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Capacity Ratio Estimation and Capability Assessment for Hybrid Grid-Following and Grid-Forming Converter Systems

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Abstract

The increasing penetration of converter-interfaced renewable generation and the declining share of synchronous generation reduce voltage and frequency support. This paper proposes a grid-forming (GFM) converter capacity ratio estimation method and a capability assessment framework for hybrid grid-following (GFL) and GFM converter systems at fixed total installed capacity. First, a model incorporating the principal control loops of both converter types is developed. The critical short-circuit ratio and the GFM converter terminal impedance are used to derive an analytical relationship between the GFM capacity ratio and the generalized short-circuit ratio. This relationship defines a continuous lower bound for the capacity ratio subject to small-signal stability and target grid strength constraints. The assessment framework uses normalized margins and a bottleneck index to evaluate basic support conditions, control parameter effects, and disturbance response performance. Generalized Nyquist analysis and time-domain simulations verify the method. Under the studied conditions, increasing the GFM capacity ratio increases equivalent grid strength and oscillation damping, reduces the peak power deviation, and shortens the settling time. Phase-locked loop parameters mainly affect synchronization dynamics and power oscillations, whereas virtual inertia and the damping coefficient primarily affect frequency support and power recovery. The method supports GFM capacity planning and control coordination.

Keywords: grid-forming converter; grid-following converter; capacity ratio; grid-forming capability assessment; generalized short-circuit ratio



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1. Introduction

With the increasing integration of wind and photovoltaic generation, the share of conventional synchronous generation is declining, whereas the share of converter-interfaced generation continues to increase. Consequently, power systems are shifting from synchronous generation toward operation dominated by converters [1]. Power electronic converters serve as grid interfaces for renewable generation. They generally use either grid-following (GFL) or grid-forming (GFM) control. GFL converters typically use current control to inject power. They employ a phase-locked loop (PLL) to track the voltage phase and frequency at the point of connection. Their stable operation therefore relies on the external grid for voltage and frequency references [2,3]. Under weak grid conditions, high grid impedance strengthens the coupling between the converter, the grid, and its control loops. This coupling reduces the synchronization stability margin and may also cause

power oscillations or transient loss of synchronism [4,5]. GFM converters autonomously establish grid voltage and frequency while providing active grid support through virtual inertia, damping, and voltage regulation. Owing to their voltage source characteristics, they are suited to weak grid and islanded operation, thereby offering an important technical solution for enhancing the stability and effective grid strength of power systems with high renewable energy penetration [6,7].

However, renewable energy plants face high retrofit costs, different control functions, and varying operating requirements. GFL and GFM converters are therefore expected to coexist for the foreseeable future. The GFM converter capacity ratio affects both the equivalent grid strength and the small-signal stability margin of the hybrid system. If this ratio is insufficient, GFM converters may provide inadequate voltage support to improve the synchronization stability and oscillation damping of GFL converters [8]. A higher GFM capacity ratio generally improves grid strength but may also increase investment costs [9]. The capacity ratio alone cannot fully characterize the grid-forming capability of a plant because support performance also depends on external grid strength, control parameters, and operating conditions. A key task in renewable energy plant planning is to determine the minimum GFM capacity ratio that satisfies the small-signal stability and target grid strength requirements. The grid-forming capability of the resulting hybrid system must also be assessed to support coordinated control design.

The existing studies on the GFM converter capacity ratio in hybrid systems have primarily addressed grid strength and small-signal stability. The generalized short-circuit ratio (gSCR) and critical short-circuit ratio (CSCR) link grid strength to the small-signal stability boundary of converters [10], while appropriate placement of GFM converters can increase the equivalent grid strength and improve the stability margin of PLL-based converters [11]. Furthermore, the study in [12] characterized the effective voltage source behavior of GFM converters from a dynamic admittance perspective and established an analytical relationship among the GFM capacity ratio, gSCR, and a specified stability margin by representing each GFM converter as an ideal voltage source behind an equivalent scalar reactance. The study in [13] determined feasible GFM capacity ranges for different GFM configurations by jointly considering gSCR, the equipment CSCR, and steady-state operating constraints. These studies provide a theoretical basis for estimating GFM capacity ratio. The equivalent reactance in [12] is obtained from the GFM impedance characteristic at a frequency of interest, whereas the capacity boundary in [13] depends on prescribed stability margins and steady-state operating constraints. For a renewable energy plant with a fixed total installed capacity, in which GFM units replace part of the existing GFL capacity, the required GFM capacity ratio should therefore be determined by accounting for the actual control parameters and frequency-dependent terminal characteristics of the GFM converters.

On the other hand, satisfying a target gSCR or small-signal stability margin does not fully characterize the actual grid-forming capability of a hybrid system during disturbances. Previous studies have shown that the GFM stability boundary is affected by inner loop parameters, network conditions, and operating points [14], and that interactions between heterogeneous GFL and GFM controls alter the oscillatory characteristics of hybrid systems [15]. Accordingly, research at the system level has expanded from gSCR assessment to control admittance and modular impedance analysis [16–18]. Although these studies deepen the understanding of the relationship between the GFM converter capacity ratio and small-signal stability, they still focus primarily on local stability. Related research has therefore expanded from stability boundaries to disturbance response performance. Regarding frequency response, ref. [19] analyzed the frequency nadir and rate of change of frequency (RoCoF) for different GFM capacity ratios. For dynamics induced by faults,

ref. [20] investigated the effects of grid strength, virtual inertia, and damping on transient synchronization. The analysis in [21] further showed that the preferred GFM converter capacity ratio differs between load disturbances and single-phase-to-ground faults. It also found that a configuration consisting entirely of GFM converters may not provide optimal voltage and frequency support under fault conditions. Thus, a capacity ratio that satisfies small-signal stability requirements does not necessarily yield optimal grid-forming support during disturbances.

Overall, most existing methods address a single stability issue or a specific disturbance. However, a clear link between preliminary estimation of the GFM capacity ratio and multidimensional dynamic assessment remains lacking. Consequently, determining an appropriate GFM capacity ratio subject to a fixed total installed capacity remains an important problem in renewable energy plant planning and control design. This task also involves a comprehensive assessment of the hybrid system under different control parameters and representative disturbances. Such an assessment encompasses equivalent grid strength, oscillation damping, frequency support, and dynamic recovery.

To address these issues, this paper considers a single-infeed hybrid wind farm comprising GFL and GFM converters with a fixed total installed capacity. A hybrid system model incorporating the principal control loops of both converter types is first established. The model is then used to determine the minimum GFM capacity ratio required to satisfy small-signal stability and target grid strength requirements. On this basis, a grid-forming capability assessment framework is developed. The framework evaluates four categories of factors, namely, system strength, the GFM converter capacity ratio, control parameters, and small-disturbance response performance. These factors are organized into three assessment levels to comprehensively characterize the grid-forming capability of the hybrid system. Finally, frequency-domain analysis and time-domain simulations validate the proposed GFM converter capacity ratio estimation method and assessment framework.

