U.S. DEPARTMENT of ENERGY

unifi consortium

universal interoperability
for grid-forming inverters

Dynamic droop specifications for GFM IBRs

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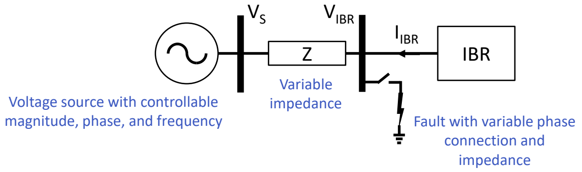
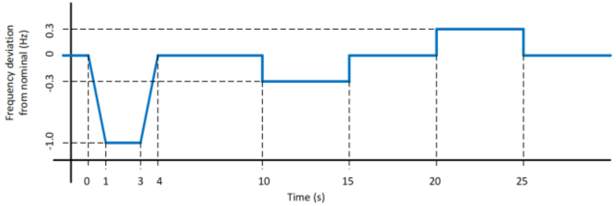
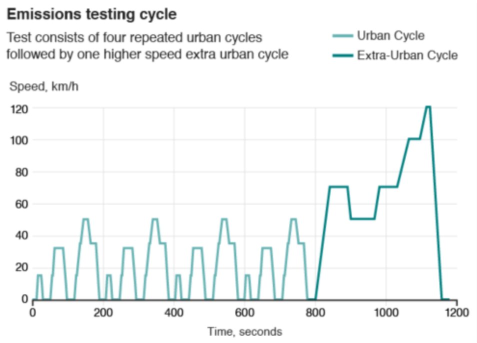
Technology agnostic standards

- **Enforcing a specific control structure not viable**
  - Too restrictive
  - Standards should be agnostic to implementation
  - Impedes innovation
- **Time domain tests may not cover the full picture**
  - What if the test scenario changes slightly?
  - Test signals (e.g., frequency profile) can be detected to ensure compliance with test case
  - May not ensure compliance with intent of the specification outside of the test case (see “Volkswagen emissions scandal”)



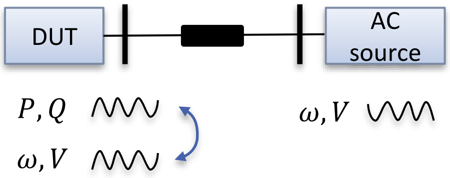




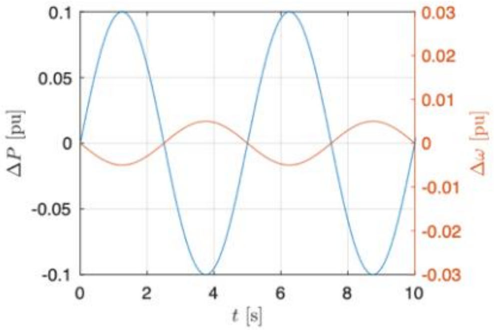
Standardizing dynamic responses

- Released as part of UNIFI specifications v3
- Non-intrusive data-driven approach to dynamic response specifications
- Ensure reliable delivery of grid support functions from wide range of resources
    - Quantitative and verifiable specifications of key grid support functions (partially applicable for GFL)
    - Quantitative specifications for two flavors of GFM control

