Universal Input-Output Model of Grid-Forming Functions and Data-Driven Verification Methods

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Introduction

The UNiversal Interoperability for grid-Forming Inverters (UNIFI) Consortium has identified system- and unit-level functional requirements and performance criteria that ensure interoperability of grid-forming (GFM) inverter-based resources (IBRs) in electric power systems at any scale without requiring vendors or system operators to reveal proprietary information in [1]. It is then necessary to translate these high-level principles into rigorous mathematical specifications that can be enforced and validated across a wide range of devices and systems. While it is challenging to establish uniform vendor-agnostic specifications for the growing number and complexity of implementations of GFM and IBR technologies, input-output modeling can support the development of universal reduced-order models of GFM functions parameterized by general network and control variables. By observing the dynamic behavior of a GFM IBR at its terminals and only considering signals that can be experimentally collected, it is possible to identify salient GFM functions without details on hardware or controls. Input-output data can be obtained using hardware experiments and blackbox models and form the basis for developing data-driven verification methods. The input-output modeling framework is envisioned to help formulate and validate specifications that bound GFM dynamics within which vendors can innovate while interoperability and stability (e.g., frequency and voltage magnitude) are guaranteed.

Methodology

Analytical Modeling: Closed-loop transfer functions that capture the dynamic behavior of GFM IBRs are derived from power flow dynamics, linearized IBR controls available in literature, and a two-bus system (Fig. 1, left). These analytical models will be used to formulate specifications for GFM functions and understand fundamental performance limits.

Numerical Modeling: A simulation model is built to numerically obtain input-output data and Bode plots that illustrate the small-signal responses at the IBR terminals (output) to perturbations from the grid (input). These numerical models are used to develop and validate stability and interoperability conditions and verification methods.

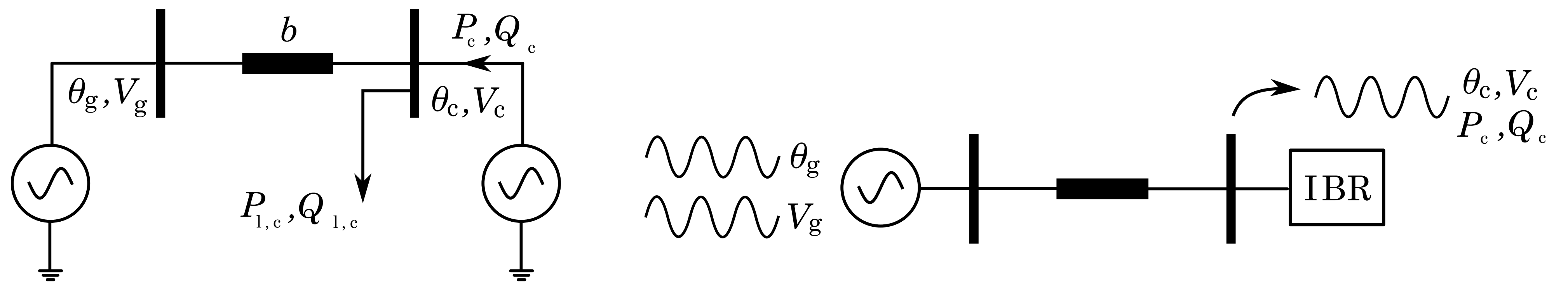

Fig. 1: [LEFT] Two-bus lossless system with a GFM IBR modeled as controlled voltage source connected to an infinite bus (i.e., the grid). [RIGHT] Sinusoidal perturbations are applied on the grid-side and measurements are collected at the terminal of a blackbox IBR. θ and V denote bus voltage phase angle and magnitude, P and Q the injected active and reactive power, P_l and Q_l the active and reactive load, and b the susceptance of the connection. The subscripts g and c denote signals attributed to the infinite bus and IBR terminal, respectively.