The main contributions of this paper are summarized as follows:

- (1) A preliminary GFM converter capacity ratio estimation method is proposed under a fixed total installed capacity. For a configuration in which GFM capacity replaces part of the existing GFL capacity, the external grid strength, the critical stability boundary of the GFL converter, and the dynamic terminal support of the GFM converter are incorporated into a unified calculation. An analytical relationship between the GFM capacity ratio and the gSCR is derived to obtain continuous lower bounds that satisfy the small-signal stability boundary and the target grid strength requirement, respectively. Frequency-domain stability is then verified using the generalized Nyquist criterion.
- (2) A multidimensional grid-forming capability assessment framework is developed for the hybrid system. The framework comprises three assessment levels of basic support conditions, control parameter effects, and disturbance response performance. It jointly examines system strength, oscillation damping, frequency deviation, RoCoF, and settling time. Normalized margins and a bottleneck index are further used to determine whether different configurations satisfy the corresponding requirements.
- (3) A systematic parametric analysis is conducted to clarify the effects of the GFM converter capacity ratio, grid strength, and key control parameters on the grid-forming capability of the hybrid system. The analysis relates each design variable to the applicable normalized margins and bottleneck index, thereby providing a quantitative basis for coordinating capacity allocation and control parameter selection.

2. Modeling of the Hybrid GFL and GFM Converter System

2.1. Control Structures and Mathematical Models of GFL and GFM Converters

The two converter types use the same three-phase power circuit and pulse-width modulation (PWM), but employ different grid connection control strategies. They are connected through filters and line impedances to the point of common coupling (PCC) and the alternating current (AC) grid. Their control structures are shown in Figure 1.

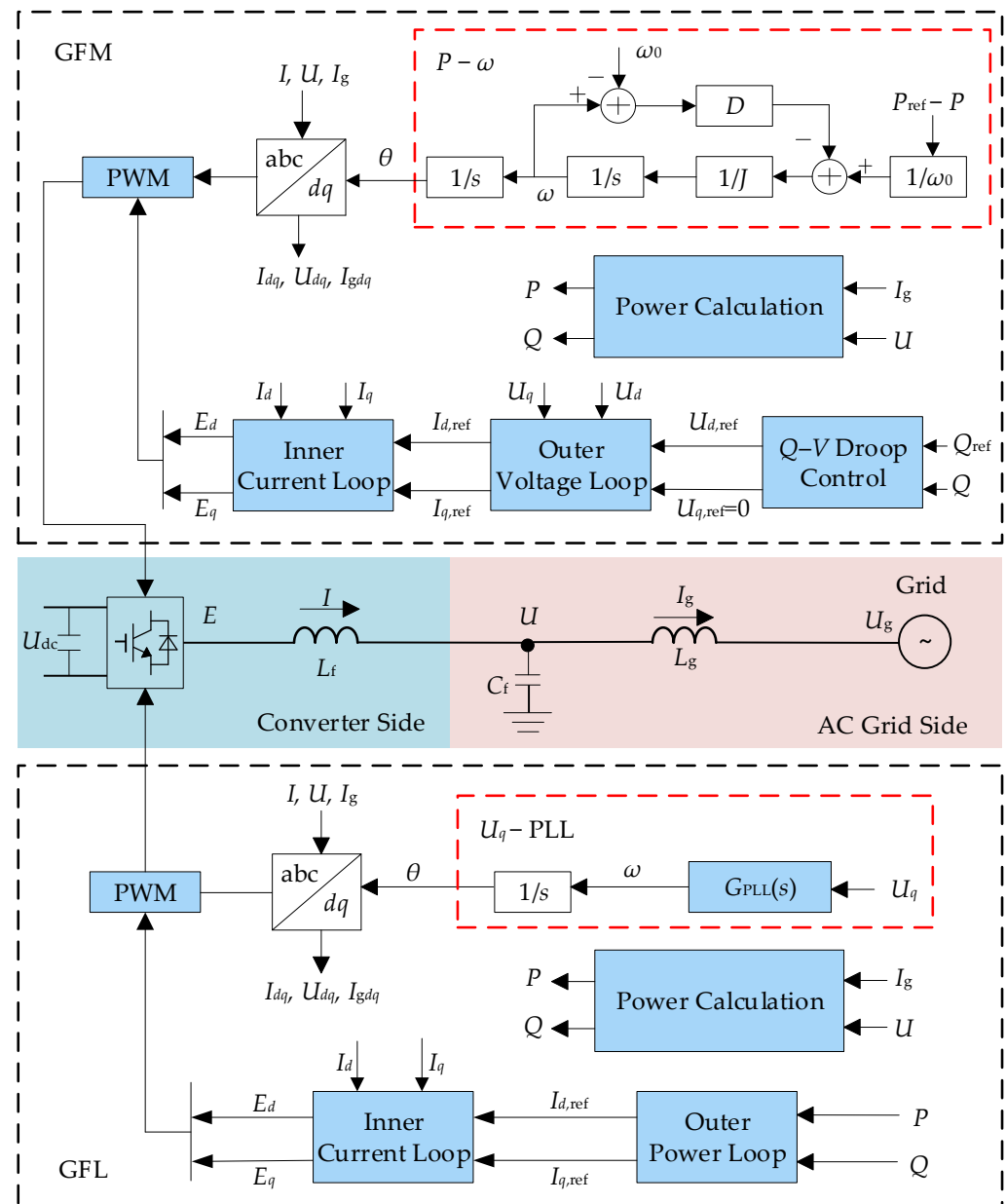


Figure 1. Control structures of the GFL and GFM converters.

The variables in Figure 1 are defined as follows. U_{dc} , E , U and U_g denote the direct current side voltage, converter output voltage, PCC voltage, and grid voltage, respectively. I and I_g denote the converter output current and AC grid current, respectively. L_f , C_f and L_g denote the filter inductance, filter capacitance, and AC grid inductance, respectively. $G_{PLL}(s)$ denotes the PLL transfer function of the GFL converter, and ω_0 denotes the fundamental system frequency. The variables ω and θ are the angular frequency and phase angle of the synchronously rotating direct-quadrature (dq) reference frame, respectively. D and J denote the damping coefficient and virtual inertia of the GFM synchronization loop, respectively.

P , P_{ref} , Q , and Q_{ref} denote the active power, active power reference, reactive power, and reactive power reference, respectively. The variables I_{dq} , U_{dq} , I_{gdq} , and E_{dq} denote the dq frame components of I , U , I_g , and E , respectively. $I_{d,\text{ref}}$ and $I_{q,\text{ref}}$ denote the d-axis and q-axis current references, respectively. $U_{d,\text{ref}}$ and $U_{q,\text{ref}}$ denote the d-axis and q-axis voltage references generated by the droop controller, respectively.