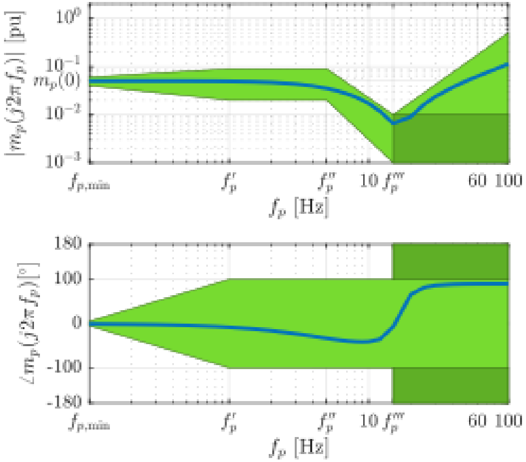
Data-driven validation



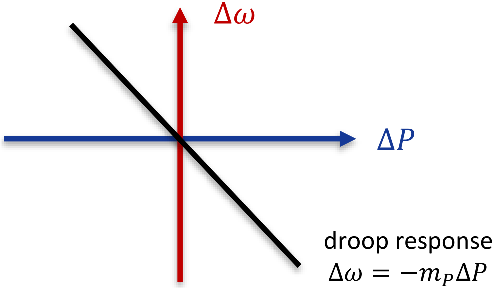
Response to probing signal



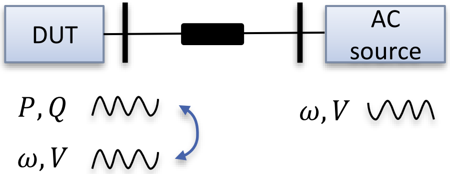
Validation against specification

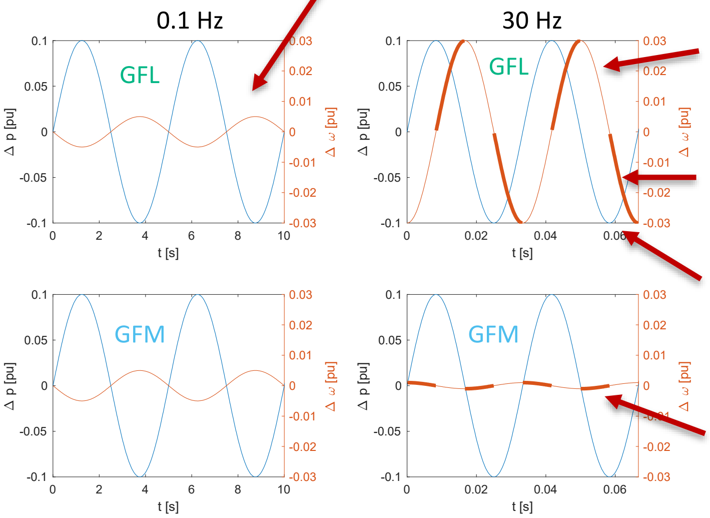


How to read dynamic droop specifications



droop response
$\Delta\omega = -m_P \Delta P$





$\Delta\omega$ is negative while ΔP is positive

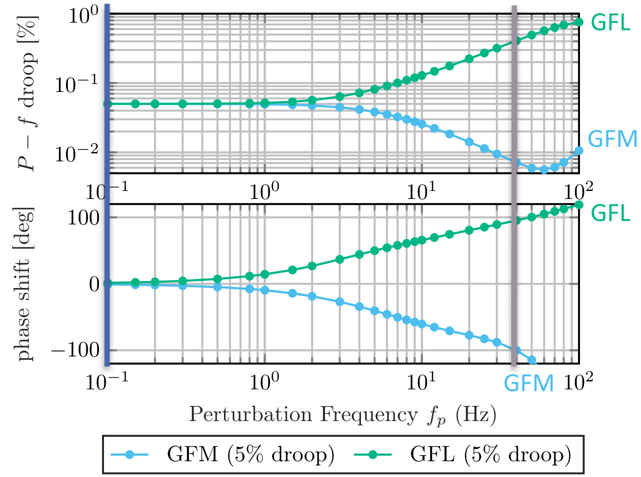
$\Delta\omega$ is positive while ΔP is positive

$\Delta\omega$ large for GFL

GFM keeps $\Delta\omega$ stiff

GFL and GFM identical at 0.1 Hz

Significant differences at 30 Hz



Frequency domain model as screening tool (I)

- GFL with 5% frequency droop
    - frequency not stiff for “fast” perturbations
- Generic GFL replicating Kauai 20Hz oscillation
    - **positive feedback at 18-20Hz**
    - frequency not stiff for “fast” perturbations
- Data-enabled frequency domain model can predict **real-world oscillation** events

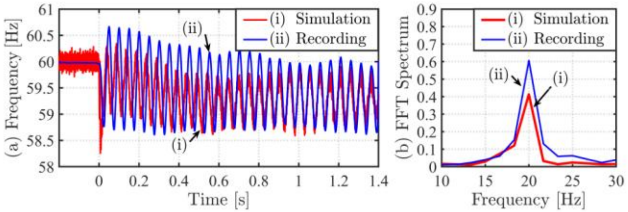
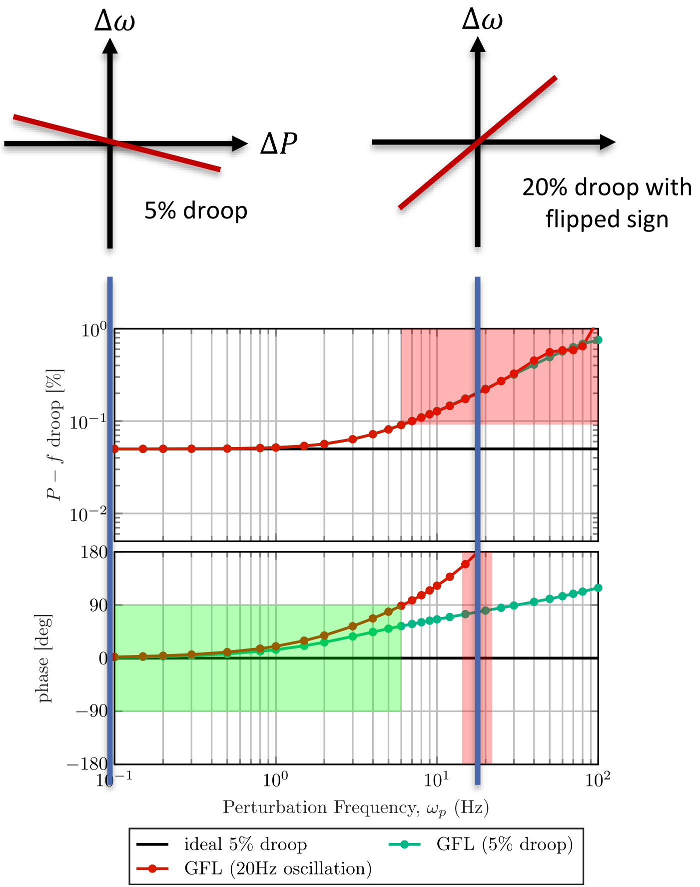
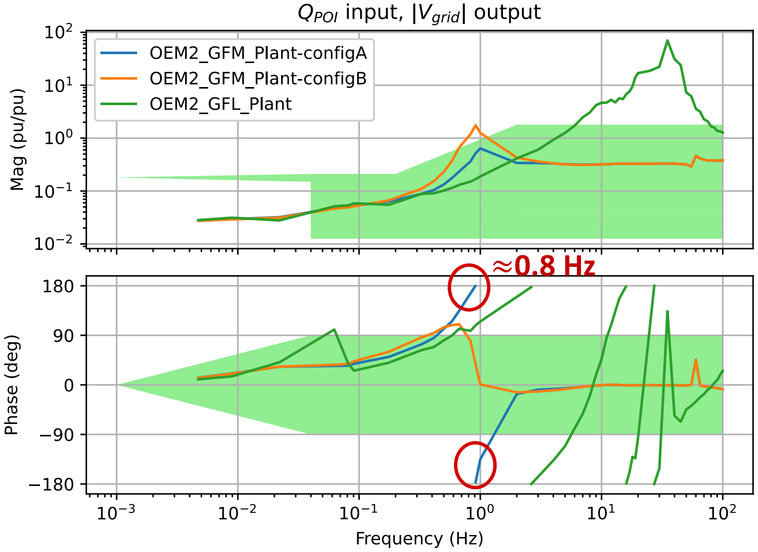


Image credit: Shuan Dong et al.: “Analysis of November 21, 2021, Kaua`i Island Power System 18-20 Hz Oscillations”, arXiv:2301.05781, 2023



