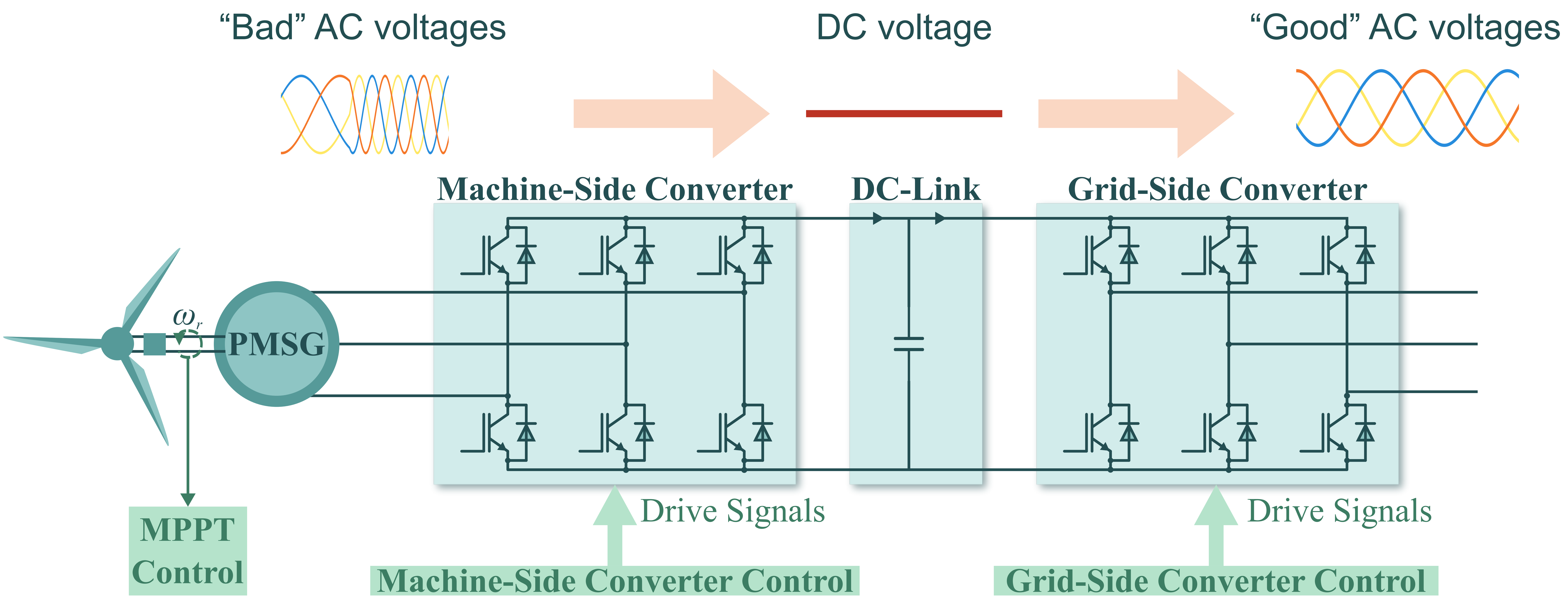
Wind turbine integration - Power converter with GFL control



Current control mode: control output current according to MPPT power and grid voltage - follow grid voltage - Grid-Following (GFL) control

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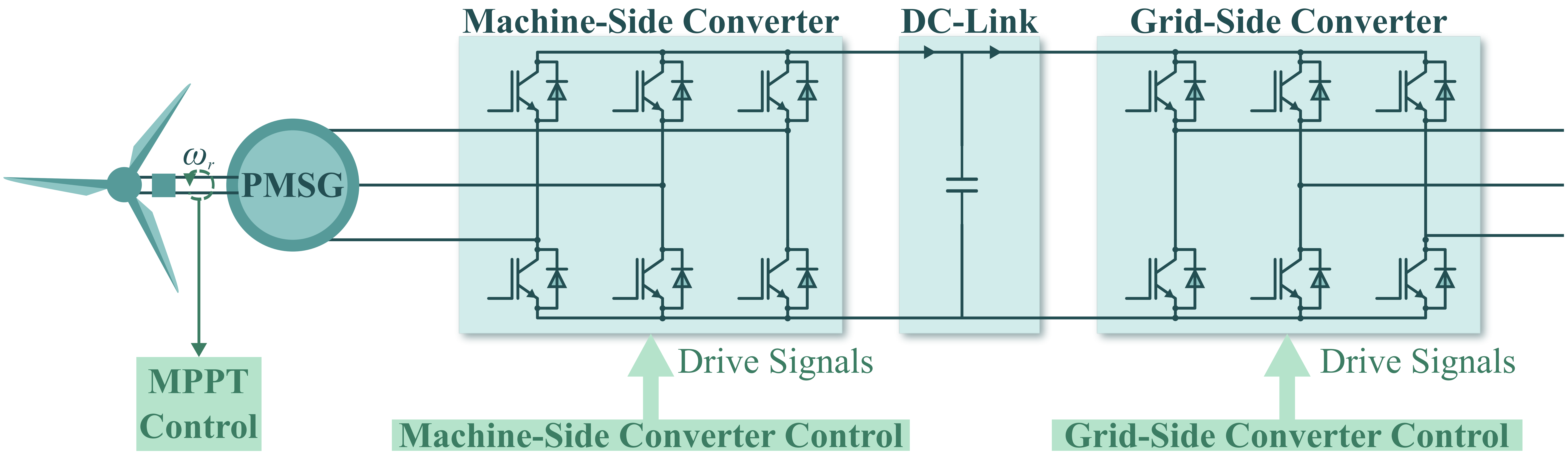
Challenge - why GFL control is not enough



Current control mode: control output current according to MPPT power and grid voltage - follow grid voltage - Grid-Following control

No inertia!!! No frequency and voltage regulation!!!

An extreme example

What to follow with 100% renewables?

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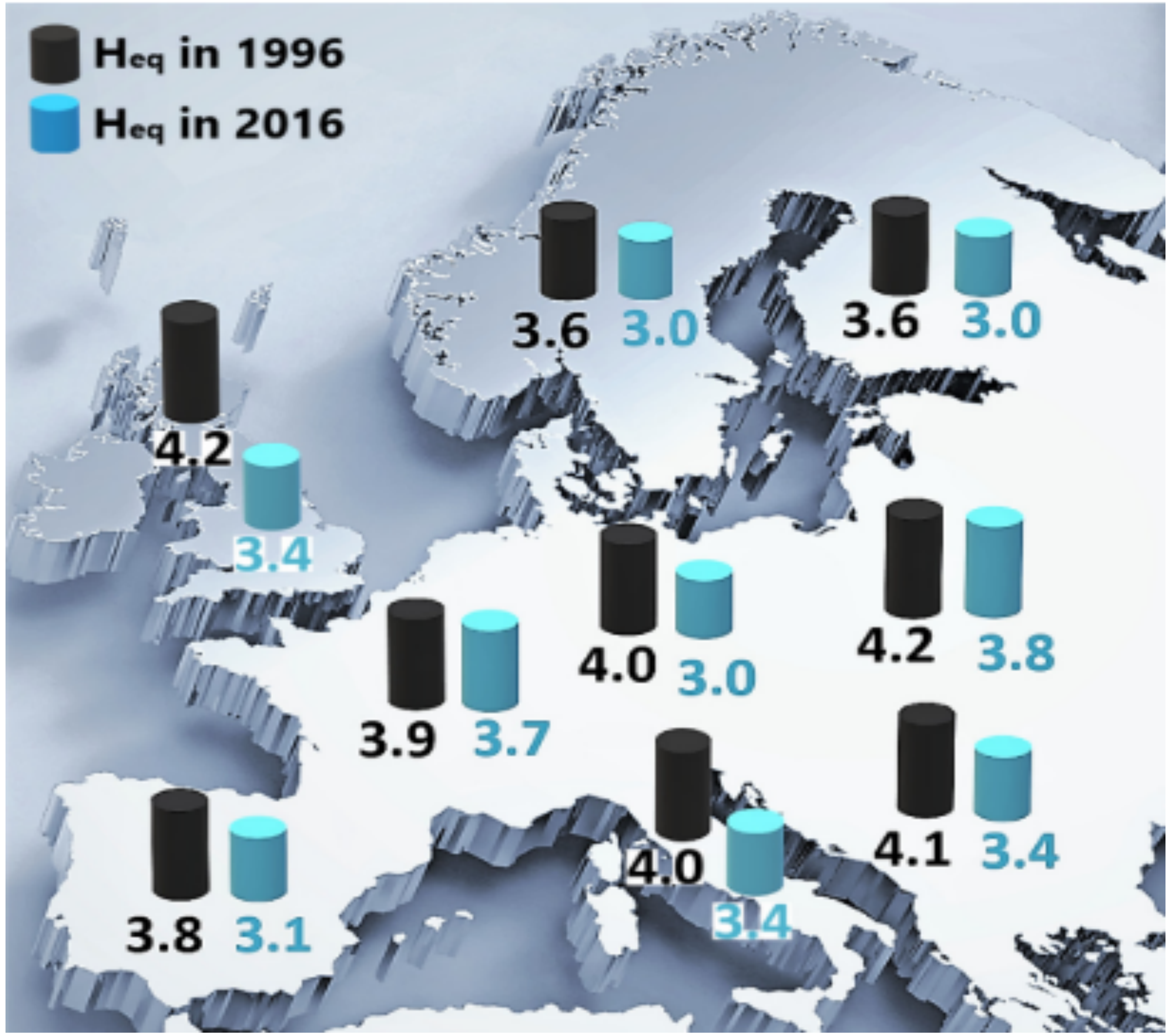
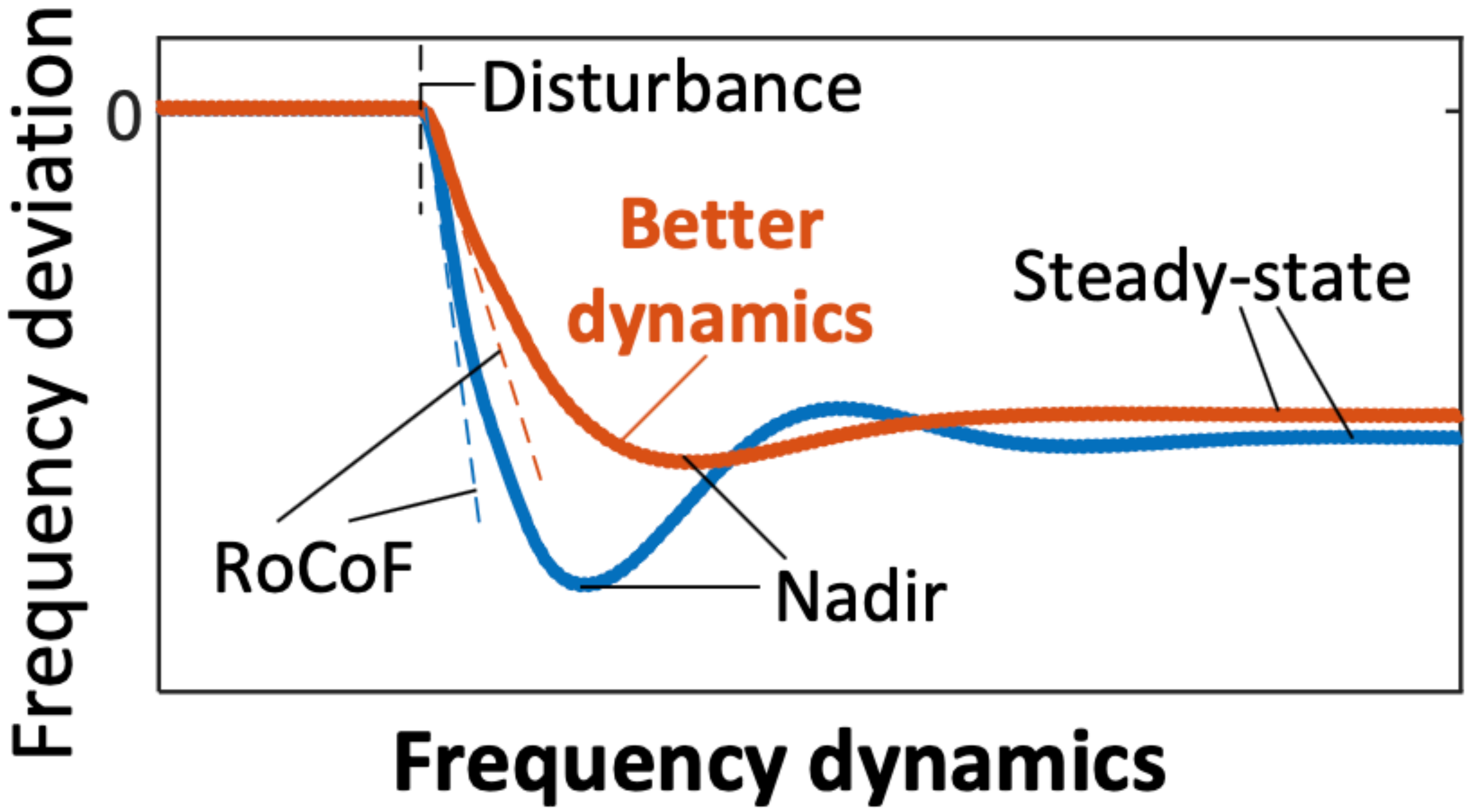
Challenge - Frequency as an example