The converters operate under either grid-following or grid-forming control. The GFL converter employs an outer power loop and an inner current loop and tracks the grid phase through a PLL. Its mathematical model is given by Equation (1).

$$\begin{cases} \theta = \frac{1}{s} [\omega_0 - G_{\text{PLL}}(s)U_q], \\ I_{d,\text{ref}} = G_{\text{P,GFL}}(s)(P_{\text{ref}} - P), \\ I_{q,\text{ref}} = G_{\text{Q,GFL}}(s)(Q_{\text{ref}} - Q), \\ E_d = U_d + G_{\text{C,GFL}}(s)(I_{d,\text{ref}} - I_d) - \omega L_f I_q, \\ E_q = U_q + G_{\text{C,GFL}}(s)(I_{q,\text{ref}} - I_q) + \omega L_f I_d, \\ P = \frac{3}{2}(U_d I_{gd} + U_q I_{gq}), \\ Q = \frac{3}{2}(U_q I_{gd} - U_d I_{gq}), \end{cases} \quad (1)$$

where $G_{\text{PLL}}(s)$ denotes the transfer function of the proportional-integral (PI) controller in the PLL. The functions $G_{\text{P,GFL}}(s)$, $G_{\text{Q,GFL}}(s)$, and $G_{\text{C,GFL}}(s)$ denote the transfer functions of the outer active power, outer reactive power, and inner current control loops, respectively. These transfer functions are defined as

$$\begin{cases} G_{\text{PLL}}(s) = K_{\text{p,PLL}} + \frac{K_{\text{i,PLL}}}{s}, \\ G_{\text{P,GFL}}(s) = K_{\text{p,P,GFL}} + \frac{K_{\text{i,P,GFL}}}{s}, \\ G_{\text{Q,GFL}}(s) = K_{\text{p,Q,GFL}} + \frac{K_{\text{i,Q,GFL}}}{s}, \\ G_{\text{C,GFL}}(s) = K_{\text{p,C,GFL}} + \frac{K_{\text{i,C,GFL}}}{s}. \end{cases} \quad (2)$$

For each controller, the corresponding K_p and K_i terms denote the proportional and integral gains, respectively.

The GFM converter employs Q-V droop control, an outer voltage loop, and an inner current loop, and achieves grid synchronization through virtual synchronous machine control. Its control model is given by Equation (3).

$$\begin{cases} J \frac{d\omega}{dt} = \frac{P_{\text{ref}}}{\omega_0} - \frac{P}{\omega_0} - D(\omega - \omega_0), \\ U_{d,\text{ref}} = U_0 + K_q(Q_{\text{ref}} - Q), \\ I_{d,\text{ref}} = G_{\text{V,GFM}}(s)(U_{d,\text{ref}} - U_d) - \omega_0 C_f U_q, \\ I_{q,\text{ref}} = G_{\text{V,GFM}}(s)(U_{q,\text{ref}} - U_q) + \omega_0 C_f U_d, \\ E_d = U_d + G_{\text{C,GFM}}(s)(I_{d,\text{ref}} - I_d) - \omega L_f I_q, \\ E_q = U_q + G_{\text{C,GFM}}(s)(I_{q,\text{ref}} - I_q) + \omega L_f I_d, \\ P = \frac{3}{2}(U_d I_{gd} + U_q I_{gq}), \\ Q = \frac{3}{2}(U_q I_{gd} - U_d I_{gq}), \end{cases} \quad (3)$$

where U_0 and K_q denote the voltage reference and Q-V droop coefficient, respectively. The functions $G_{\text{V,GFM}}(s)$ and $G_{\text{C,GFM}}(s)$ denote the transfer functions of the outer voltage and inner current control loops, respectively. These transfer functions are defined as

$$\begin{cases} G_{\text{V,GFM}}(s) = K_{\text{p,V,GFM}} + \frac{K_{\text{i,V,GFM}}}{s}, \\ G_{\text{C,GFM}}(s) = K_{\text{p,C,GFM}} + \frac{K_{\text{i,C,GFM}}}{s}. \end{cases} \quad (4)$$

For each controller, the corresponding K_p and K_i terms denote the proportional and integral gains, respectively.

2.2. Hybrid System Configuration

The hybrid wind farm employs both GFL and GFM control strategies. Figure 2 shows the system configuration. The system consists of one equivalent GFL converter and one equivalent GFM converter. Each converter operates at 690 V and is connected to a common 35 kV bus through a 690 V/35 kV step-up transformer. The common 35 kV bus is connected to the 220 kV transmission grid through a 35 kV/220 kV step-up transformer [22,23].

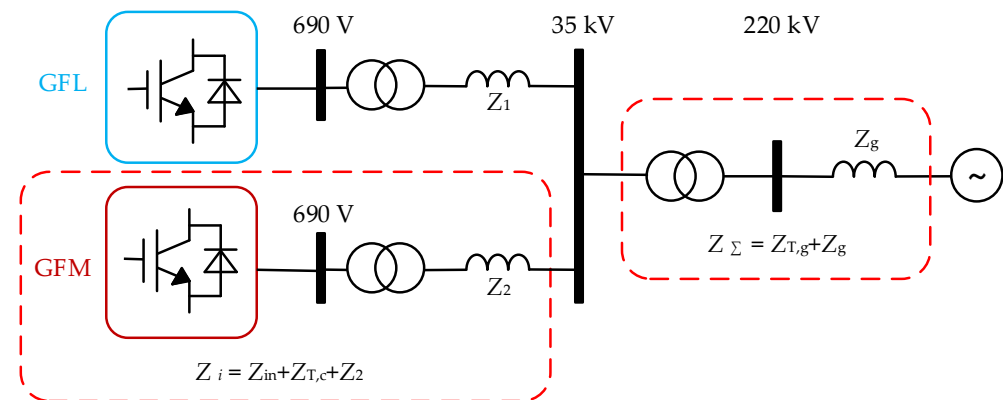


Figure 2. Schematic diagram of the hybrid GFL and GFM converter system.

Subscripts 1 and 2 refer to the impedances of the GFL and GFM branches, respectively. Z_{Σ} denotes the equivalent impedance seen from the PCC toward the upstream AC grid. It includes the equivalent series impedance $Z_{T,g}$ of the 35 kV/220 kV step-up transformer and the equivalent grid impedance Z_g .

Based on the small-signal voltage source representation of the GFM converter [11], the GFM converter and its step-up transformer connected in series can be modeled as an ideal voltage source behind an equivalent internal impedance Z_i . The impedance Z_i consists of the GFM converter internal impedance Z_{in} , the equivalent series impedance $Z_{T,c}$ of the 690 V/35 kV transformer, and the 35 kV connection branch impedance Z_2 . The impedance is expressed as $Z_i = R_i + jX_i$.