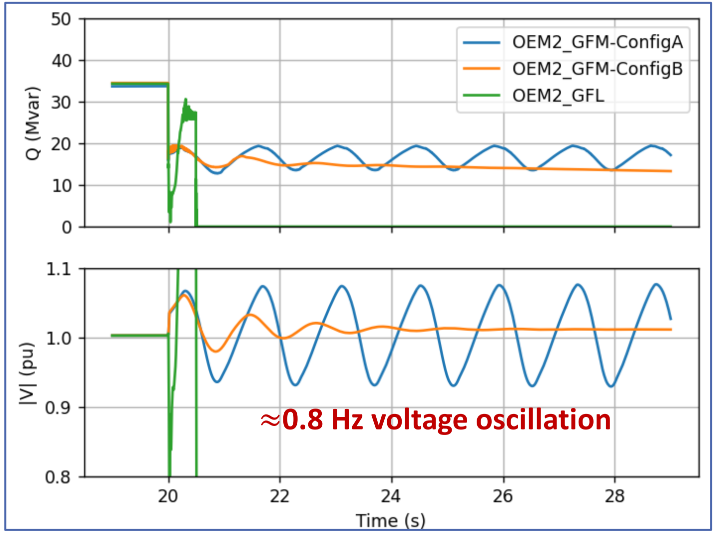
Frequency domain model as screening tool (II)

- Model of GFM BESS system has problematic voltage response at approx. 0.8 Hz to 0.9 Hz
- Simulation of trip of last synchronous generator exhibits 0.8 Hz oscillation



≈0.8 Hz

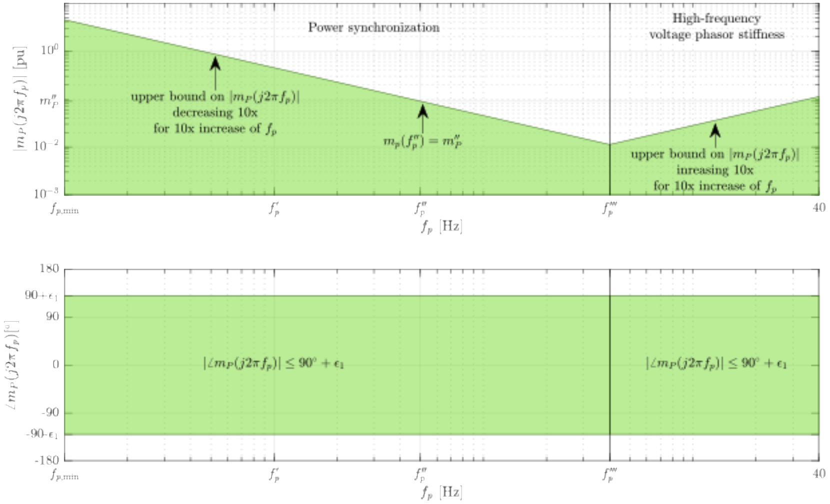
$m_Q(j2\pi f_p)$ for GFL and two GFM plant configurations



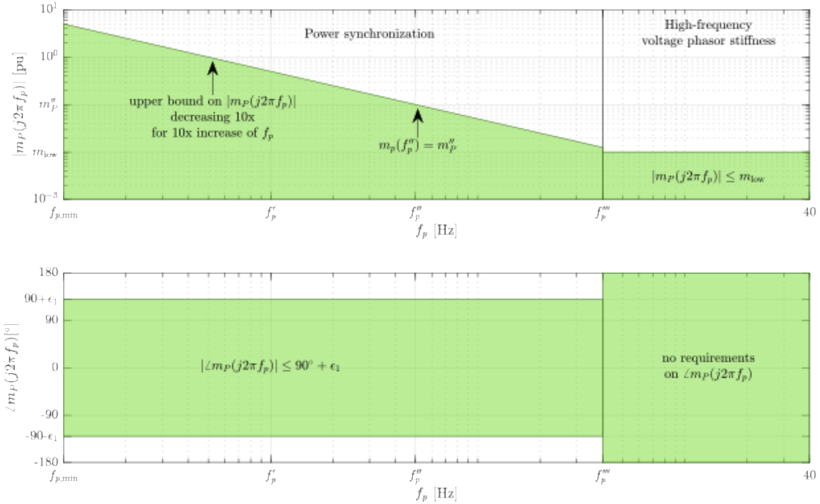
≈0.8 Hz voltage oscillation

Loss of last synchronous machine for OEM BESS model

GFM IBR flavors



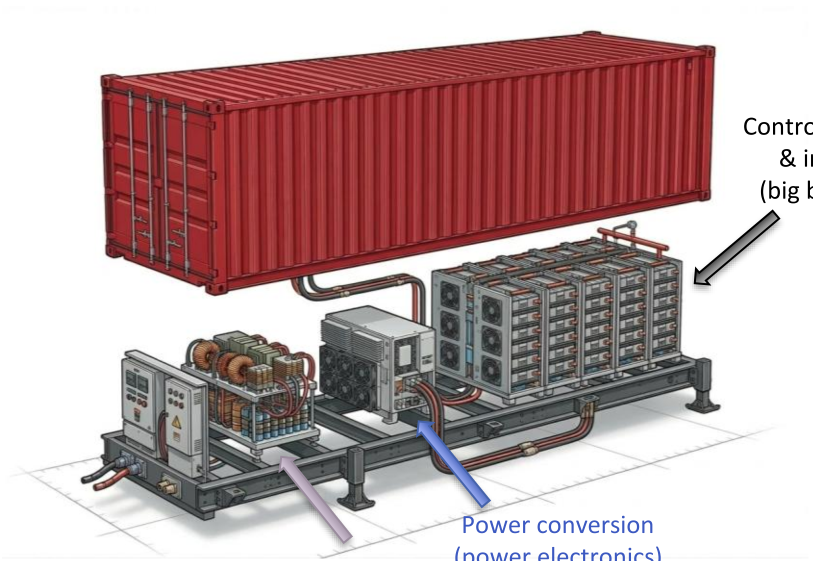
Power synchronization and passive high-frequency voltage phasor stiffness



Power synchronization and low-gain high-frequency voltage phasor stiffness

- Power synchronization encodes requirement for GFM IBR to synchronize through power
  - allows for frequency synchronization without steady-state droop
- Passive “high-frequency” response: remain in phase with droop specifications for at least half a cycle
- Low-gain “high-frequency” response: negligible droop -> frequency stiff