Equivalent inertia constants estimated in EU-28[1]



The Irish grid operator estimates that generating units will need to withstand a rate of change of frequency (RoCoF) of **1 Hz/s (currently 0.5 Hz/s)** if inverter-based generating units account for 75% of the total.

[1] A. F.-Guillamon, et al., "Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time" (2019)

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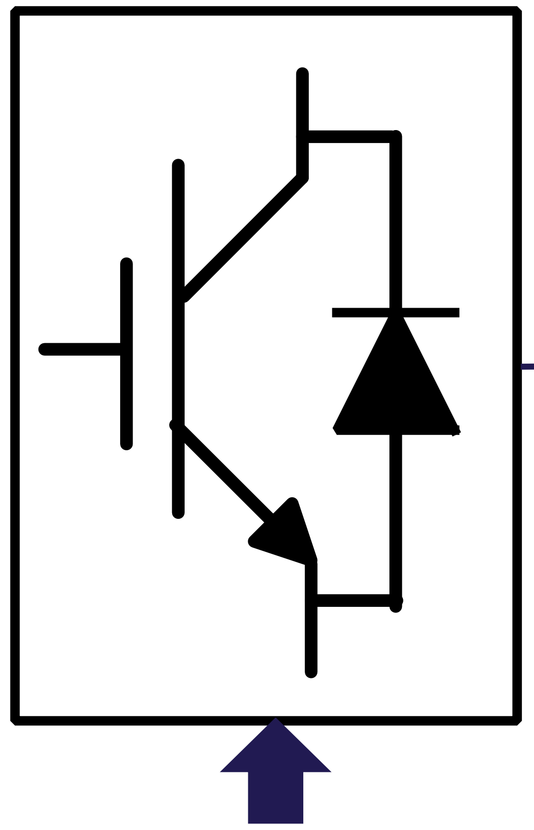
Challenge - Modern power systems

Synchronous Generator (SG)
+
Control (Governor, AVR, etc.)

Source: https://researcherstore.com/courses/synchronous-generator/

Power Grid



Grid-following control

Renewable energy generation
(PV, wind, storage, etc.)

Dominant sources

Power system with low sustainability

Grid-forming control strategy

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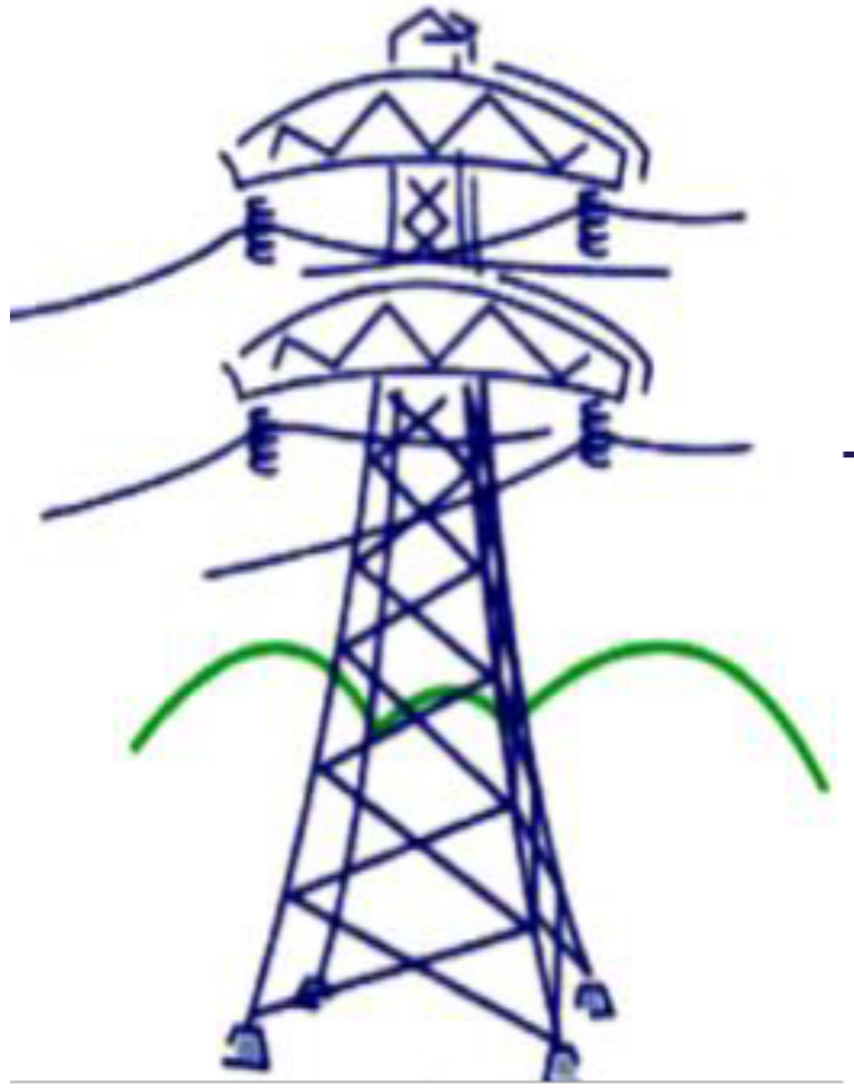
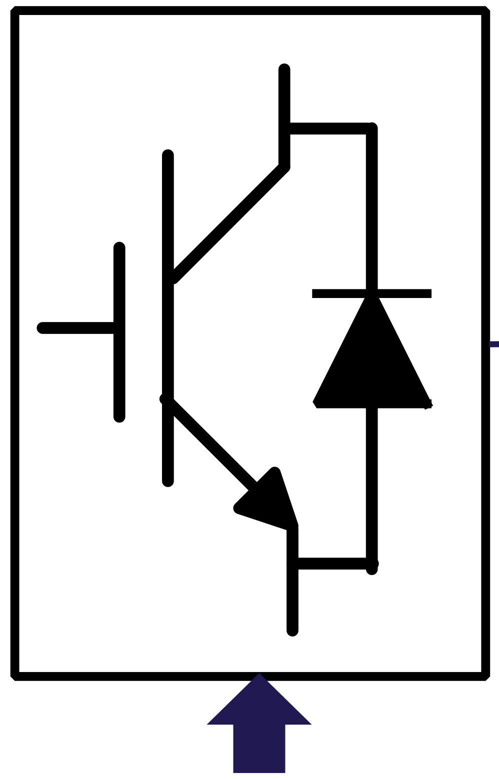
Motivation - better control strategy (SG emulation, to form grid voltage)

Synchronous Generator (SG)
+
Control (Governor, AVR, etc.)

Source: https://researcherstore.com/courses/synchronous-generator/



Power Grid



Grid-forming (GFM) control

Renewable energy generation (PV, wind, storage, etc.)

Replacement

- Frequency and voltage support
- Inertia
- Islanded operation
- More!!!