The corresponding admittance is

$$\begin{cases} Y_i = \frac{1}{Z_i} = \frac{R_i}{R_i^2 + X_i^2} - j\frac{X_i}{R_i^2 + X_i^2} = G_i - jB_i, \\ G_i = \frac{R_i}{R_i^2 + X_i^2}, \\ B_i = \frac{X_i}{R_i^2 + X_i^2} > 0, \end{cases} \quad (5)$$

where G_i is the conductance and B_i is the magnitude of the inductive susceptance of the equivalent GFM branch. The value of B_i quantifies the contribution of the GFM branch to the equivalent system strength. If the branch resistance is neglected and a common per-unit (p.u.) base is adopted, $Y_i = -j/X_i$ and $B_i = 1/X_i$. On the common per-unit base, B_i is a real scalar. It can therefore be combined with SCR_0 to derive a scalar expression for the gSCR.

The calculation of B_i establishes a control-parameter-dependent mapping between the dynamic characteristics of the GFM converter and its contribution to the equivalent grid strength. The complete dq impedance matrix is evaluated at the system-specific critical oscillation frequency, with the transformer and line impedances explicitly included. Therefore, the resulting capacity estimate reflects the converter control parameters and the network configuration considered in the analysis.

The following assumptions are made to highlight the stability mechanism at the system level while keeping the model tractable:

- (1) Because this study focuses on grid strength at the transmission level, interactions among individual wind turbines are neglected. A single equivalent grid connection point is retained at the plant level. The model includes the PLL, the inner current loop, and the outer active and reactive power loops.
- (2) The external AC grid is represented by an infinite bus with constant voltage magnitude and frequency. Its capacity is assumed to be much larger than the capacity of the local wind farm. The infeed bus is connected to the infinite bus through line and transformer impedances. Grid strength is determined jointly by these impedances and the converter capacity connected to the bus.
- (3) The study focuses on small-signal stability and grid-forming capability assessment under normal operating conditions. The model retains the dominant factors governing grid strength and converter control behavior. These factors include connected converter capacity and the main control bandwidths. High-frequency switching dynamics, current limiting and saturation associated with severe faults, and other secondary dynamics are omitted. The subsequent time-domain simulations focus on the retained low-frequency electromechanical and control dynamics.

3. Estimation of the GFM Converter Capacity Ratio Using the Generalized Short-Circuit Ratio

A common per-unit system is adopted. The total installed capacity $S_{\text{total}} = 2$ MVA and the rated PCC voltage $U_N = 35$ kV are selected as the power and voltage bases, respectively. The total installed capacity is given by

$$S_{\text{total}} = S_{\text{GFM}} + S_{\text{GFL}}, \quad (6)$$

where S_{GFM} and S_{GFL} denote the capacities of the GFM and GFL converters, respectively.

The GFM converter capacity ratio β is defined as the ratio of the GFM converter capacity to the total installed capacity

$$\beta = \frac{S_{\text{GFM}}}{S_{\text{total}}} = \frac{S_{\text{GFM}}}{S_{\text{GFM}} + S_{\text{GFL}}}. \quad (7)$$

Accordingly, the GFM and GFL converter capacities are expressed as $S_{\text{GFM}} = \beta S_{\text{total}}$ and $S_{\text{GFL}} = (1 - \beta)S_{\text{total}}$, respectively.

By definition, $\beta \in [0, 1]$. When $\beta = 0$, the system consists entirely of GFL converters. Increasing β shifts capacity from GFL to GFM converters while keeping the total installed capacity constant. Because a nonzero GFL capacity is required for the stability analysis, the subsequent analysis considers $0 \leq \beta < 1$.

For a single-infeed system connected to an infinite bus, the short-circuit ratio (SCR) is commonly used to characterize grid strength and is defined as

$$\text{SCR} = \frac{S_{\text{ac}}}{S_{\text{total}}} = \frac{U_N^2}{S_{\text{total}}} \cdot \frac{1}{|Z_{\Sigma}|} = \frac{1}{|Z_{\Sigma, \text{pu}}|}, \quad (8)$$

where S_{ac} denotes the short-circuit capacity of the external AC system, and $Z_{\Sigma, \text{pu}}$ denotes the total per-unit impedance seen from the PCC toward the upstream grid.

For a system with multiple converter infeeds, the conventional SCR is extended to the gSCR. The gSCR accounts for the network parameters and the rated capacities of the connected converters. For a single-infeed system, the matrix formulation of the gSCR reduces to the conventional SCR. Hence, $\text{gSCR}_0 = \text{SCR}_0$. The quantity SCR_0 denotes the baseline SCR at $\beta = 0$ and is determined by the external grid parameters and S_{total} . When these quantities are fixed, SCR_0 is independent of β . Under a fixed total installed capacity,

increasing β reallocates capacity from GFL to GFM converters. Using the common per unit system defined above, the impedances used to evaluate SCR_0 and B_i are referred to the common 35 kV PCC. Therefore, SCR_0 and B_i represent the baseline grid strength and GFM branch susceptance, respectively, on the same per-unit basis. Based on the equivalent voltage source representation of the GFM converter and the inductive branch assumption, the corresponding source admittance contributions at the PCC are additive. On the common base, the GFM branch contributes βB_i , while the remaining GFL capacity is $(1 - \beta)S_{total}$. Normalizing the total source admittance by the remaining GFL capacity gives [12]

$$gSCR(\beta) = \frac{SCR_0}{1 - \beta} + \frac{\beta B_i}{1 - \beta}. \quad (9)$$

The CSCR is defined as the SCR at which a GFL converter connected to an infinite bus reaches its small-signal stability boundary. For the system with a single-infeed considered here, the critical gSCR is equal to the CSCR. The equivalent external grid impedance is gradually varied for fixed control parameters and a specified steady-state operating point. The CSCR is reached when the dominant complex-conjugate eigenvalue pair first reaches the imaginary axis while all remaining eigenvalues remain in the open left half-plane. The corresponding condition is

$$\alpha(A_{GFL}) = \max_k \text{Re}(\lambda_k) = 0, \quad (10)$$

where A_{GFL} denotes the state matrix obtained by linearizing the GFL converter system at the specified control parameters and steady-state operating point. The symbol λ_k denotes the k th eigenvalue of A_{GFL} . The functions $\alpha(\cdot)$ and $\text{Re}(\cdot)$ denote the spectral abscissa and real part, respectively.

Accordingly, the stability boundary is

$$gSCR(\beta) \geq CSCR. \quad (11)$$

The minimum GFM converter capacity ratio required for small-signal stability is therefore

$$\beta_{\min} = \max \left\{ 0, \frac{CSCR - SCR_0}{B_i + CSCR} \right\}. \quad (12)$$

The target gSCR of the hybrid system is denoted by $gSCR^*$, where $gSCR^* \geq CSCR$. The capacity ratio that satisfies the target grid strength requirement must satisfy

$$\beta \geq \frac{gSCR^* - SCR_0}{B_i B_i + gSCR^*}. \quad (13)$$

The corresponding minimum GFM converter capacity ratio required to meet the target grid strength is

$$\beta_{\min} = \max \left\{ 0, \frac{gSCR^* - SCR_0}{B_i + gSCR^*} \right\}. \quad (14)$$

In engineering practice, grid strength is often classified empirically according to the SCR. A grid with $SCR < 2$ is generally classified as very weak, one with $2 \leq SCR < 3$ as weak, and one with $SCR \geq 3$ as strong [24]. To ensure that the GFL converter terminal is not connected to a very weak grid, $SCR_{0.69} \geq 2$ is adopted as an auxiliary engineering criterion. This threshold is compared with the CSCR, and the larger of the two thresholds is adopted.