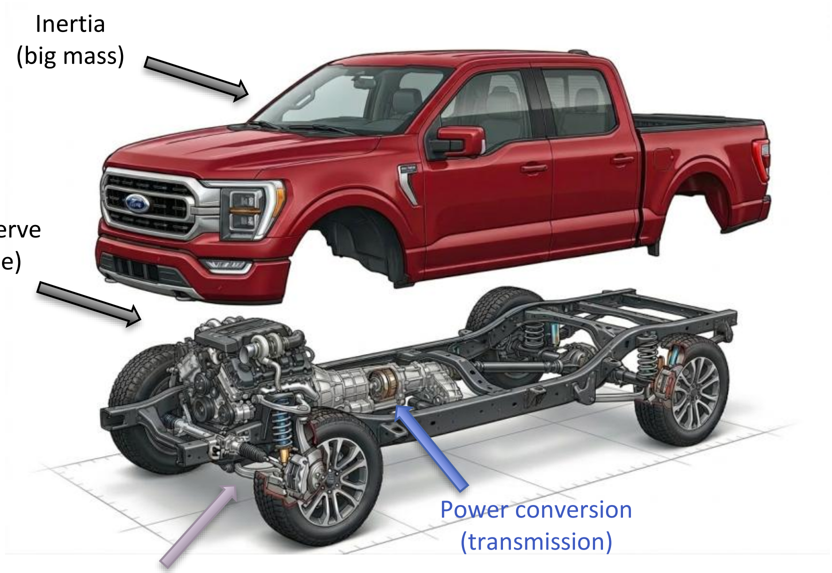
Big picture: GFM IBR flavors



Control reserve
& inertia
(big battery)

Power conversion
(power electronics)

Damping
(LCL filter + transformer)



Inertia
(big mass)

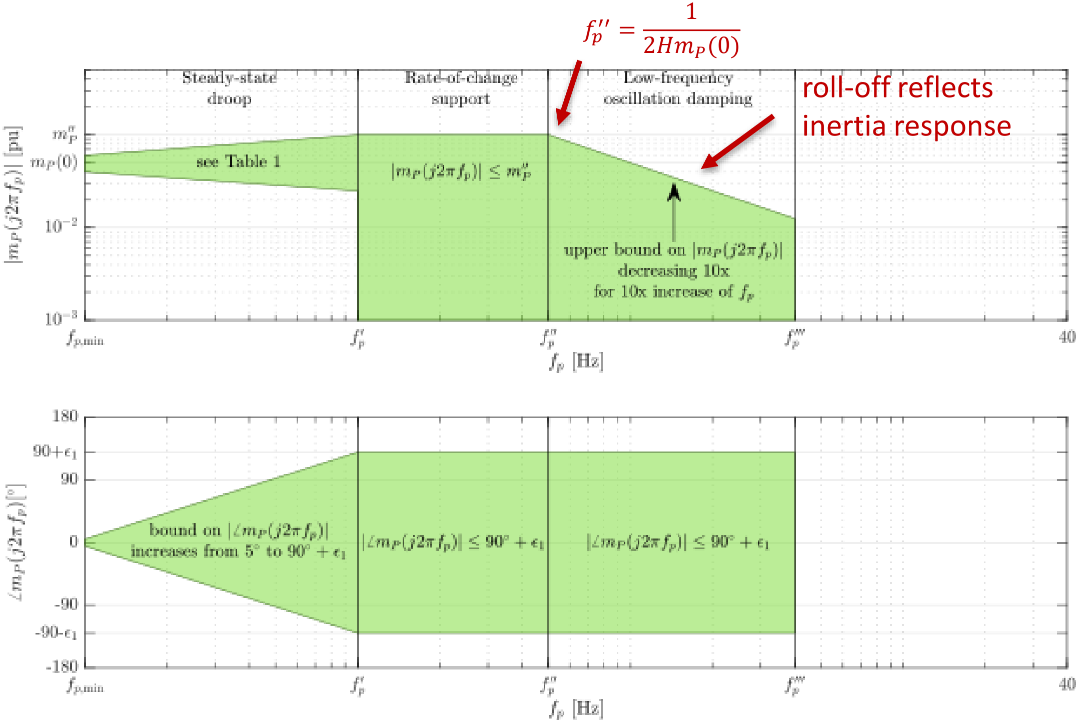
Control reserve
(big engine)

Power conversion
(transmission)

Damping
(suspension + tire)

- **VSM behind impedance** approach **relies** on **large transformer impedance** and **significant energy storage**
- **Standards** should be **open** to **nimble & efficient** approaches

IBR Unit Capabilities: frequency/active power



$$f_p'' = \frac{1}{2Hm_P(0)}$$

roll-off reflects inertia response

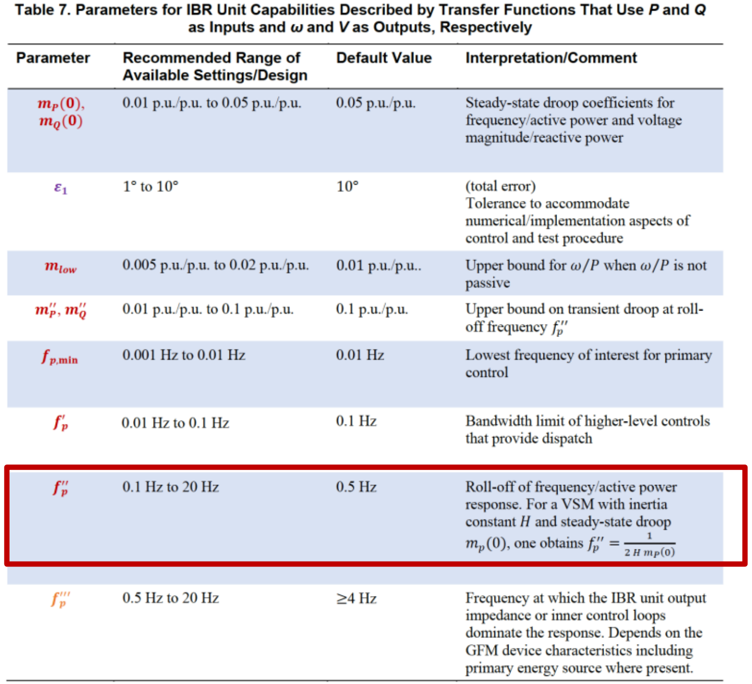


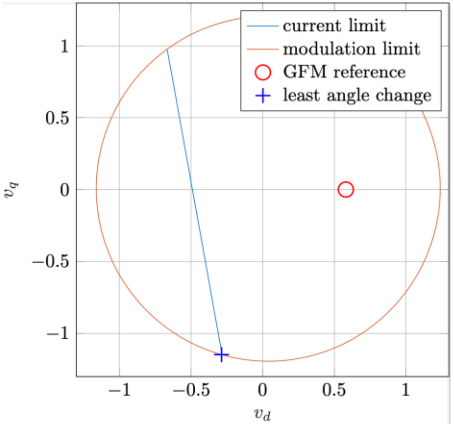
Table 7. Parameters for IBR Unit Capabilities Described by Transfer Functions That Use *P* and *Q* as Inputs and *ω* and *V* as Outputs, Respectively