Power system with High sustainability

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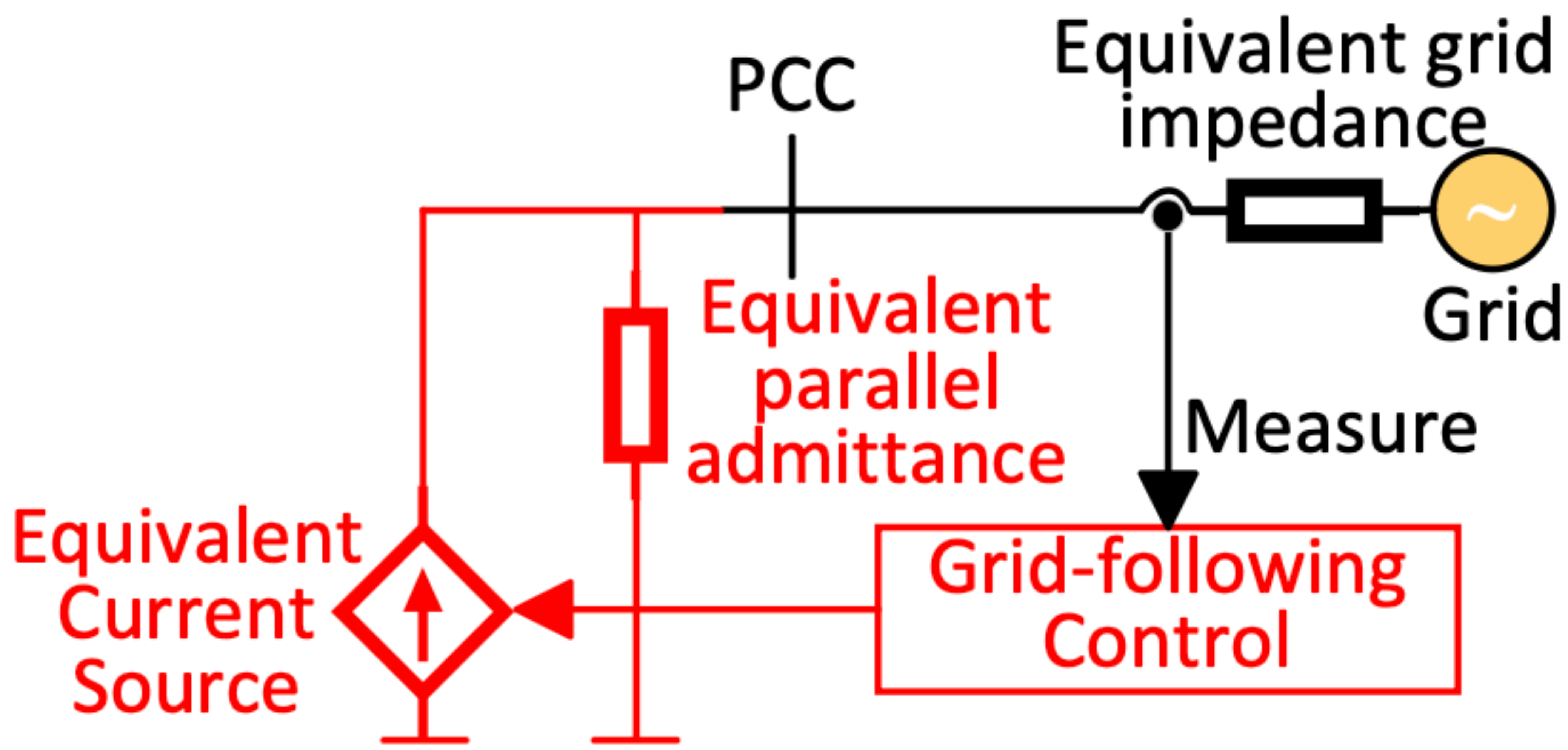
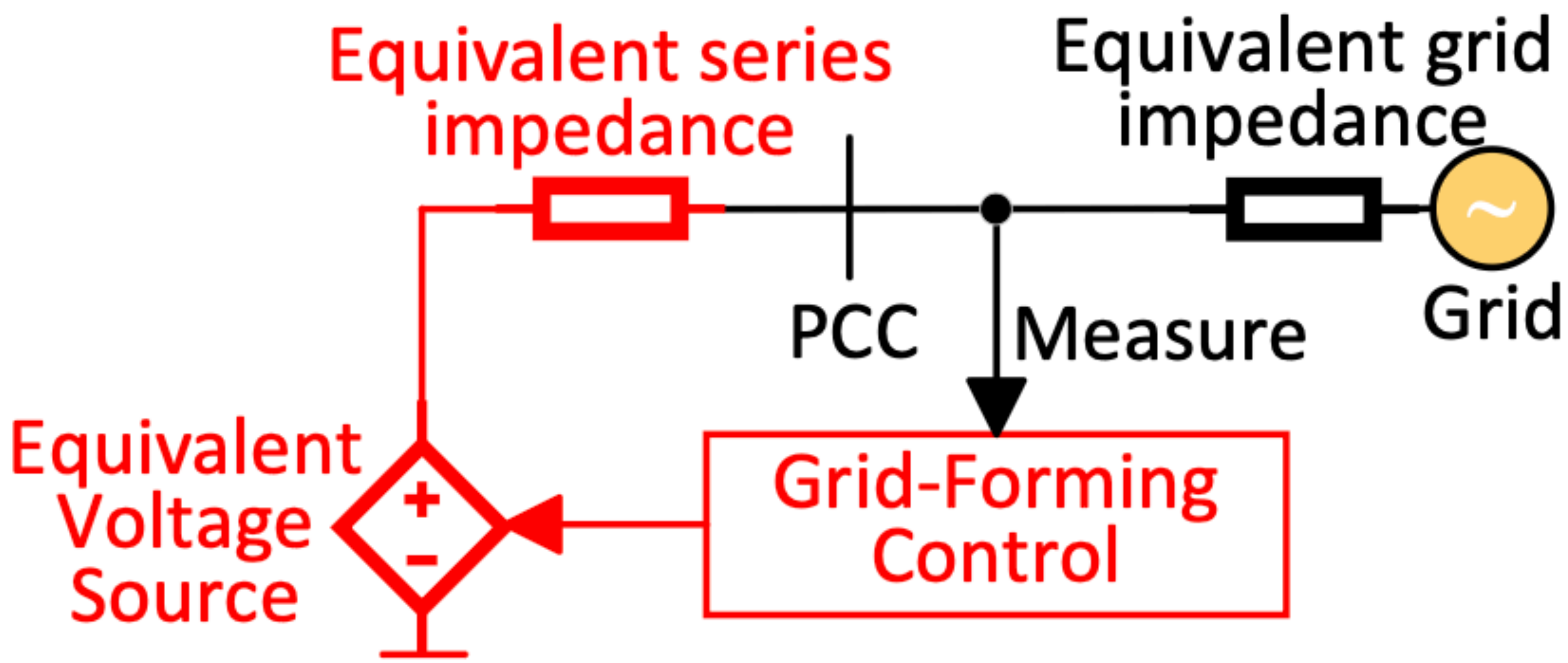
Motivation - Equivalent circuit



Grid-following control



Grid-forming control

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LCL high-frequency resonance in wind integration

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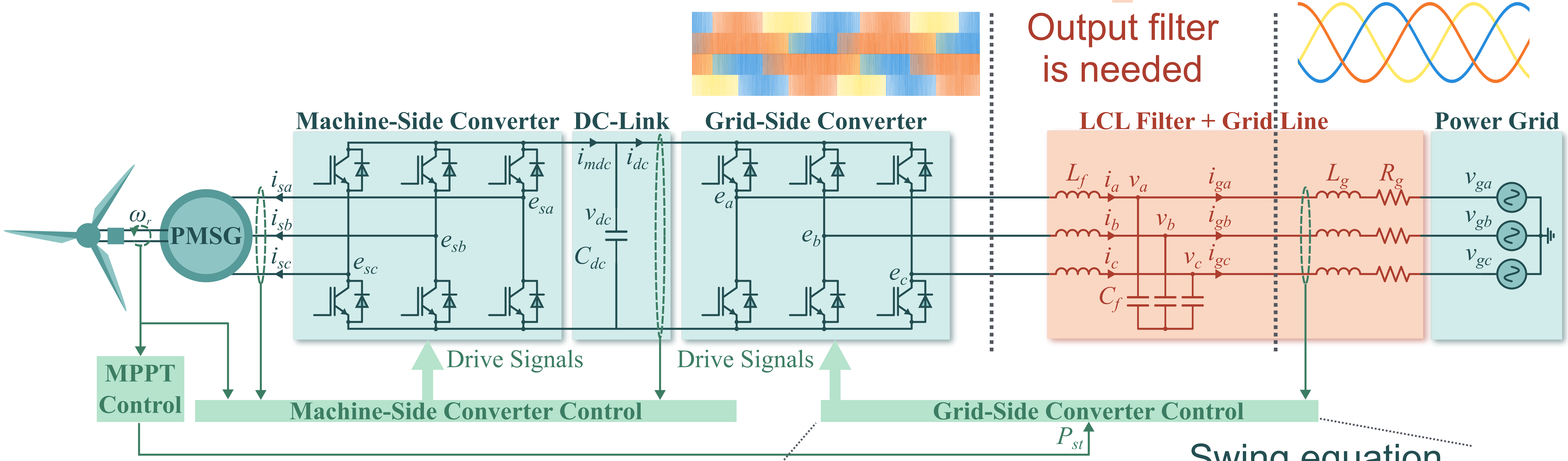
Challenge

Resonance may occur!!!

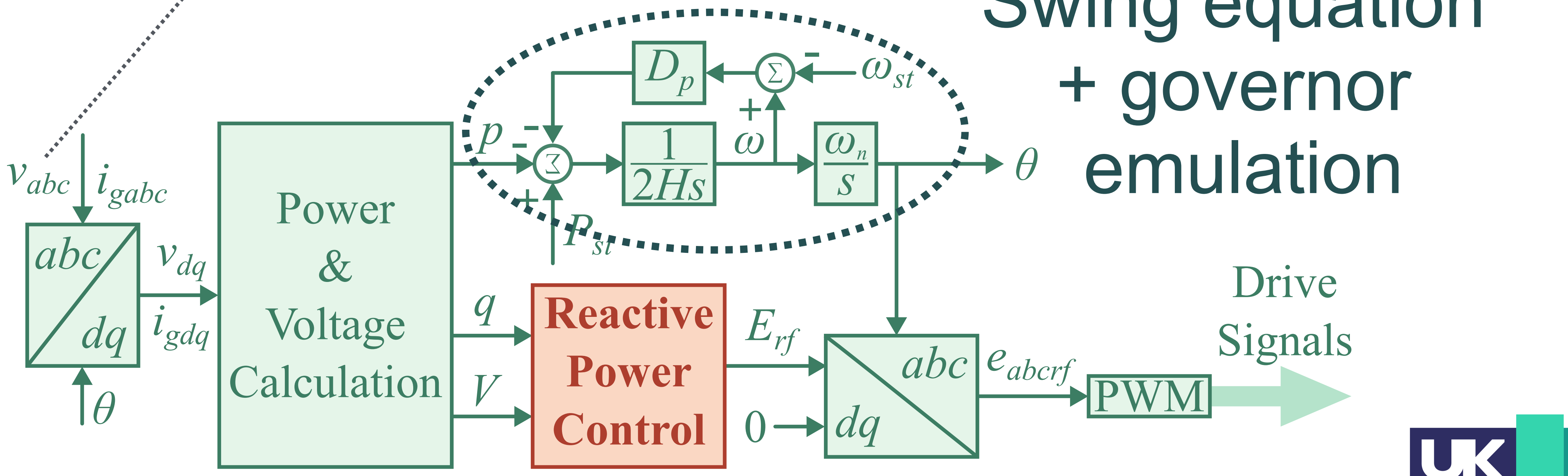
Pulse width modulation (PWM) waveform

Output filter is needed



Swing equation + governor emulation

- Active power control forms the frequency
- Reactive power control forms the magnitude



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LCL high-frequency resonance in GFM wind turbine

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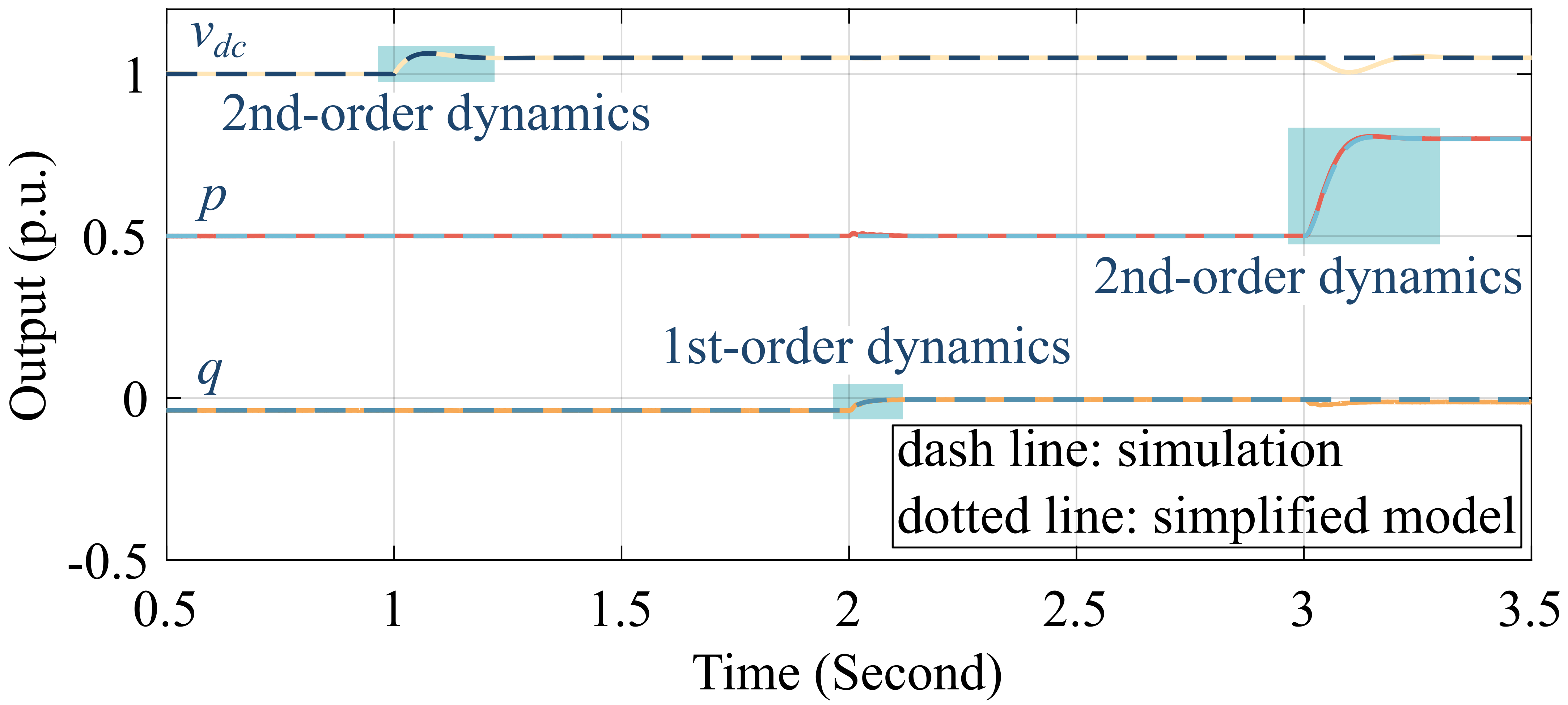
Conventional modelling