The electrical distance between the 690 V terminal of the GFL converter and the common 35 kV bus is represented by the transformer reactance $X_{0.69/35} = 0.080082$ p.u. When this criterion is referred to the common 35 kV bus, the equivalent gSCR threshold becomes

$gSCR_{35} = 1/(1/SCR_{0.69} - X_{0.69/35}) \geq 2.3814$. This threshold is used in the subsequent GFM converter capacity ratio analysis.

Using the parameters listed in Table A1 of Appendix A, the CSCR is calculated as 2.3984, with a corresponding critical oscillation frequency of $f_c = 176.86$ Hz. The associated critical eigenvalue pair is $-0.00044 \pm j1111.27 \text{ s}^{-1}$. The PLL states and the d- and q-axis components of the GFL grid current have combined participation factors of 51.79% and 44.64%, respectively. Thus, the critical mode involves coupled PLL synchronization and GFL grid current dynamics. Figure 3 shows that the maximum singular value of the dq impedance matrix at the GFM converter terminal is $\bar{\sigma}[Z_{GFM}(j2\pi f_c)] = 0.065761$ p.u. Using an equivalent inductance model, this value is referred to the fundamental frequency. For $f_0 = 50$ Hz, the equivalent internal reactance is calculated as $X_{in} = 0.014493$ p.u.

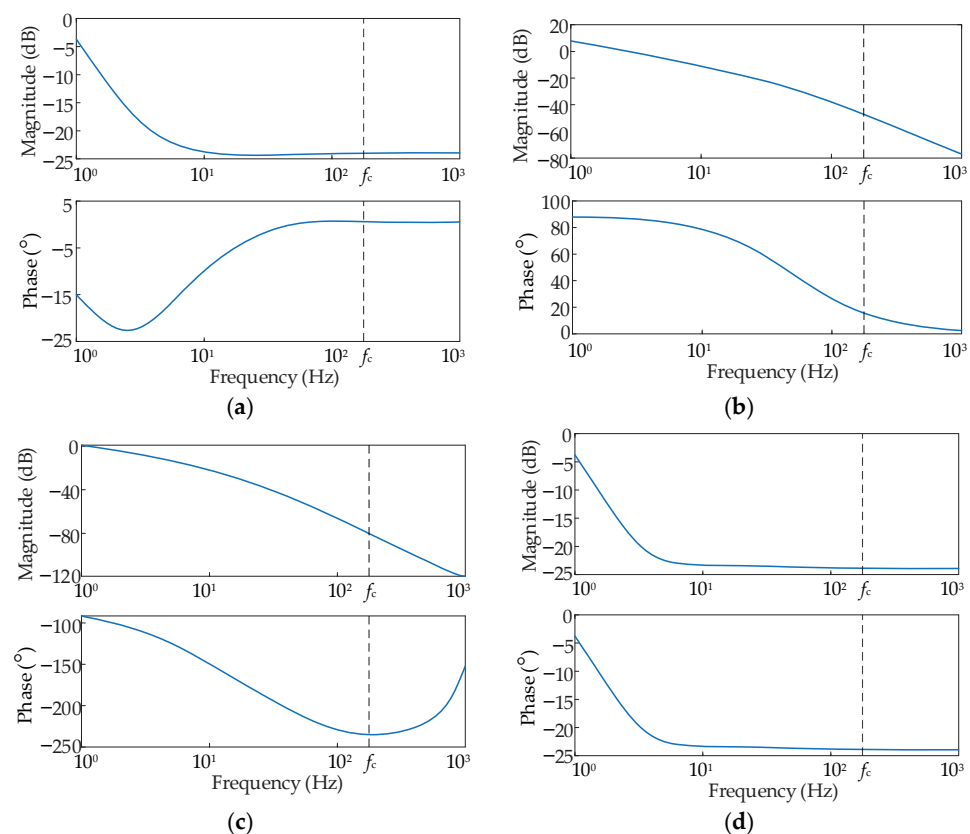


Figure 3. Frequency responses of the dq impedance matrix at the GFM converter terminal: (a) Z_{dd} . (b) Z_{dq} . (c) Z_{qd} . (d) Z_{qq} .

Adding the reactances of the 690 V/35 kV transformer and the 35 kV connection branch gives the total GFM branch reactance $X_i = 0.094504$ p.u. With the branch resistance neglected, $B_i = 1/X_i = 10.5816$ p.u. The GFL and GFM converters have different 35 kV connection branch inductances. Accordingly, B_i is evaluated from the GFM branch impedance, whereas SCR_0 is evaluated from the GFL branch impedance for the all GFL system at $\beta = 0$. The initial gSCR at the 35 kV PCC is $gSCR_0 = SCR_0 = 1/|Z_{\Sigma,pu}| = 2.20$.