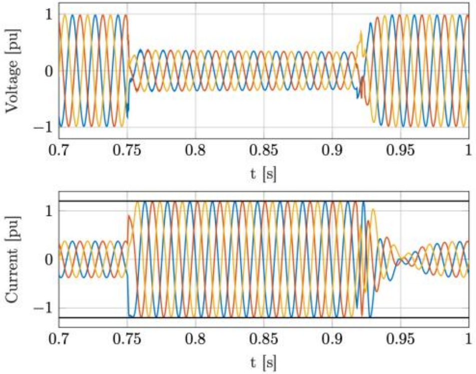
Parameter	Recommended Range of Available Settings/Design	Default Value	Interpretation/Comment
$m_P(0)$, $m_Q(0)$	0.01 p.u./p.u. to 0.05 p.u./p.u.	0.05 p.u./p.u.	Steady-state droop coefficients for frequency/active power and voltage magnitude/reactive power
ε_1	1° to 10°	10°	(total error) Tolerance to accommodate numerical/implementation aspects of control and test procedure
m_{low}	0.005 p.u./p.u. to 0.02 p.u./p.u.	0.01 p.u./p.u..	Upper bound for ω/P when ω/P is not passive
m_P'', m_Q''	0.01 p.u./p.u. to 0.1 p.u./p.u.	0.1 p.u./p.u.	Upper bound on transient droop at roll-off frequency f_p''
$f_{p,\min}$	0.001 Hz to 0.01 Hz	0.01 Hz	Lowest frequency of interest for primary control
f_p'	0.01 Hz to 0.1 Hz	0.1 Hz	Bandwidth limit of higher-level controls that provide dispatch
f_p''	0.1 Hz to 20 Hz	0.5 Hz	Roll-off of frequency/active power response. For a VSM with inertia constant H and steady-state droop $m_p(0)$, one obtains $f_p'' = \frac{1}{2\,H\,m_P(0)}$
f_p'''	0.5 Hz to 20 Hz	≥4 Hz	Frequency at which the IBR unit output impedance or inner control loops dominate the response. Depends on the GFM device characteristics including primary energy source where present.

- Capabilities are mapped to GFM Tiers in UNIFI specs:
  - STATCOMs are not required to be able to provide steady-state droop or rate-of-change support
  - GFM BESS need to have steady-state droop, rate-of-change support, and low-frequency oscillation damping capability

Next steps for UNIFI and IEEE2800.1

- Ongoing work
  - $P - V$ and $Q - f$ cross coupling?
  - How should a GFM IBR respond when reaching a limit (i.e., power, current, voltage)
- UNIFI v3 specs as starting point for IEEE 2800.1
  - what should go into IEEE 2800.1
  - Normative vs. informative specifications
  - What is our risk tolerance?
    - <90° phase bound is safe
    - 180° phase shift is not safe
    - In-between it depends on the system





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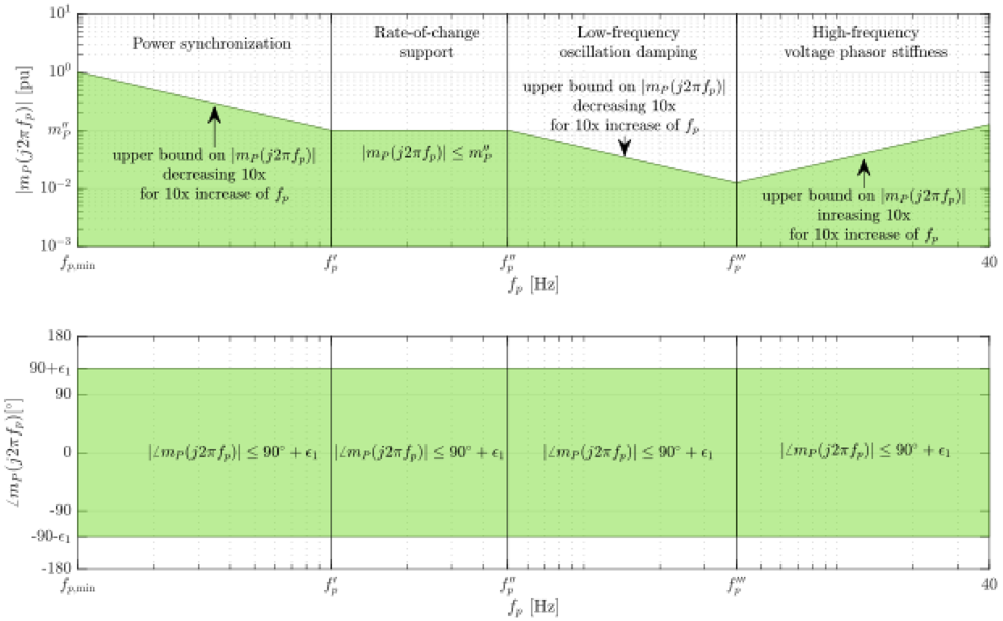
Thank you