- Switching frequency (PWM): ~kHz
- Filter resonance frequency: ~100 Hz to ~kHz
- Power control bandwidth: <50 Hz

LCL resonance is typically neglected due to frequency separation and parasitic resistance in the system



Comparison between simplified and detailed models

$$G_{dc\_sim}(s) := \left(k_{pdc} + \frac{k_{idc}}{s}\right)\frac{\omega_n}{C_{dc}s + \omega_n G_{dcv}(s)}$$

$$G_{p\_sim}(s) := \frac{1}{2Hs + D_p}\frac{\omega_n}{s}G_{p\delta}(s)$$

$$G_{q\_sim}(s) := G_{qE}(s)/[(1/k_q)s + D_q G_{VE}(s)]$$

$$G_{dcv}(s) := -E_{rf0}i_{d0}/v_{dc0}^2$$

$$G_{p\delta}(s) := (E_{rf0}V_g/X_{eq})\cos\delta_0$$

$$G_{qE}(s) := [2E_{rf0}X_g + V_g\cos\delta_0(2X_f - X_{eq})]/X_{eq}^2$$

$$G_{VE}(s) := \frac{X_g(E_{rf0}X_g + V_g X_f\cos\delta_0)}{X_{eq}\sqrt{E_{rf0}^2X_g^2 + 2E_{rf0}V_gX_fX_g\cos\delta_0 + V_g^2X_f^2}}$$

Although the simplified model matches the detailed model well, we find that the conclusion **is not always reliable**.

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Grid-forming-induced LCL resonance

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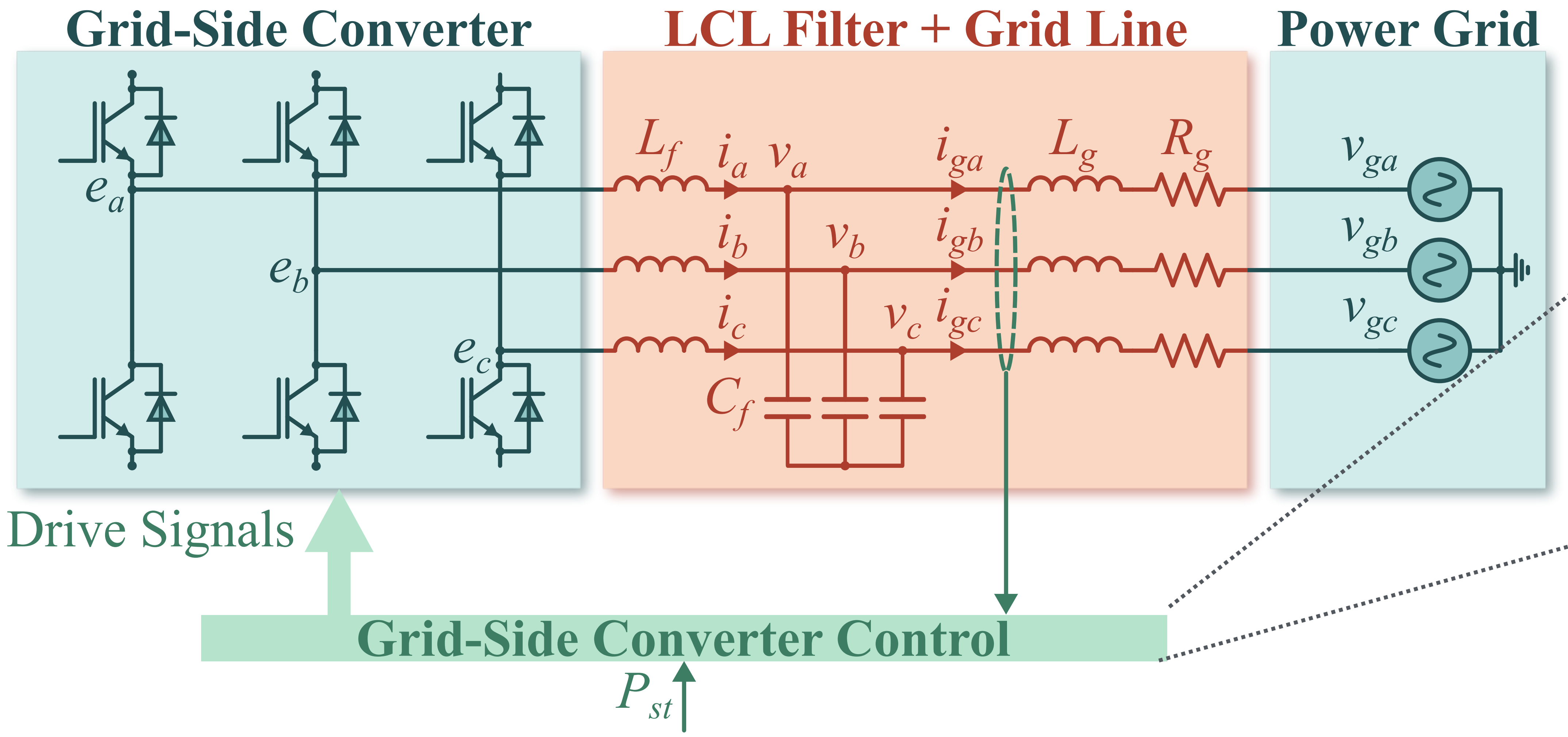
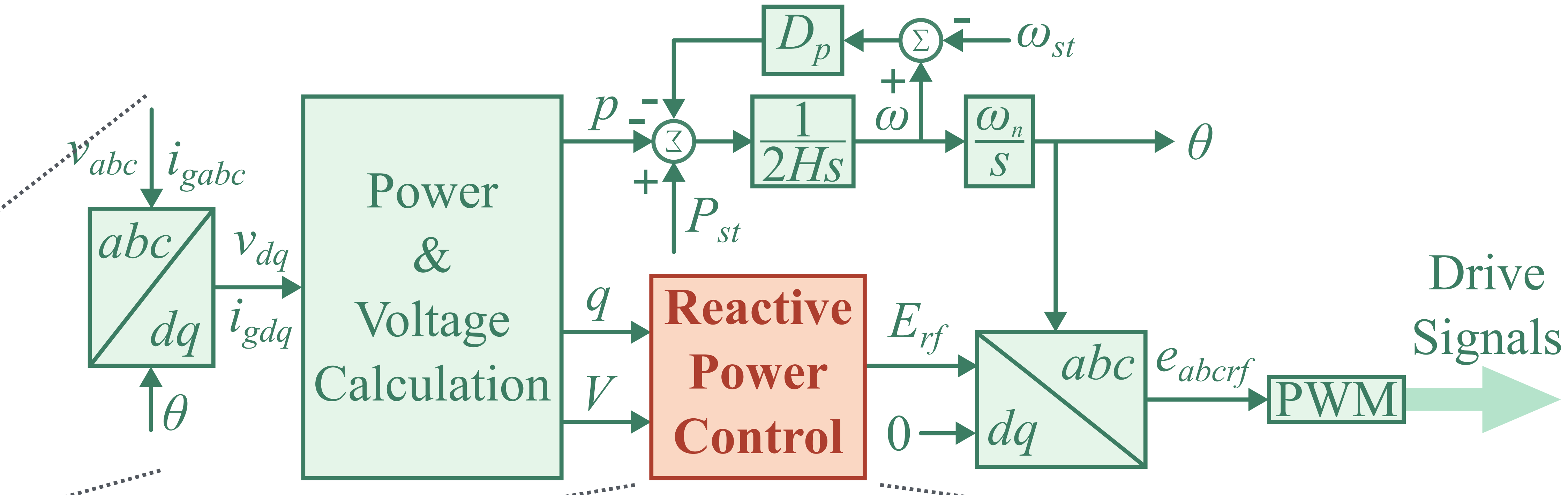
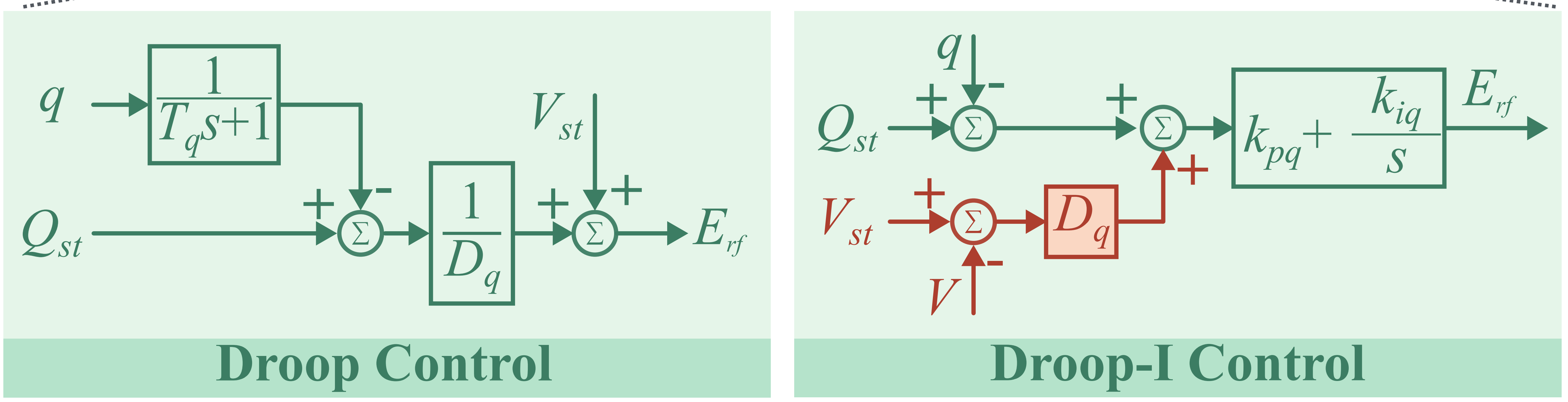
Two typical droop-based reactive power control