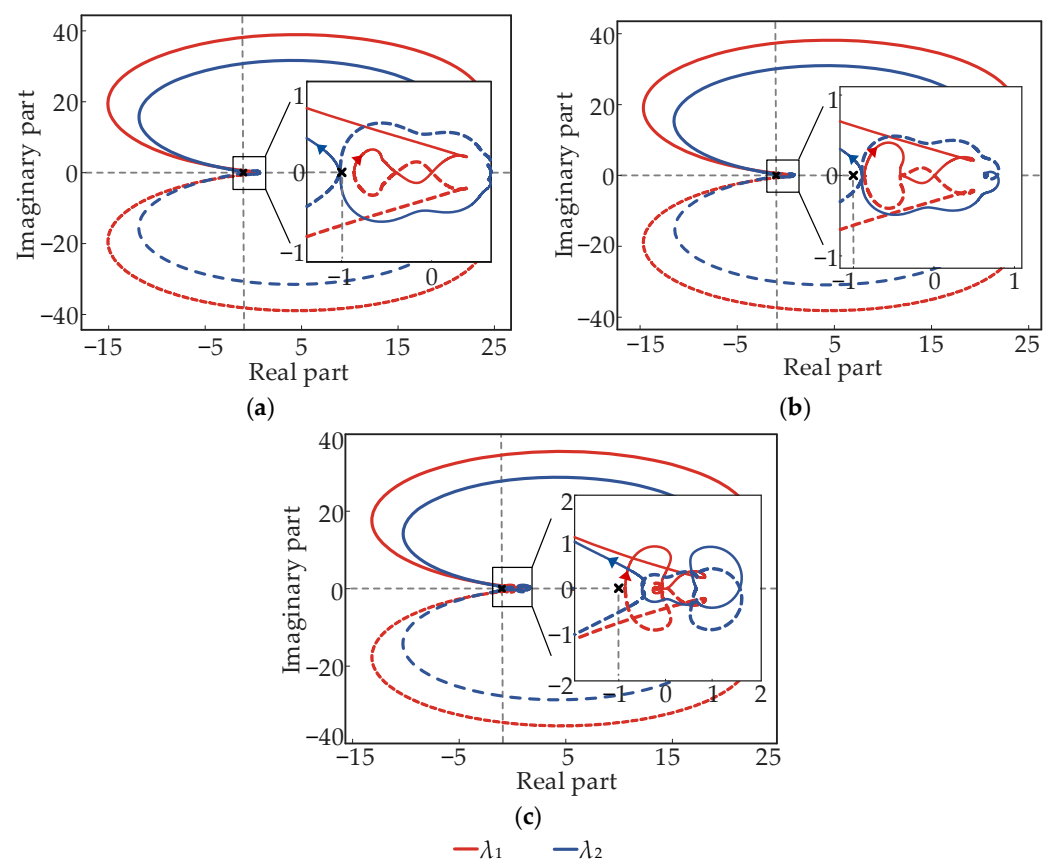
Table 1 presents the estimated GFM converter capacity ratios for different target gSCR values. Because the initial grid strength is below the CSCR, the minimum GFM converter capacity ratio required for small-signal stability is $\beta_{min} = 1.53\%$. When gSCR* is set to 5.00 and 10.00, the corresponding minimum capacity ratios are 17.97% and 37.90%, respectively. These ratios correspond to GFM converter capacities of 0.359 MVA and 0.758 MVA. The results show that a higher target grid strength requires a higher GFM converter capacity ratio.

Table 1. Estimated minimum GFM converter capacity ratios for the hybrid system.

gSCR*	Minimum GFM Converter Capacity Ratio (%)	S _{GFM} (MVA)	S _{GFL} (MVA)
CSCR	1.53	0.031	1.969
3.00	5.89	0.118	1.882
5.00	17.97	0.359	1.641
8.00	31.21	0.624	1.376
10.00	37.90	0.758	1.242

To verify the consistency between the estimated capacity ratios and the stability criterion in the frequency domain, generalized Nyquist analysis is performed for $\text{SCR}_0 = 2.20$ at $\beta = 1\%$, 3% , and 10% . These cases represent a capacity ratio below the continuous lower bound, a ratio above the lower bound, and a higher capacity ratio, respectively.

In Figure 4, the point $(-1, j0)$ serves as the critical point in the complex plane. Clockwise net encirclements are counted as positive, whereas counterclockwise net encirclements are counted as negative. The quantities λ_1 and λ_2 denote the eigenvalues of the return ratio matrix, and their trajectories form the characteristic loci. The return ratio matrix has no poles in the right half-plane under the specified parameters. When $\beta = 1\%$, the characteristic loci encircle the critical point twice clockwise. The closed loop therefore has two poles in the right half-plane and is unstable. For $\beta = 3\%$ and 10% , the characteristic loci do not encircle the critical point. The corresponding closed loops have no poles in the right half-plane and are stable. For all three cases, the generalized Nyquist results are consistent with the analytical capacity ratio estimate.

**Figure 4.** Generalized Nyquist plots for different GFM converter capacity ratios: (a) $\beta = 1\%$. (b) $\beta = 3\%$. (c) $\beta = 10\%$.

To further assess the continuous lower bound on the GFM converter capacity ratio, β is varied continuously at $\text{SCR}_0 = 2.20$, and the eigenvalues of the linearized closed-loop model of the hybrid system are calculated. The critical eigenvalue pair reaches the imaginary axis at a GFM converter capacity ratio of 1.3578%. The estimated minimum GFM converter capacity ratio of 1.5282% differs from this boundary by 0.1704 percentage points, and all eigenvalues remain in the left half-plane at the estimated value.

4. Assessment of Grid-Forming Capability Using Normalized Margins and a Bottleneck Index

The gSCR characterizes the equivalent grid strength of the hybrid system for a given GFM converter capacity ratio and set of branch parameters. However, neither the GFM converter capacity ratio nor the gSCR alone provides a comprehensive assessment of grid-forming capability. A comprehensive assessment therefore also needs to account for time-domain dynamic performance. Accordingly, a grid-forming capability assessment framework for the hybrid system is developed based on four categories of factors, including system strength, the GFM converter capacity ratio, control parameters, and disturbance response. These factors are further organized into three assessment levels corresponding to basic support conditions, control parameter effects, and disturbance response performance [17].

$$\begin{cases} \mathbf{u} = [\beta, K_{p,PLL}, K_{i,PLL}, J, D]^T, \\ \mathbf{y} = [\text{gSCR}, \zeta, \Delta P_{pk}, \Delta Q_{pk}, \Delta f_{pk}, R_{f,max}, T_s]^T, \end{cases} \quad (15)$$

where $\mathbf{u}$ denotes the configuration and control parameter vector and $\mathbf{y}$ denotes the grid-forming capability index vector. The index ζ denotes the equivalent damping ratio. The quantities ΔP_{pk} , ΔQ_{pk} , and Δf_{pk} are the peak deviations in active power, reactive power, and frequency following a disturbance, respectively. $R_{f,max}$ denotes the peak RoCoF, and T_s denotes the settling or recovery time following a disturbance. The simulations use a fixed-step solver with a step size of 1 μs .

The basic support conditions are characterized by the gSCR and β . The gSCR reflects the combined effects of grid impedance and connected capacity, whereas β denotes the GFM converter capacity ratio. Indices derived from the SCR directly characterize the relative strengths of the AC system and power electronic equipment and therefore serve as primary metrics for assessing voltage support strength. For grid-connected power electronic equipment, however, the SCR alone cannot characterize all stability issues. System impedance, equipment control characteristics, and dynamic responses must also be considered.

Control parameter effects are assessed using $K_{p,PLL}$, $K_{i,PLL}$, J , and D . These parameters are varied to determine their effects on synchronization dynamics, inertial response, and oscillation damping. Capacity optimization methods based solely on the SCR cannot capture the influence of control parameters on the capacity ratio boundary.

The disturbance response performance is characterized by ζ , ΔP_{pk} , ΔQ_{pk} , Δf_{pk} , $R_{f,max}$, and T_s . These indices are used to assess oscillation damping, frequency support, and power recovery following small disturbances and load switching events.