GFM Tier 2



- Example: GFM Tier 2 specification

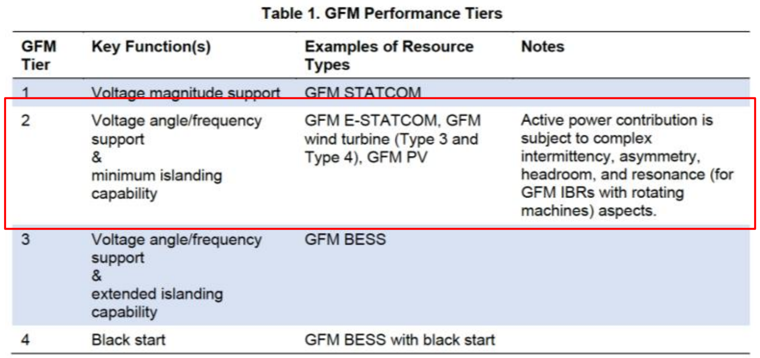
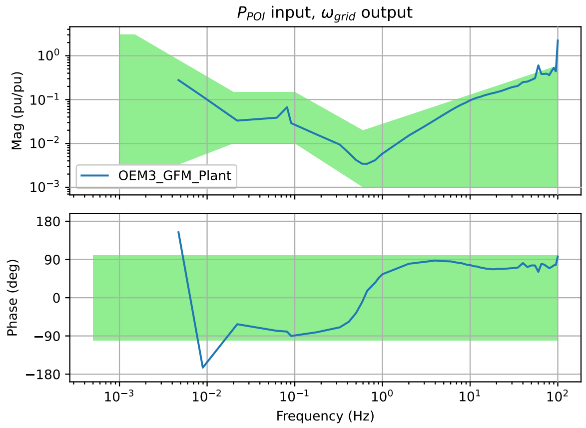


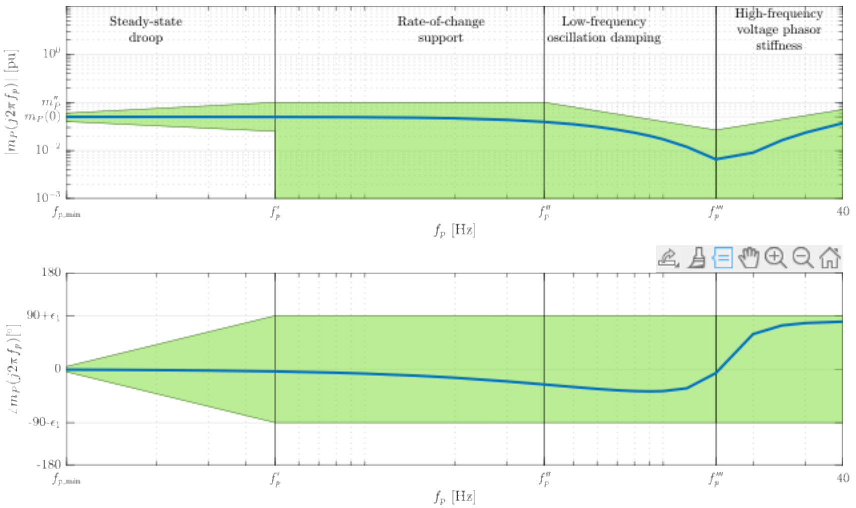
Table 1. GFM Performance Tiers

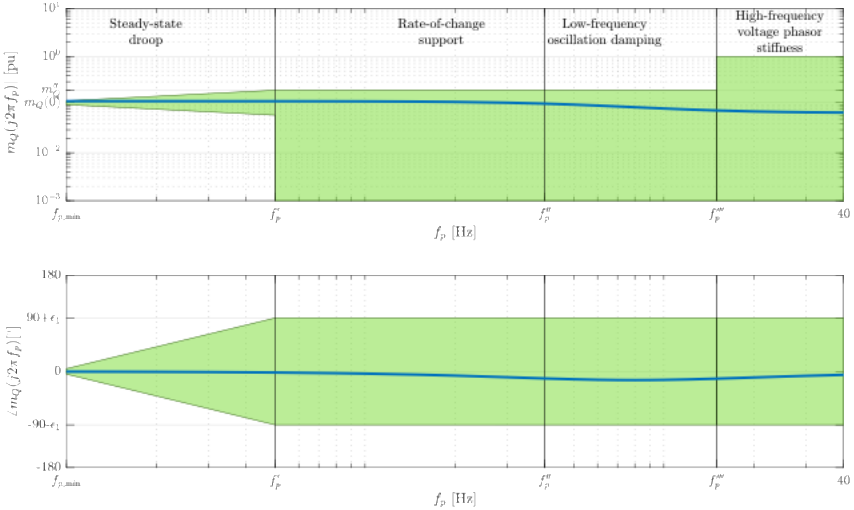
GFM Tier	Key Function(s)	Examples of Resource Types	Notes
1	Voltage magnitude support	GFM STATCOM	
2	Voltage angle/frequency support & minimum islanding capability	GFM E-STATCOM, GFM wind turbine (Type 3 and Type 4), GFM PV	Active power contribution is subject to complex intermittency, asymmetry, headroom, and resonance (for GFM IBRs with rotating machines) aspects.
3	Voltage angle/frequency support & extended islanding capability	GFM BESS	
4	Black start	GFM BESS with black start	

E-STATCOM (vendor model)



GFM Tier 3





- Example: GFM VSM without inner loops

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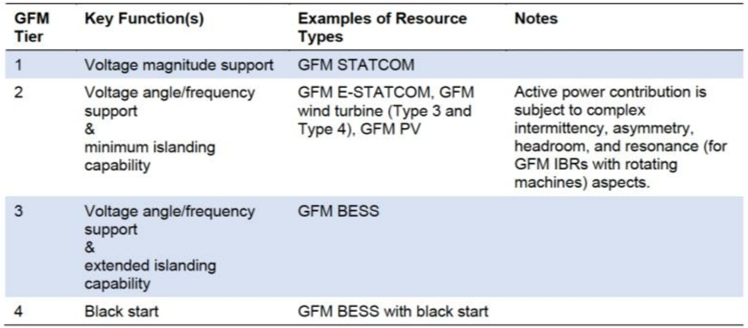