Results

Closed-Loop Block Diagrams

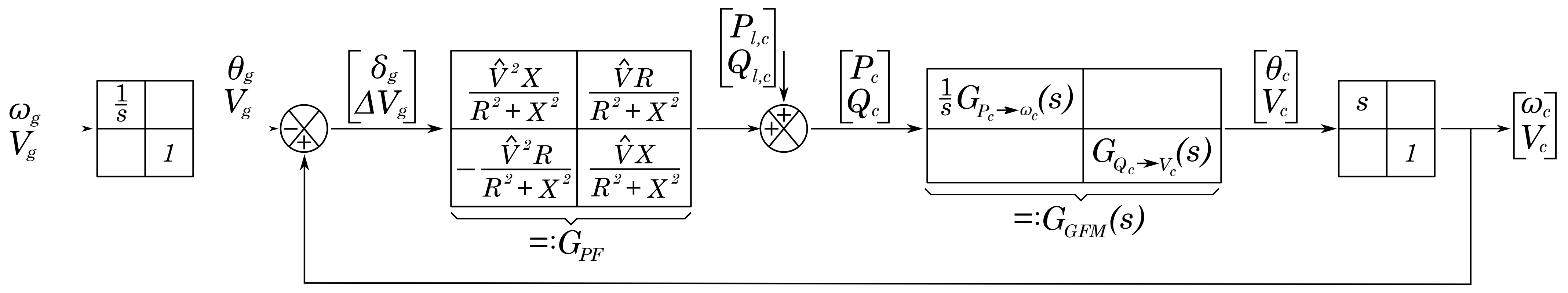

Fig. 2: Example of a closed-loop block diagram resulting from the system in Fig. 1 used to derive analytical input-output models. G_{PF} contains linearized power flow equations where R and X are the resistance and reactance of the connection and $\hat{V}$ the nominal voltage magnitude at both buses. $G_{GFM}(s)$ denotes GFM controls that map active and reactive power injections to inverter frequency and voltage magnitude references, respectively.

Closed-Loop Transfer Functions

Table 1: One set of closed-loop transfer functions from external inputs to IBR terminal signals for a GFM IBR, resulting from Fig. 2

	ω_c	P_c
ω_g	$G_{\omega_g \to \omega_c}(s) = -\frac{1}{1+\frac{1}{b}G_{P_c \to \omega_c}(s)}$	$\frac{1}{s}G_{P_c \to \omega_c}(s)G_{\omega_g \to \omega_c}(s)$
$P_{l,c}$	$-\frac{s}{b}G_{\omega_g \to \omega_c}(s)$	$-G_{\omega_g \to \omega_c}(s)$