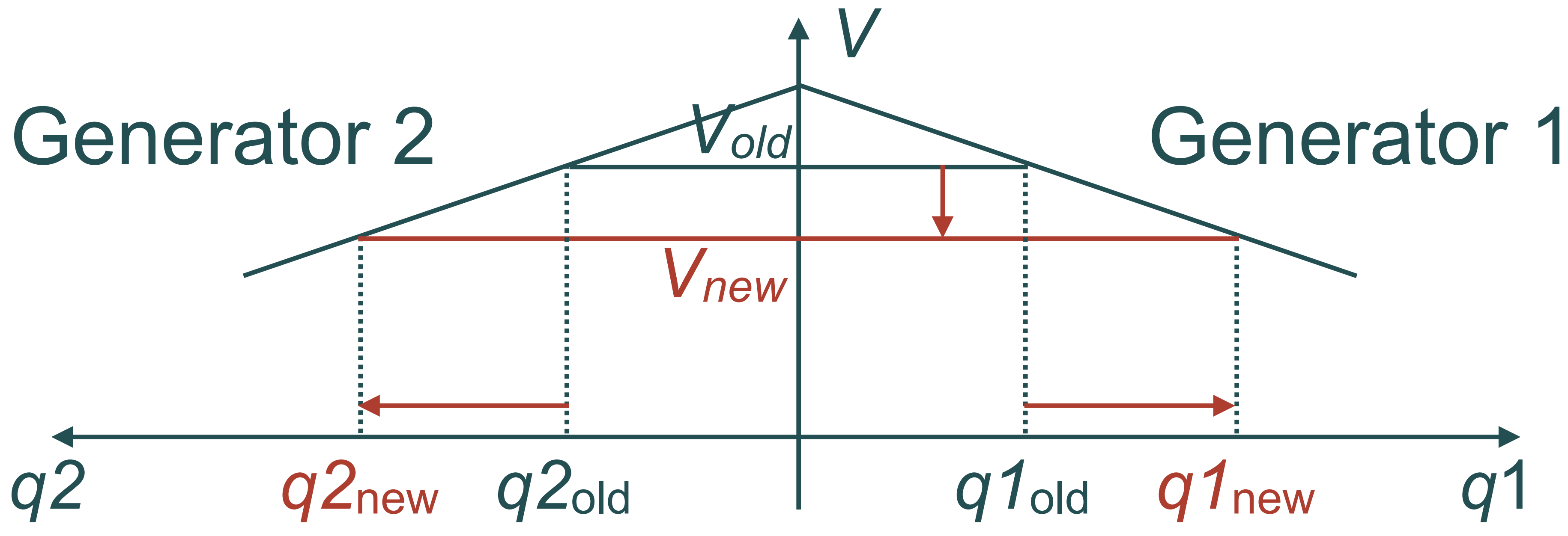


(a) (b)

- Simple
- Not robust droop

- Robust droop

Droop characteristics



Automatic load sharing among generators

They can provide similar low-frequency dynamics, but **significantly different high-frequency characteristics.**

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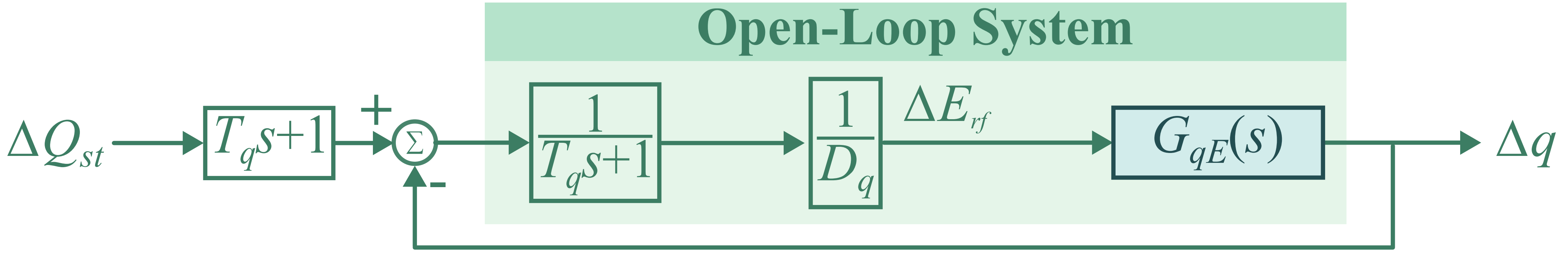
Grid-forming-induced LCL resonance

Detailed model based analysis



$$G_{RA\_droop}(s) := \frac{N_{qE}(s)}{D_q(T_q s+1)\det(\boldsymbol{A})\det(\boldsymbol{B})}$$

open-loop poles are exactly corresponding to the LCL resonance and reactive power control, and they are decoupled - **Always open loop stable**

Some definitions

$$G_{qE}(s) := \frac{N_{qE}(s)}{\det(\boldsymbol{A})\det(\boldsymbol{B})}$$

$$G_{VE}(s) := \frac{N_{VE}(s)}{\det(\boldsymbol{B})}$$

$$\det(\boldsymbol{A}) := \frac{s^2}{\omega_n^2} + \omega_g^2$$

$$\det(\boldsymbol{B}) := \frac{L_g^2}{\omega_{LC}^4}(s^2+\omega_1^2)(s^2+\omega_2^2)$$

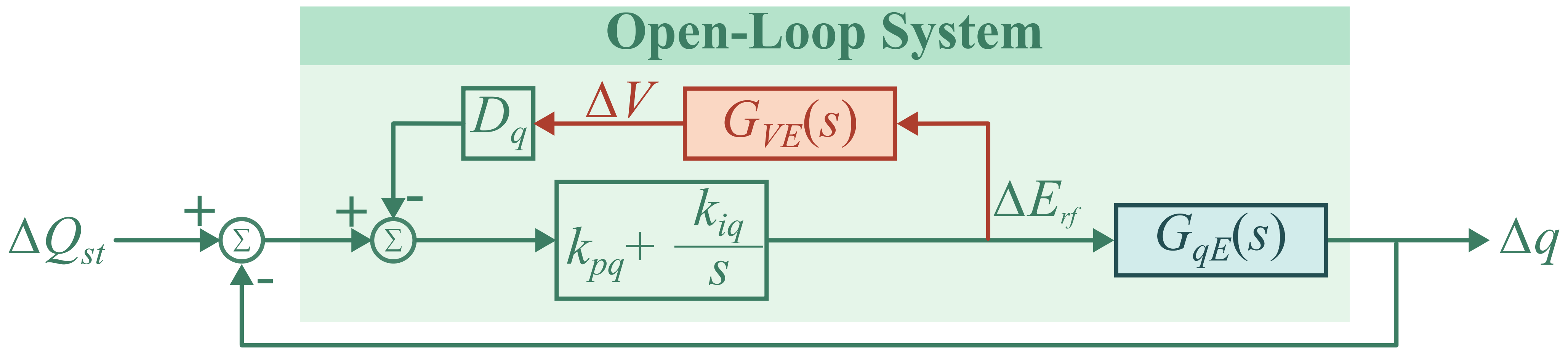
$$N_{VE}(s) := \frac{L_f C_f L_g^2}{V_0 \omega_n^2}\left[(s^2+\omega_1\omega_2)v_{d0} - 2\omega_{L_g} v_{q0} s\right]$$

$$\omega_{LC} := \omega_n \sqrt{\frac{1}{L_f C_f}}$$

$$\omega_1 := \omega_{LCL} - \omega_{L_g}$$

$$\omega_2 := \omega_{LCL} + \omega_{L_g}.$$

$$\omega_{LCL} := \omega_n \sqrt{\frac{L_f + L_g}{L_f C_f L_g}}. \qquad \omega_{L_g} := \omega_n \omega_g$$



$$G_{RA\_droopI}(s) := \frac{k_{pq}s + k_{iq}}{s + (k_{pq}s+k_{iq})D_q G_{VE}(s)} G_{qE}(s)$$

$$= \frac{(k_{pq}s+k_{iq})\,\cancel{\det(\boldsymbol{B})}}{s\det(\boldsymbol{B}) + (k_{pq}s+k_{iq})D_q N_{VE}(s)} \frac{N_{qE}(s)}{\det(\boldsymbol{A})\,\cancel{\det(\boldsymbol{B})}}$$

$$= \frac{(k_{pq}s+k_{iq})N_{qE}(s)}{\underbrace{[s\det(\boldsymbol{B}) + (k_{pq}s+k_{iq})D_q N_{VE}(s)]}_{\text{new open-loop poles}}\det(\boldsymbol{A})}.$$

Reactive power control and LCL resonance are coupled with each other so that new open-loop poles emerge.

Still open loop stable?

Grid-forming-induced LCL resonance

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Analysis on open-loop poles when with droop-I control

Open-loop characteristic equation

$$s\det(\boldsymbol{B}) + (k_{pq}s + k_{iq})D_q N_{VE}(s) = 0$$

$$s^5 + a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0$$

$$a_3 := \omega_1^2 + \omega_2^2 + \frac{D_q k_{pq} \omega_{LC}^2 v_{d0}}{V_0}$$

$$a_2 := \frac{D_q \omega_{LC}^2}{V_0}(k_{iq} v_{d0} - 2k_{pq} \omega_{L_g} v_{q0})$$

$$a_1 := \omega_1^2 \omega_2^2 + \frac{D_q \omega_{LC}^2}{V_0}(\omega_1 \omega_2 k_{pq} v_{d0} - 2k_{iq} \omega_{L_g} v_{q0})$$

$$a_0 := \frac{v_{d0} k_{iq} D_q \omega_{LC}^2 \omega_1 \omega_2}{V_0}.$$

In **ideal inductive grid**, it is **always open-loop unstable** at resonant frequencies. It is a fundamental **structural property** and cannot be mitigated by tuning control or system parameters.

Parasitic impact in practical cases

Routh array

$$\begin{array}{llll}
s^5: & 1 & a_3 & a_1 \\
s^4: & \varepsilon & a_2 & a_0 \\
s^3: & a_3 - a_2/\varepsilon & a_1 - a_0/\varepsilon & \\
s^2: & a_2 - (a_1\varepsilon^2 - a_0\varepsilon)/(a_3\varepsilon - a_2) & a_0 & \\
s: & a_1 + \frac{(a_0 a_3^2 - a_0 a_1)\varepsilon + a_0^2 - a_0 a_2 a_3}{a_1\varepsilon^2 - (a_0 + a_2 a_3)\varepsilon + a_2^2} & & \\
s^0: & a_0 & &
\end{array}$$

- As **bandwidth** of reactive power control increases (although still < 50 Hz), system transitions from minimum phase to non minimum phase with unstable open-loop poles.
- As **grid impedance** increases (weaker), system transitions to open-loop unstable.

Low robustness, resonance is much more easy to occur!!!