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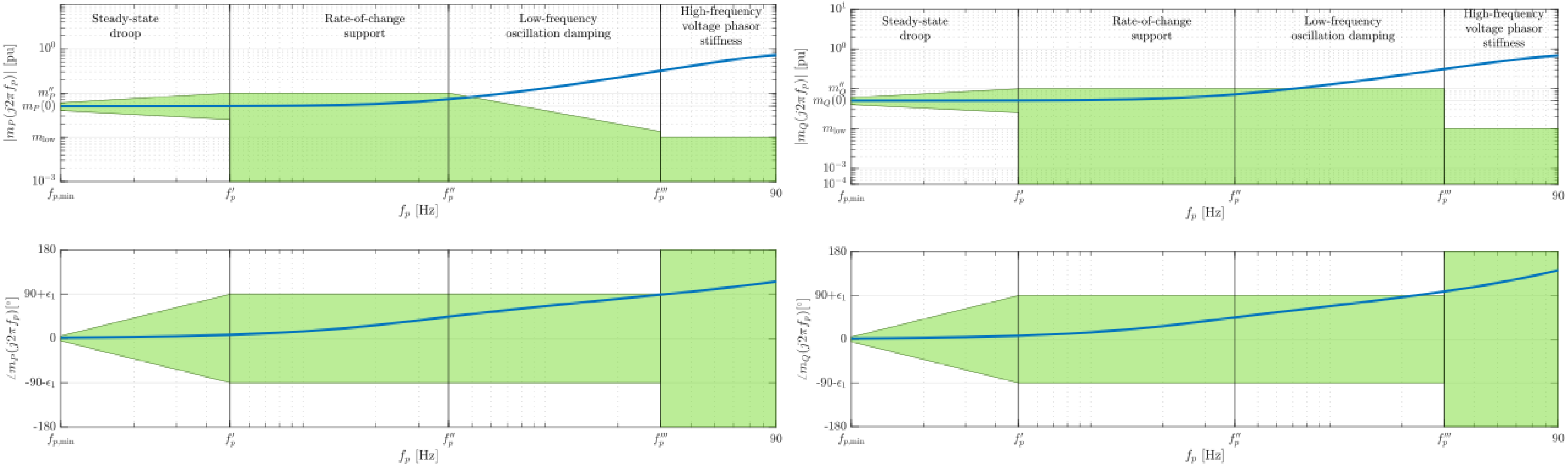
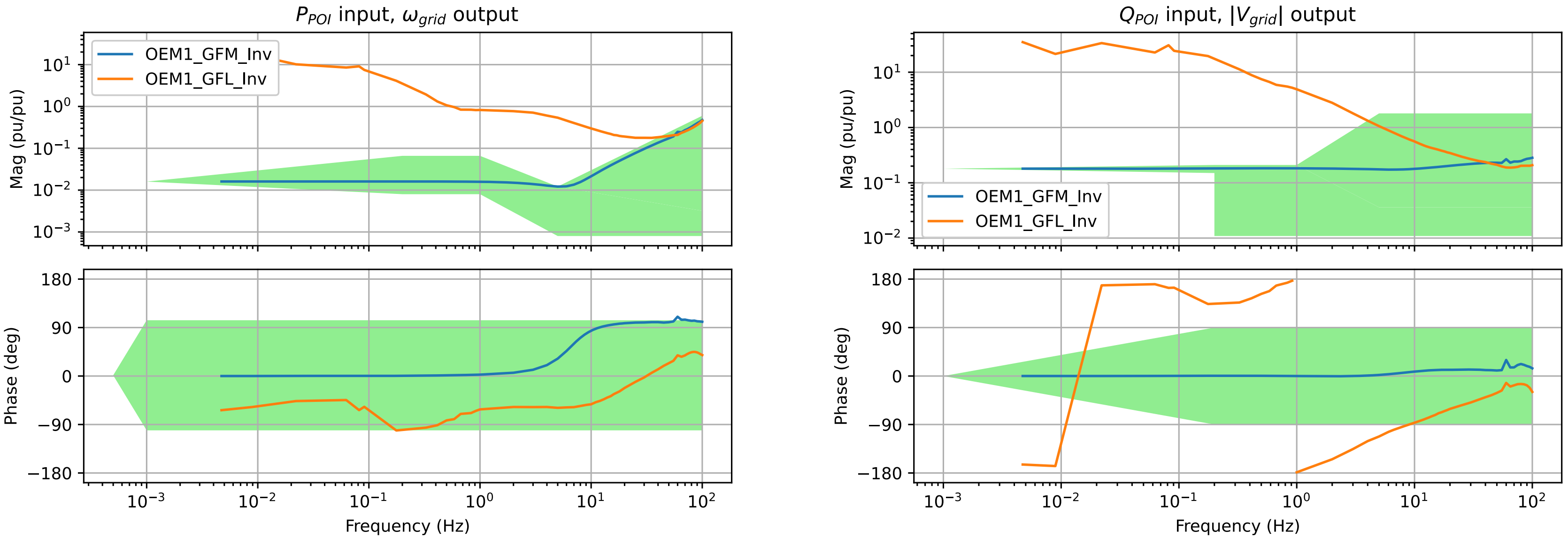
4	Black start	GFM BESS with black start	