Analytically Derived

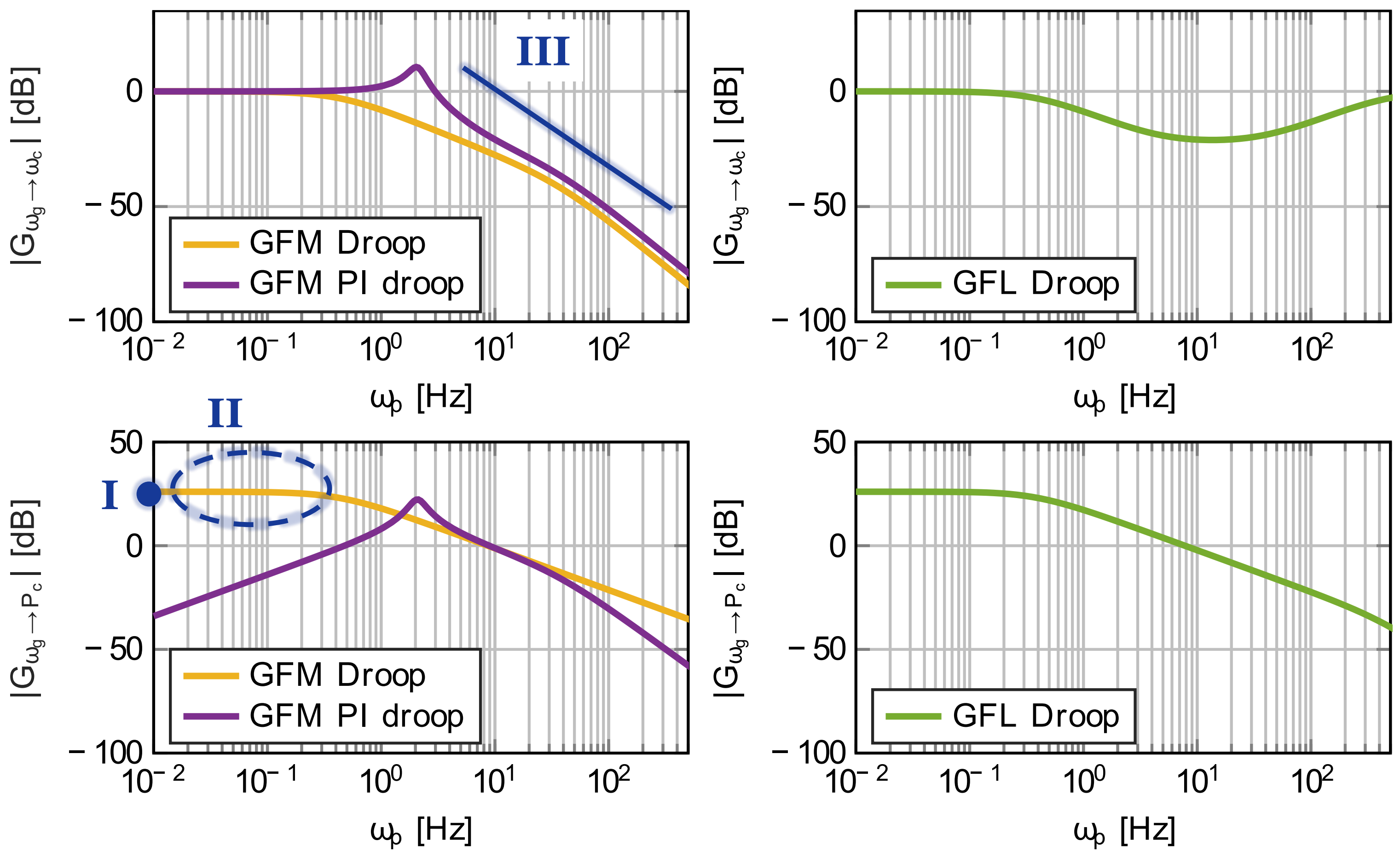

Fig. 3: Analytically derived Bode magnitude plots for GFM droop control, GFM proportional integral (PI) control, and grid-following (GFL) with droop. Several GFM functions can be observed.