For a response variable x , the peak deviation and settling time are defined by

$$\begin{cases} \Delta x_{pk} = \max_{t \geq t_0} |x(t) - x_\infty|, \\ t_s(\varepsilon) = \inf\{t \geq t_0 : |x(\tau) - x_\infty| \leq \varepsilon_x, \forall \tau \geq t\}, \\ T_s(\varepsilon) = t_s(\varepsilon) - t_0, \end{cases} \quad (16)$$

where $x \in \{P, Q, f\}$. The quantity Δx_{pk} denotes the maximum absolute deviation of x from its post-disturbance steady-state value. The quantity $t_s(\varepsilon)$ denotes the time at which the response first enters the settling band and remains within it thereafter. The quantities t_0 and x_∞ denote the time at which the disturbance is applied or cleared and the post-disturbance steady-state value, respectively. The quantity ε_x denotes the absolute settling band for x .

The peak RoCoF, logarithmic decrement, and damping ratio are defined by

$$\begin{cases} R_{f,\max} = \max_{t \geq t_0} \left| \frac{df(t)}{dt} \right|, \\ \delta = \ln \left(\frac{A_k}{A_{k+1}} \right), \\ \zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}, \end{cases} \quad (17)$$

where $A_k = |x(t_k) - x_\infty|$ and $A_{k+1} = |x(t_{k+1}) - x_\infty|$ denote the amplitudes of two successive peaks in the same direction relative to the steady-state value. The quantity δ denotes the logarithmic decrement. The expression for ζ is based on a single dominant underdamped mode or an approximately second-order response.

For operating cases in which both active and reactive power responses are available, $\zeta = \min\{\zeta_P, \zeta_Q\}$ and $T_s = \max\{T_{s,P}, T_{s,Q}\}$ are used to characterize the least favorable oscillation damping and the slowest recovery process, respectively.

The screening criteria are assigned to the corresponding response variables and disturbance scenarios. For the 5% three-phase symmetrical voltage sag cases, the dominant mode damping ratio is estimated from the active and reactive power responses at the PCC after the disturbance, with a lower threshold of $\zeta_{\lim} = 0.050$ [25]. The power settling time is measured from the clearance of the voltage sag until both responses enter and remain within their respective absolute settling bands of 0.020 p.u. [26]. With reference to the 0.150 s dynamic response interval in [27], $T_{\lim} = 0.150$ s is adopted as a threshold specific to this study for the settling time metric defined in Equation (16). For the 0.1 p.u. load step cases, the peak frequency deviation and peak RoCoF are calculated from the GFM converter frequency, with thresholds of $\Delta f_{pk,\lim} = 0.100$ Hz [28] and $R_{\lim} = 2.00$ Hz/s [29], respectively. In the PLL parameter study, Δf_{pk} instead denotes the peak deviation of the frequency estimated by the GFL converter PLL following the voltage sag, and the same numerical threshold of $\Delta f_{pk,\lim} = 0.100$ Hz is applied.

To account for differences in units and numerical scales, each grid-forming capability index is normalized by its corresponding threshold. For indices for which larger values indicate better performance, such as the damping ratio and system strength, the normalized margin is defined as the ratio of the calculated value to the lower threshold. For indices for which smaller values indicate better performance, such as frequency deviation, RoCoF, and settling time, the normalized margin is defined as the ratio of the upper threshold to the calculated value. Consequently, the dimensional response quantities are evaluated using dimensionless normalized margins relative to their corresponding thresholds rather than being compared directly. These margins are defined by

$$\begin{cases} M_g^{(m)} = \frac{g_{\text{SCR}}^{(m)}}{C_{\text{SCR}}}, \\ M_\zeta^{(m)} = \frac{\zeta^{(m)}}{\zeta_{\lim}}, \\ M_f^{(m)} = \frac{\Delta f_{pk,\lim}}{\Delta f_{pk}^{(m)}}, \\ M_R^{(m)} = \frac{R_{\lim}}{R_{f,\max}^{(m)}}, \\ M_T^{(m)} = \frac{T_{\lim}}{T_s^{(m)}}, \end{cases} \quad (18)$$

where m denotes the operating case. The five quantities $M_g^{(m)}$, $M_\zeta^{(m)}$, $M_f^{(m)}$, $M_R^{(m)}$, and $M_T^{(m)}$ denote the system strength margin, damping margin, frequency deviation margin, RoCoF margin, and settling time margin, respectively.

Accordingly, unity defines the constraint boundary for each normalized index. A value greater than unity indicates that the corresponding requirement is satisfied with a positive margin. A value equal to unity indicates operation at the constraint boundary. A value less than unity indicates that the corresponding requirement is not satisfied.

$$K_{\text{GFM}}^{(m)} = \min_{i \in \mathcal{A}^{(m)}} M_i^{(m)}, \quad (19)$$

where the quantity $K_{\text{GFM}}^{(m)}$ denotes the bottleneck index for grid-forming capability under operating case m . The quantity $M_i^{(m)}$ denotes the normalized margin of index i . The set $\mathcal{A}^{(m)} \subseteq \{g, \zeta, f, R, T\}$ contains the indices applicable to operating case m .

By definition,

$$K_{\text{GFM}}^{(m)} \geq 1 - M_i^{(m)} \geq 1, \forall i \in \mathcal{A}^{(m)}. \quad (20)$$

Thus, $K_{\text{GFM}}^{(m)} \geq 1$ is equivalent to all applicable indices satisfying their respective constraints for operating case m . The bottleneck index is defined as the minimum of the applicable normalized margins. The method introduces no subjective weights and does not allow an index with satisfactory performance to compensate for an index that fails to meet its requirement. Moreover, $K_{\text{GFM}}^{(m)} \geq 1$ indicates only that the indices selected in this study for operating case m satisfy their respective screening criteria. It does not certify that the equipment complies with a comprehensive grid-forming interconnection standard.

By jointly considering basic support conditions, control parameter effects, and disturbance response performance, the method provides a quantitative basis for assessing grid-forming capability through simulations and determining the GFM converter capacity ratio in hybrid GFL and GFM converter systems.

5. Simulation Studies

To validate the proposed GFM converter capacity ratio estimation method and grid-forming capability assessment framework for a hybrid GFL and GFM converter system, a simulation model is developed in MATLAB/Simulink R2022b. Power oscillations, frequency support, and recovery performance following disturbances are compared under different capacity ratios, grid strengths, control parameters, and disturbance scenarios. For each operating case, the applicable indices are selected based on the available response curves. The applicable index sets are $\mathcal{A}^{(m)} = \{g, \zeta, T\}$ for the capacity ratio and grid strength studies, $\mathcal{A}^{(m)} = \{f\}$ for the PLL parameter studies, and $\mathcal{A}^{(m)} = \{f, R\}$ for the virtual inertia and damping coefficient studies. The bottleneck index $K_{\text{GFM}}^{(m)}$ is calculated using Equation (19). Throughout this section, all normalized margins and bottleneck indices are calculated using unrounded simulation data. The simulation parameters are provided in Table A1 of Appendix A.