Example: SRF-PLL GFL with P-f and Q-V droop



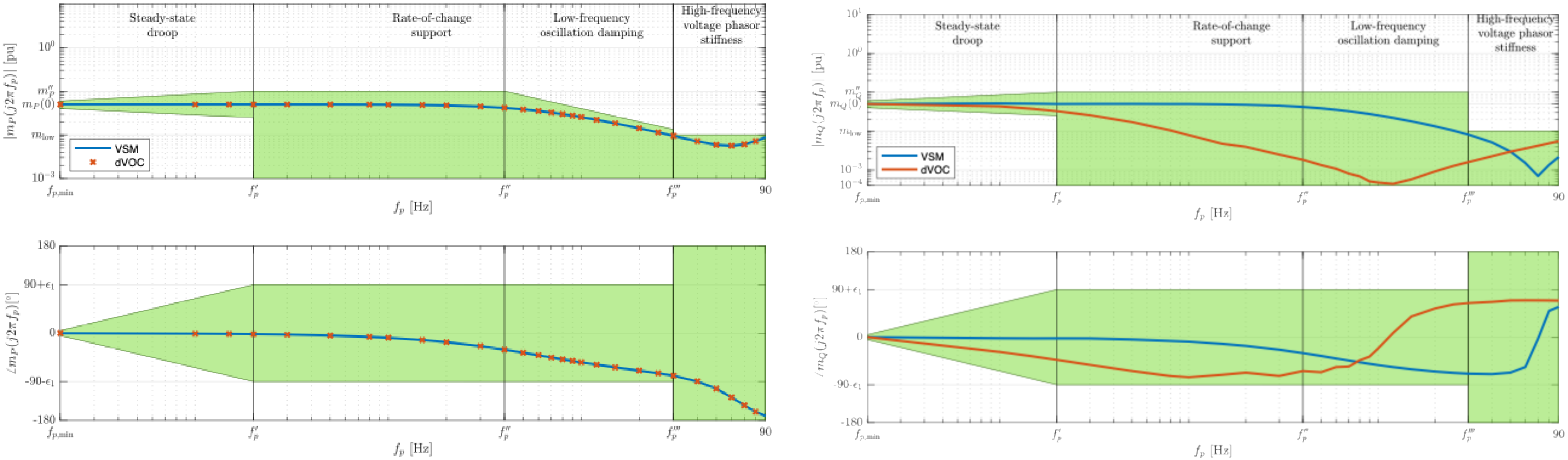
- Whitebox model from academic literature
- Does not provide low-frequency oscillation damping specification
- Does not meet passive or low-gain “high-frequency” specification

Example: OEM model of GFL and GFM BESS



- GFL implementation works well down to comparably low SCR
- GFM shows expected response for VSM type controls

GFM VSM and dVOC with inner loops

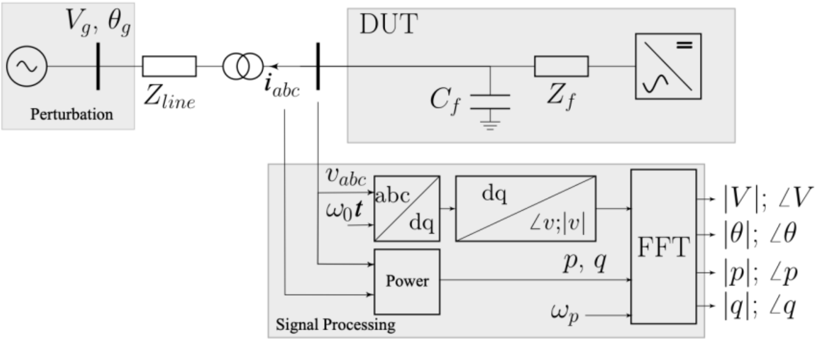


- Cascaded dual-loop control structure with inner current and voltage control
- Low-gain “high-frequency” response
- Voltage/reactive power response differs between controls

Obtaining models from data

Perturbation of AC voltage magnitude and frequency

$$V_g = V^* + A_V \sin(2\pi f_p t)$$
$$\omega_g = \omega_0 + A_\omega \sin(2\pi f_p t)$$



Signal processing recovers phase and magnitude of

- voltage magnitude
- voltage phase angle
- active power
- reactive power

- Data $(\,)_\omega$ obtained by perturbing frequency (i.e., $A_V = 0,\ A_\omega > 0$)
- Data $(\,)_V$ obtained by perturbing magnitude (i.e., $A_V > 0,\ A_\omega = 0$)

$$Y(j2\pi f_p) = \begin{bmatrix} \Delta\omega_\omega(j\omega_p) & \Delta\omega_V(j\omega_p) \\ \Delta V_\omega(j\omega_p) & \Delta V_V(j\omega_p) \end{bmatrix}$$

$$U(j2\pi f_p) = \begin{bmatrix} \Delta P_\omega(j\omega_p) & \Delta P_V(j\omega_p) \\ \Delta Q_\omega(j\omega_p) & \Delta Q_V(j\omega_p) \end{bmatrix}$$

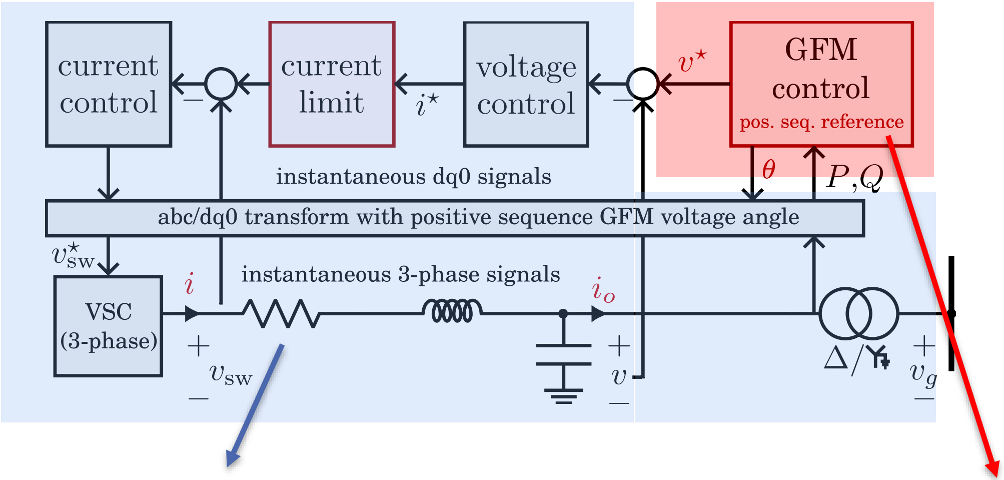
- Least squares used to solve for dynamic droop model

$$Y(j\omega_p) = \begin{bmatrix} m_P(j\omega_p) & \xi_Q(j\omega_p) \\ \xi_P(j\omega_p) & m_Q(j\omega_p) \end{bmatrix} U(j\omega_p)$$

Notes:

- A_V and A_ω need to be selected large enough to ensure sufficient excitation but small enough to not activate limiters
- GFM IBRs provide identical response if AC voltage source is replaced by AC current source

Coordinates and timescale separation



Impedances dictate harmonics

- Circuit and inner loops in dq-frame
- approximately linear in v_{dq} and i_{dq}
- natural choice for line frequency and beyond
- well-understood in industry

Slow dynamics govern system-wide interactions

- imposed by outer GFM control
- approximately linear in (ω, V) and (P, Q)
- insightful up to line frequency