Numerically Obtained

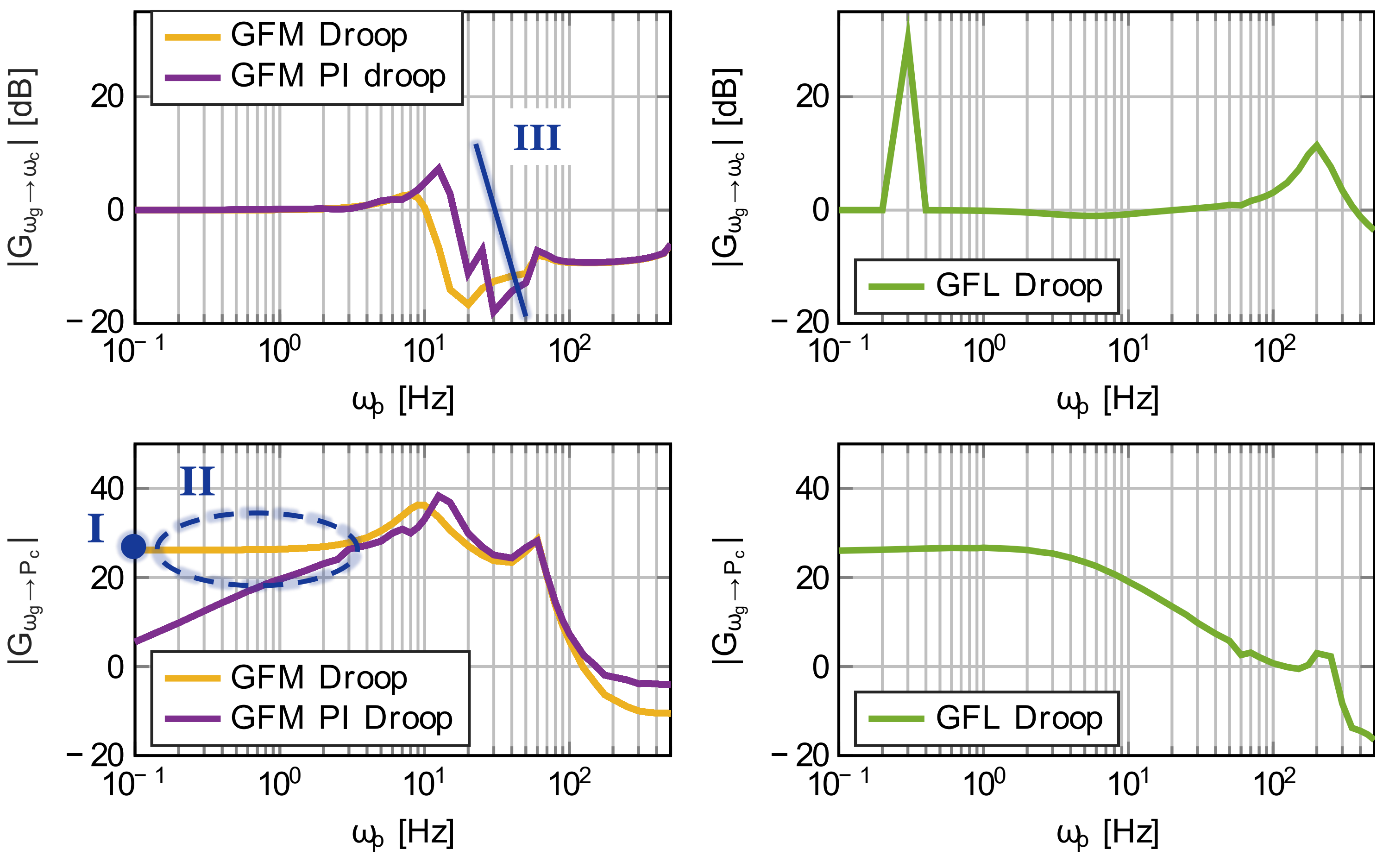

Fig. 4: Numerically obtained Bode magnitude plots for GFM droop control, GFM proportional integral (PI) control, and grid-following (GFL) with droop. GFM functions identified in Fig 3. can also be observed.

Observed Grid-Forming Functions

I. Droop response determining steady-state behavior for power sharing with DC gain equal to the inverse of the droop coefficient (m_p):

$$|G_{\omega_g \to P_c}(j\omega_p = 0)| = \frac{1}{m_p}$$

II. Fast frequency response with fast droop response and maximum response time (T_{dr}):

$$\left|G_{\omega_g \to P_c}(j\omega_p)\right| \geq \left|\frac{m_p}{T_{dr} j\omega_p + 1}\right|, \forall \omega_p \geq 0$$

III. Frequency smoothing – attenuation of frequency oscillations at the IBR terminal. Given an inertial time constant (T_ω),

$$\left|G_{\omega_g \to \omega_c}(j\omega_p)\right| \leq \left|\frac{1}{T_\omega j\omega_p + 1}\right|, \forall \omega_p \geq 0$$

Performance Limitations of Grid-Following Control

Since the GFL control scheme includes droop, the dynamic behavior of the GFL IBR matches that of the GFM IBR in the low frequency range. Analytical results show that GFL control cannot be retuned to overcome its performance limitations. In other words, Figs. 3 and 4 demonstrate that GFL control cannot support frequency smoothing as well as GFM control. Its synchronization mechanism (typically phase-locked-loop) is unable to track and attenuate a large range of high frequency oscillations.

Conclusion, Future Work, and References

Input-output modeling of GFM IBRs has provided key insights into the development of vendor-agnostic specifications for GFM technologies. A theoretical foundation and experimental methodology for obtaining reduced-order input-output models of GFM IBRs were investigated. Several GFM functions were identified and mapped to specifications applicable to closed-loop transfer functions and Bode magnitude plots, making them readily interpretable and enforceable.

Future work will include:

- Identifying boundaries and regions on Bode plots that guarantee interoperability and stability
- characterizing the impact of non-negligible network resistances on the input-output models
- how and to what level of accuracy the input-output dynamics can be identified using data-driven methods that only use measurement data

[1] B. Kroposki et. al, “UNIFI Specifications for Grid-forming Inverter-based Resources—Version 1,” UNIFI-2022