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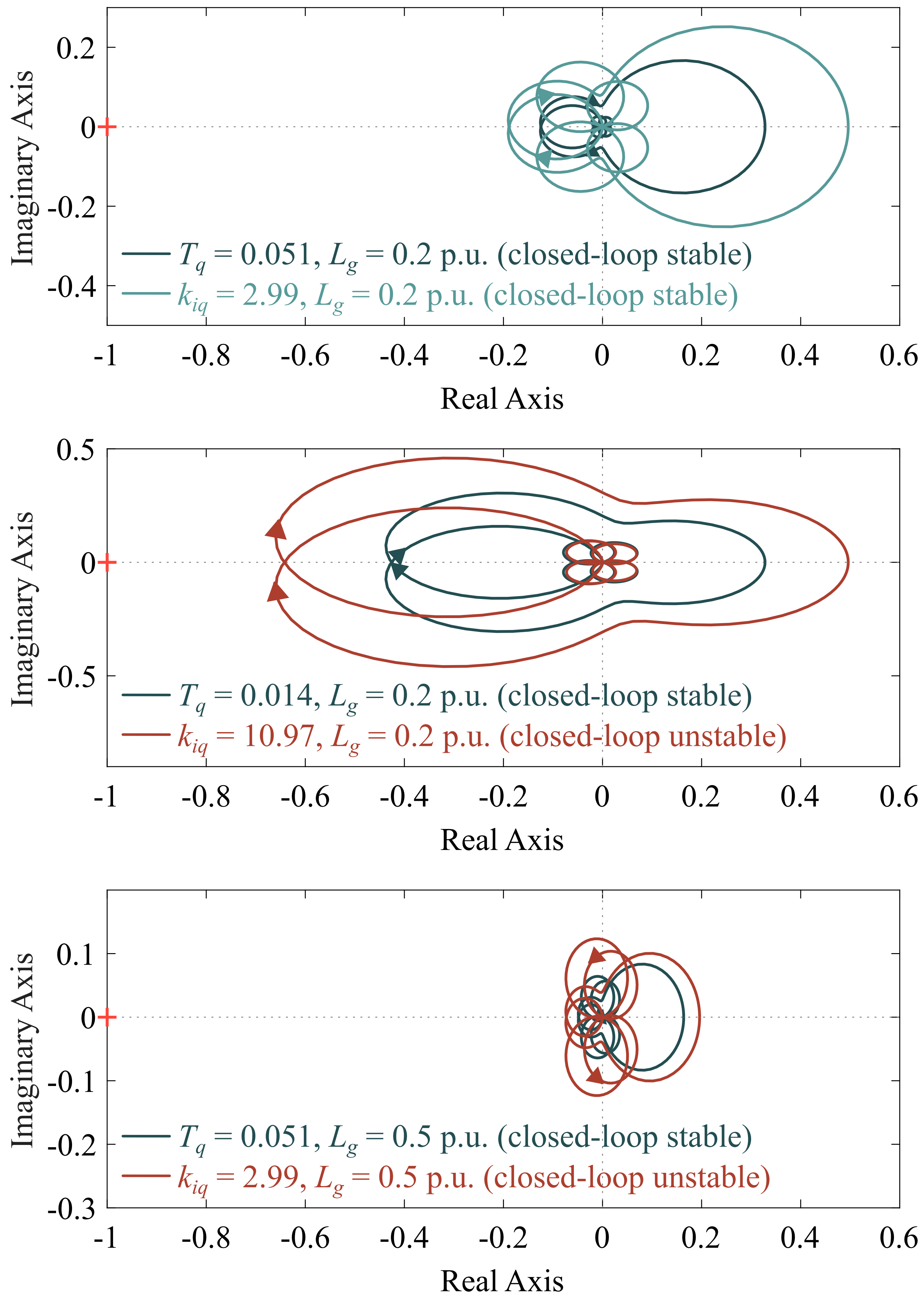
Grid-forming-induced LCL resonance

Quantitative comparison of stability

Parameters	Description	Values
S_n	Nominal power	5 MW (1 p.u.)
V_n	Nominal line-to-line RMS voltage	690 V (1 p.u.)
f_n	Nominal frequency	50 Hz (1 p.u.)
C_f	Filter capacitor	1.6 mF
L_f	Inverter-side filter inductor	32 μH
L_g	Grid-side filter inductor + line	60 μH
X_g/R_g	X/R ratio of the line	8
H	Inertia constant	0.5 s
D_p	Damping of active power control	50
D_q	Droop coefficient of $q-V$ control	10
ω_{st}	Set-point of angular frequency	1 p.u.
Q_{st}	Set-point of reactive power	0 p.u.
V_{st}	Set-point of voltage magnitude	1 p.u.
k_{pq}	Proportional gain of droop-I control	0
k_{iq}	Integral gain of droop-I control	4
T_q	Time constant of $q-V$ droop control	0.051

Droop Control		Droop-I Control	
Values	Open-loop poles	Values	Open-loop poles
$T_q = 0.051$ $L_g = 0.2$ p.u.	-19.6 $-6.8 \pm j5786.6$ $-6.8 \pm j5158.3$	$k_{iq} = 2.99$ $L_g = 0.2$ p.u.	-19.6 $-2.2 \pm j5786.3$ $-1.7 \pm j5158.6$
$T_q = 0.014$ $L_g = 0.2$ p.u.	-71.4 $-6.8 \pm j5786.6$ $-6.8 \pm j5158.3$	$k_{iq} = 10.97$ $L_g = 0.2$ p.u.	-71.4 $10.1 \pm j5785.3$ $12.1 \pm j5159.9$
$T_q = 0.051$ $L_g = 0.5$ p.u.	-19.6 $-3.4 \pm j5173.8$ $-3.4 \pm j4545.5$	$k_{iq} = 2.99$ $L_g = 0.5$ p.u.	-24.8 $2.4 \pm j5173.4$ $3.2 \pm j4545.9$



While droop control keeps stable, **instability arise in droop-I control from unstable open-loop poles.**

Active damping (AD) on GFM-induced LCL resonance

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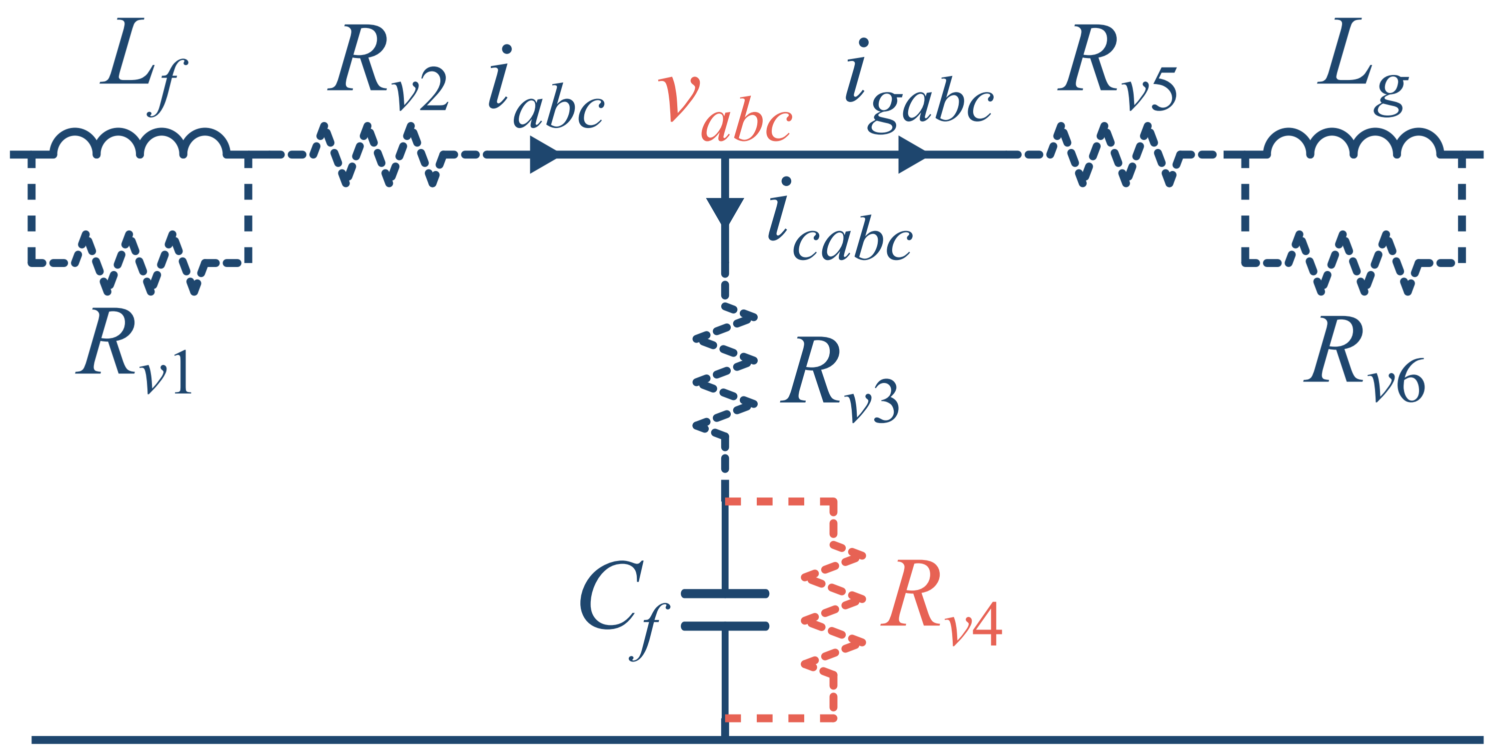
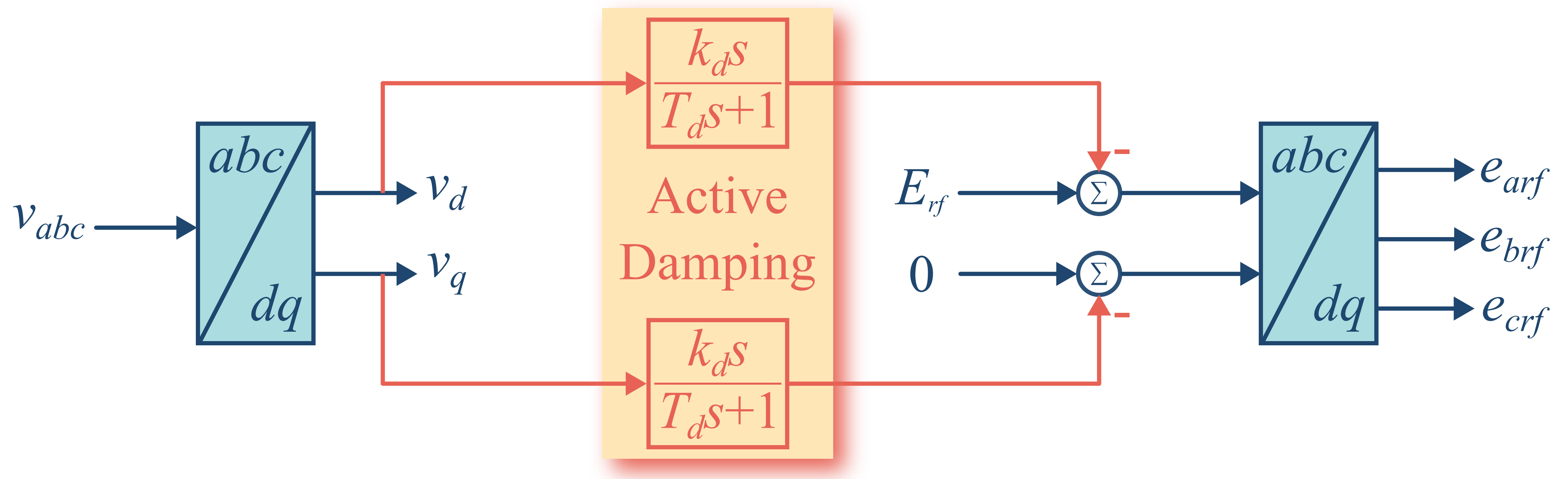
Equivalent virtual resistor strategy



Equivalent circuit of various virtual resistor implementations



Block diagram of AD strategy

$$G_{ad}(s) := \frac{k_d s}{T_d s + 1}$$ uses voltage signals v_{abc} to achieve R_{v4}

Optimal selection principles

- Number of sensors
- Complexity
- Effectiveness

Active Damping design

- Define specification (bandwidth, grid strength)
- Determine stability margin
- Root locus based design

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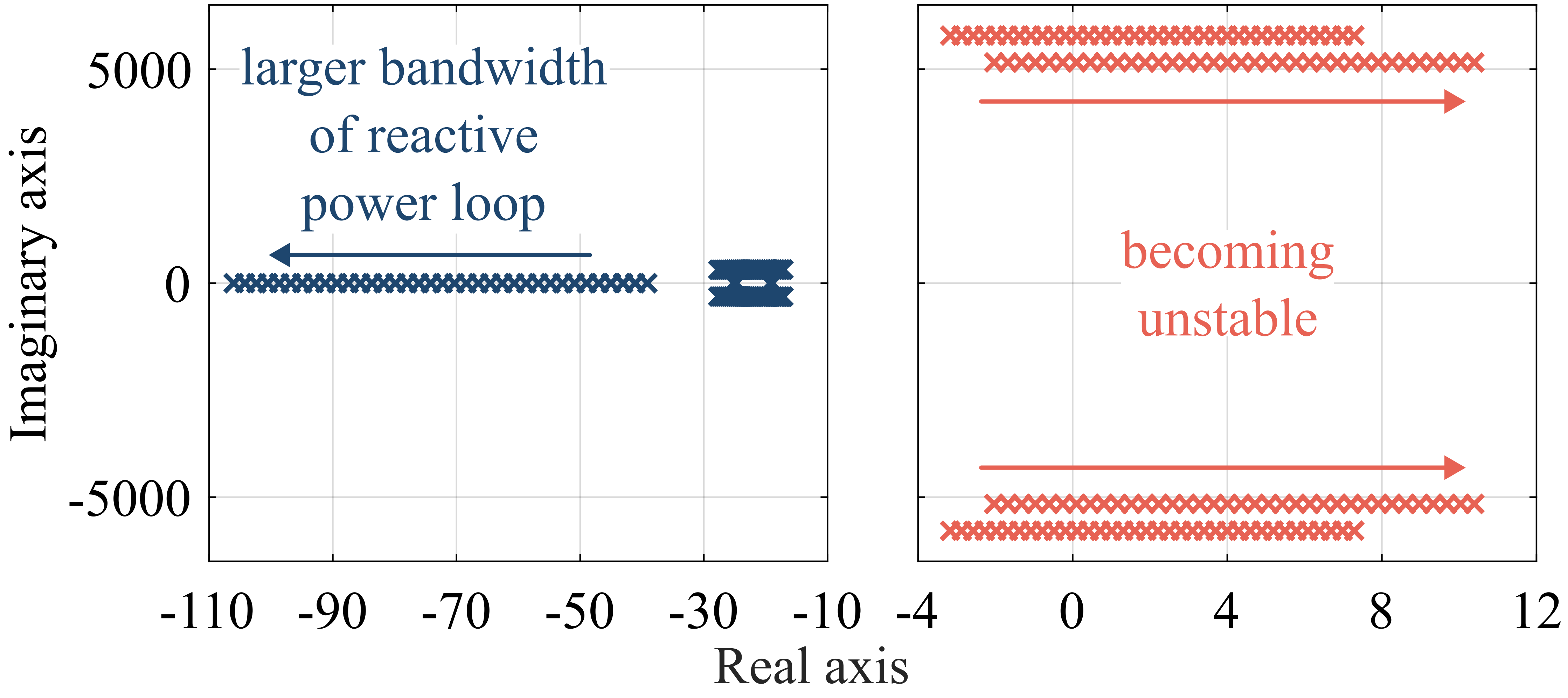
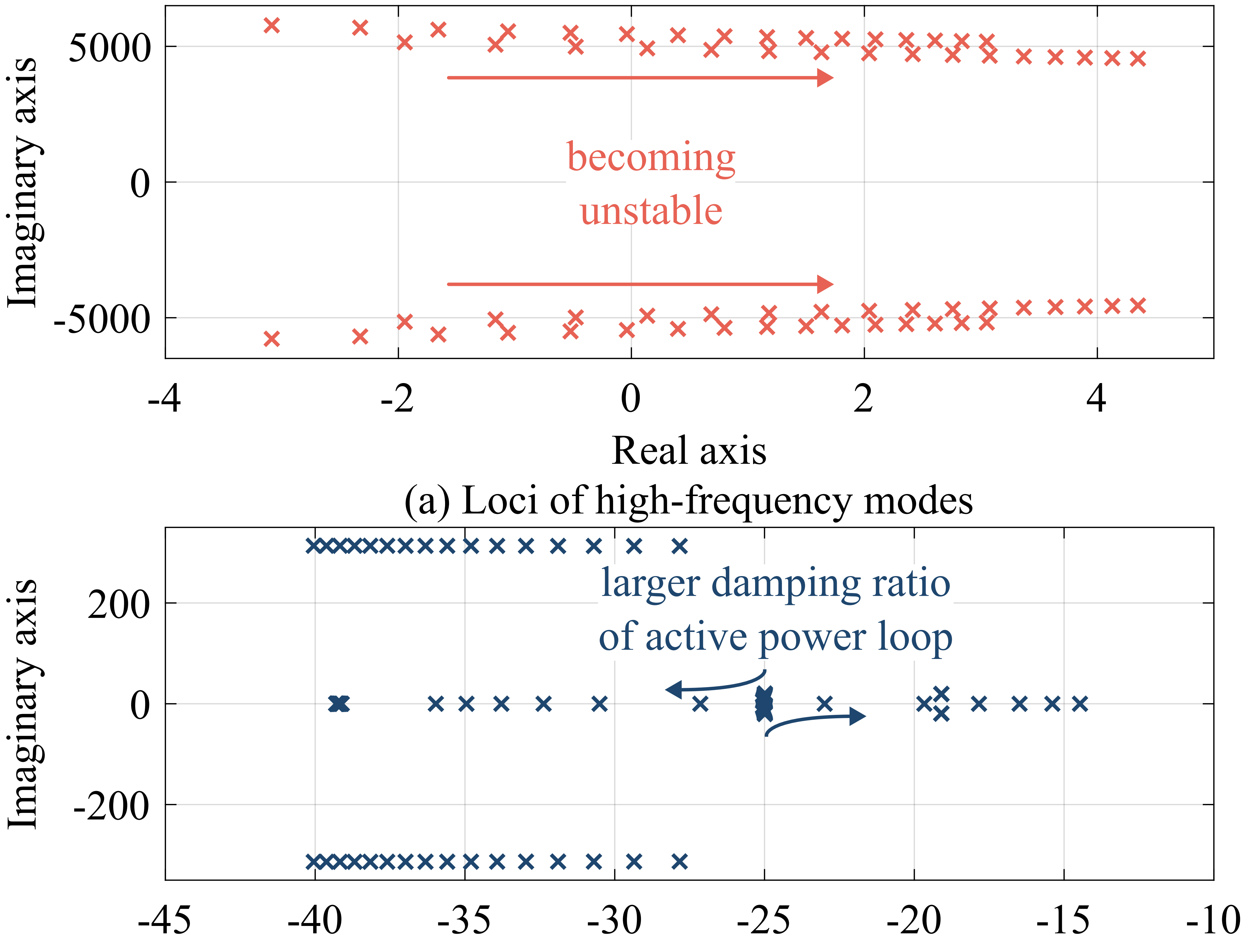
Active damping (AD) on GFM-induced LCL resonance

Root locus analysis



Chang of reactive power bandwidth



(a) Loci of high-frequency modes

(b) Loci of low-frequency modes

Change of grid strength (grid impedance)

Within the interested range, the relationship is monotone

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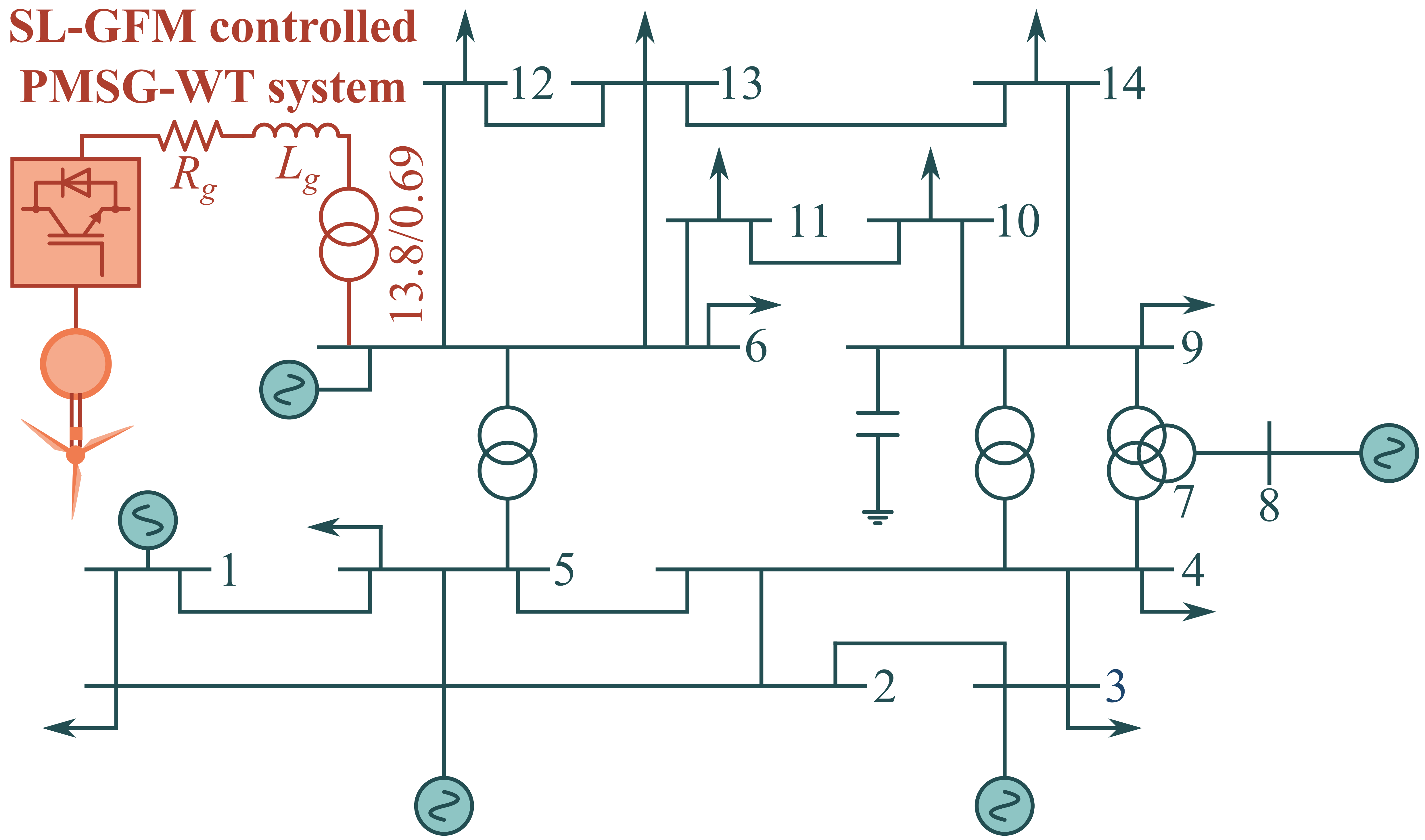
Simulation validation

IEEE 14 Bus Test system



Single-line diagram of test system with connection of a 5 MW GFM wind turbine system

System specification

- 14 buses, 5 generators, and 11 loads
- 3 voltage levels, 69kV/18kV/13.8kV
- Total load 259 MW + j73.5 MVar
- Total capacity of generators 785 MVA

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Simulation validation

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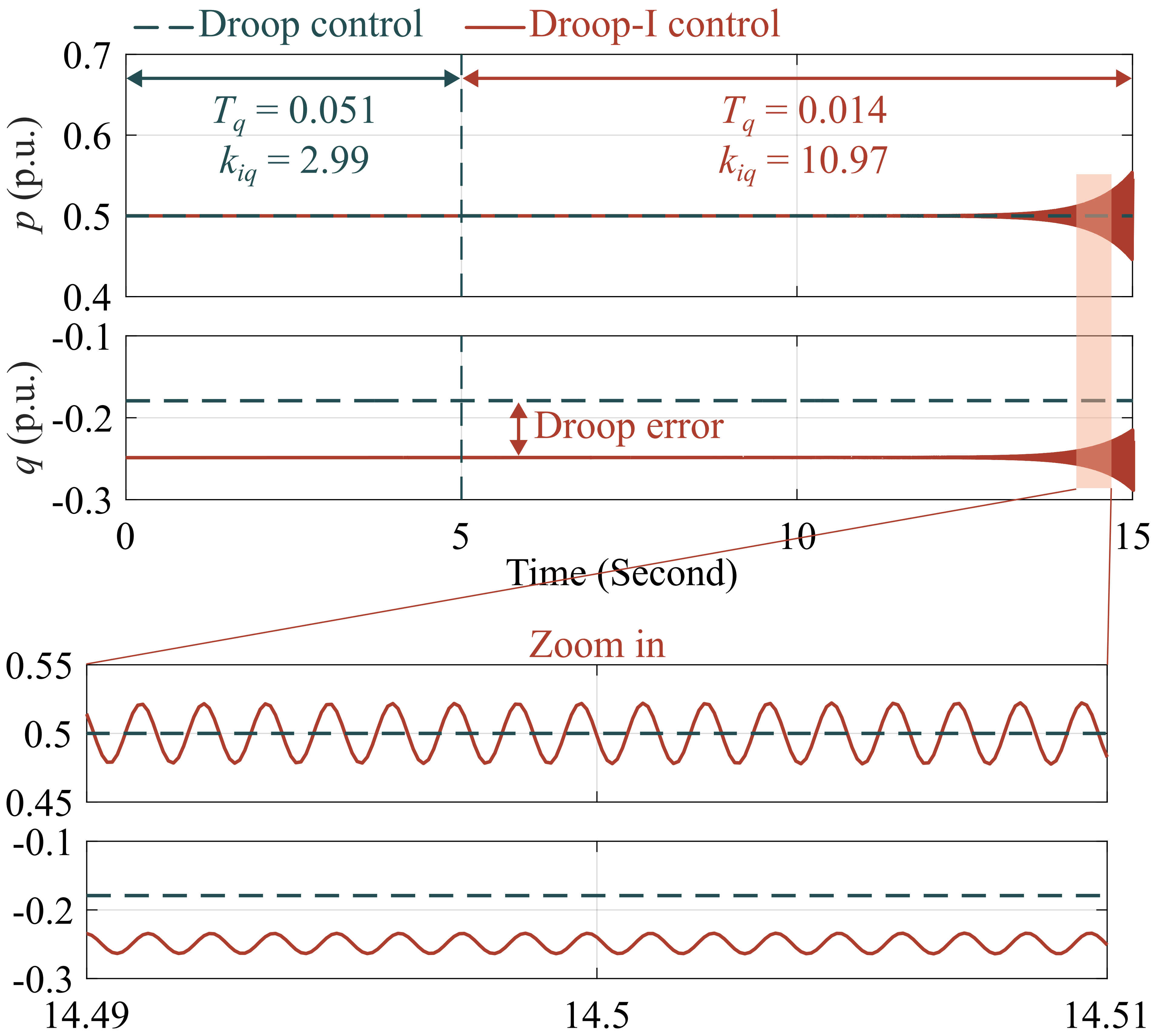
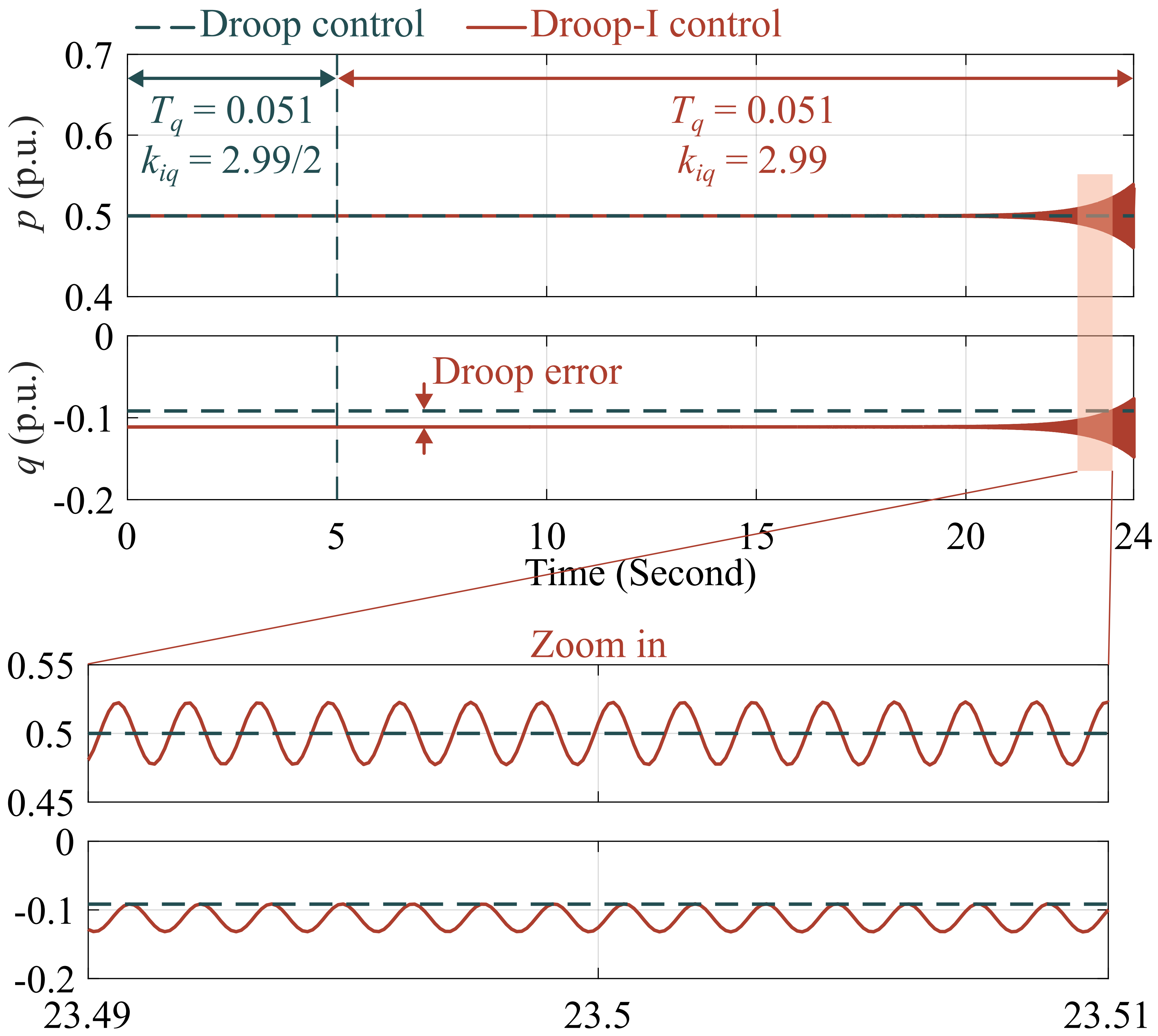
GFM-induced resonance



Case 1: L_g = 0.2 p.u.



Case 2: L_g = 0.5 p.u.

While droop control keeps stable, **high-frequency resonance arises in droop-I control when reactive power control becomes quicker or grid becomes weaker.**

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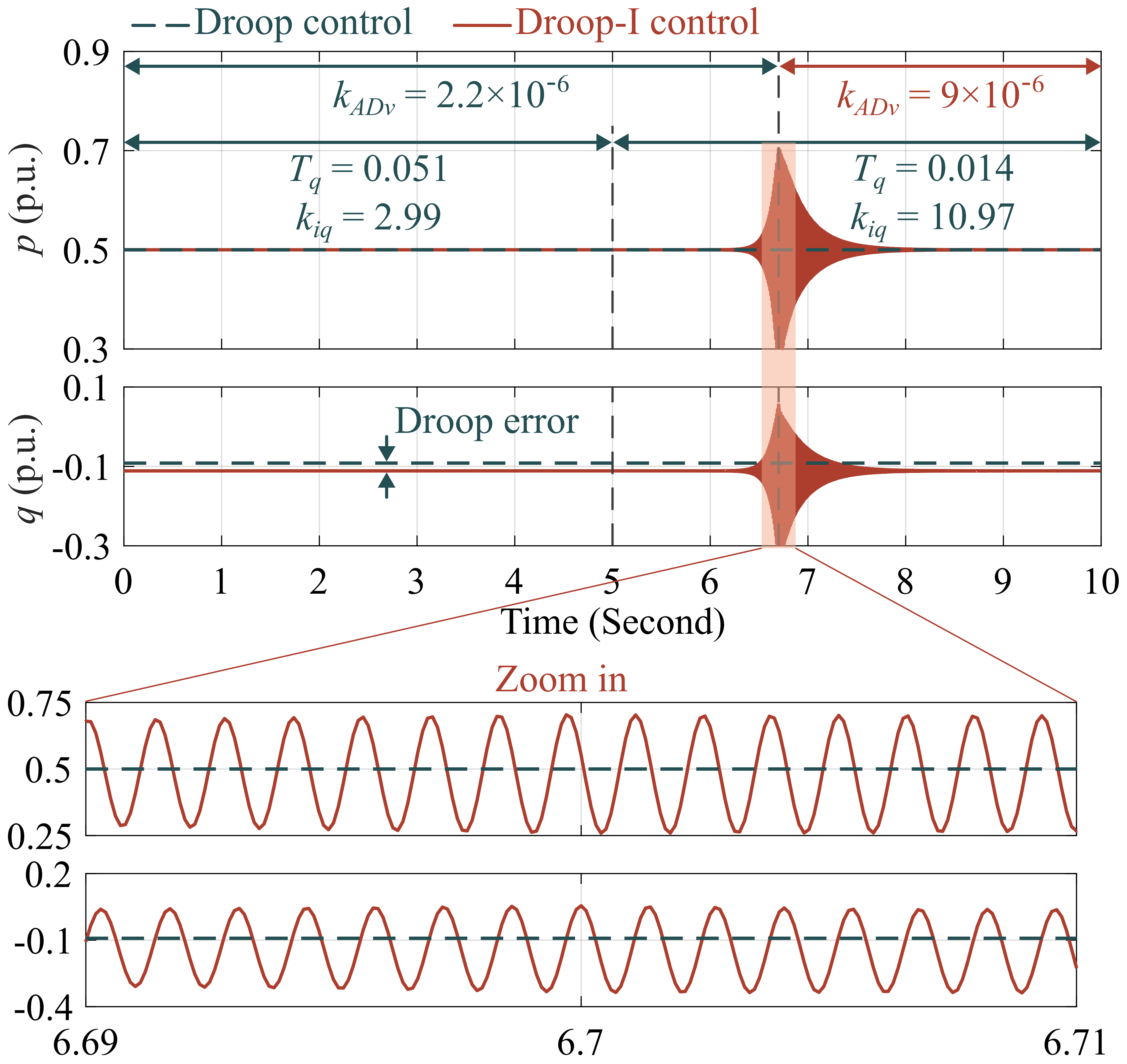
Effectiveness of active damping



L_g = 0.2 p.u. case

- The proposed AD strategy can effectively damp the resonance
- Compared to droop control, the **droop-I control needs larger damping** to bring the unstable open-loop poles back into the left-half plane

Summary

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- Renewables such as wind turbines (WTs) are increasingly expected to support both frequency and voltage stability in power systems, known as **grid-forming (GFM) capability**.
- The integration of GFM-WTs can introduce new instability phenomena into modern power systems like **high-frequency resonance.**
- Droop control-based reactive power control always remain **minimum phase** but has droop errors.
- The additional voltage magnitude feedback in droop-I control causes **unstable open-loop poles at resonant frequencies**, which is identified as a structural instability in ideal inductive grid.
- In practice of droop-I control, both **larger bandwidth** of reactive power control and **weaker grid** will drive the system to become open-loop unstable, making the droop-I control more sensitive to parameters.
- **Active damping** is proposed based on equivalent virtual resistance, and compared to the droop control, droop-I control needs larger damping to suppress the resonance.

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