5.1. Verification of Small-Disturbance Grid-Forming Capability Under Different Capacity Ratios

To examine the effect of the GFM converter capacity ratio on the small-disturbance grid-forming capability of the hybrid system, the initial SCR is fixed at $\text{SCR}_0 = 2.20$. The quantity β is set to 3%, 10%, and 20%, yielding $g\text{SCR}$ values of 3.42, 4.51, and 6.40, respectively. At $t = 2.0$ s, a 5% three-phase symmetrical voltage sag is applied at the infinite bus and cleared after 10 ms. The active and reactive power responses at the PCC are shown in Figure 5.

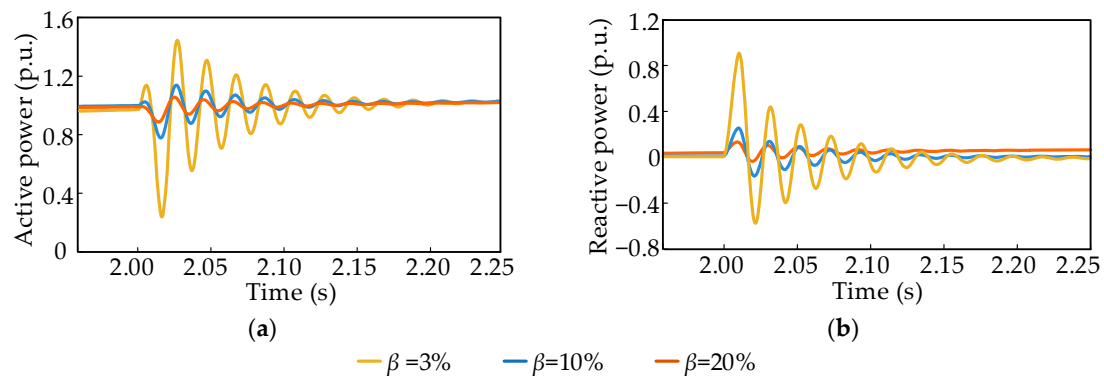


Figure 5. Active and reactive power responses at the PCC under different GFM converter capacity ratios: (a) active power response; (b) reactive power response.

As shown in Figure 5, for $\beta = 3\%$, 10% , and 20% , the values of $M_g^{(m)}$ are 1.426, 1.880, and 2.668, respectively. All three values satisfy $M_g^{(m)} \geq 1$. The corresponding peak power deviations $\max\{\Delta P_{pk}, \Delta Q_{pk}\}$ are 0.915 p.u., 0.250 p.u., and 0.131 p.u. As β increases from 3% to 10% and then to 20%, the peak power deviation decreases by approximately 72.7% and 47.6%, respectively. The values of ζ are 0.062, 0.065, and 0.092, and the corresponding $M_\zeta^{(m)}$ values are 1.246, 1.304, and 1.836. All three values exceed unity. Thus, the small-disturbance oscillations at all three capacity ratios decay with damping that meets the prescribed lower limit. The settling times T_s for the absolute settling band are approximately 0.202 s, 0.142 s, and 0.119 s. The corresponding $M_T^{(m)}$ values are 0.743, 1.060, and 1.266. The corresponding bottleneck index values $K_{GFM}^{(m)}$ are 0.743, 1.060, and 1.266. At $\beta = 3\%$, the bottleneck index is determined by the settling time margin and is less than unity. At $\beta = 10\%$ and 20% , all applicable indices satisfy their respective constraints.

These results quantitatively demonstrate that, under the specified operating conditions, increasing the GFM converter capacity ratio increases the equivalent gSCR, improves oscillation damping, reduces the peak power deviation, and shortens the settling time.

5.2. Verification of Small-Disturbance Grid-Forming Capability Under Different Grid Strengths

To analyze the influence of grid strength on the grid-forming capability of the hybrid system, the equivalent grid impedance is varied to establish different initial SCR values. With β fixed at 20%, SCR_0 is set to 3.50, 6.50, and 15.00, yielding gSCR values of 7.02, 10.77, and 21.40, respectively. At $t = 2.0$ s, a 5% three-phase symmetrical voltage sag is applied at the infinite bus and cleared after 10 ms. The active and reactive power responses at the PCC are shown in Figure 6.

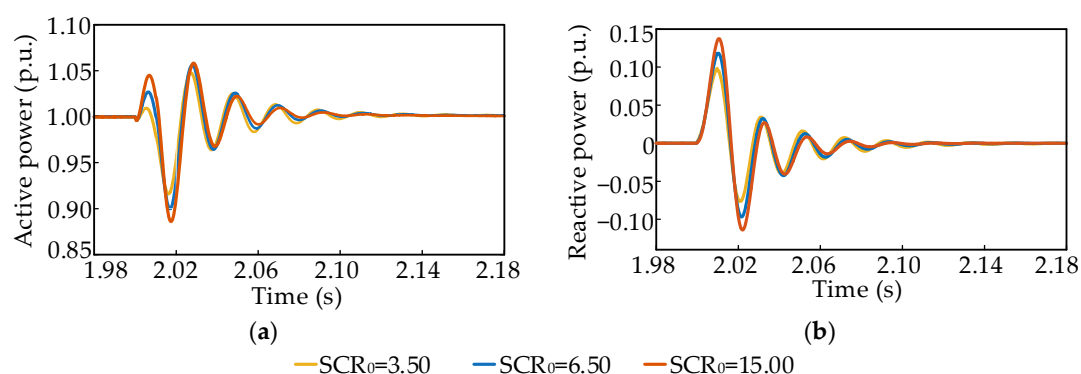


Figure 6. Active and reactive power responses at the PCC under different grid strengths: (a) active power response; (b) reactive power response.

As shown in Figure 6, for $SCR_0 = 3.50, 6.50$, and 15.00 , the values of $M_g^{(m)}$ are 2.927, 4.490, and 8.923, respectively. All three values satisfy $M_g^{(m)} \geq 1$ and increase markedly with grid strength. The corresponding peak power deviations $\max\{\Delta P_{pk}, \Delta Q_{pk}\}$ are 0.102 p.u., 0.123 p.u., and 0.142 p.u., respectively, indicating a slight increase in the peak power deviation as grid strength increases. The values of ζ are 0.107, 0.128, and 0.155, and the corresponding $M_\zeta^{(m)}$ values are 2.149, 2.566, and 3.092. All three values exceed unity. As $gSCR$ increases, the oscillations decay more rapidly, indicating improved small-disturbance damping. The settling times T_s for the absolute settling band are 0.063 s, 0.051 s, and 0.051 s. The corresponding M_T values are 2.398, 2.955, and 2.947. The corresponding bottleneck index values $K_{GFM}^{(m)}$ are 2.149, 2.566, and 2.947. All applicable indices satisfy their respective constraints in the three grid strength cases.

These results show that increasing grid strength increases the system strength and oscillation damping margins, although it may slightly increase the peak power deviation immediately after the disturbance.

5.3. Verification of Small-Disturbance Grid-Forming Capability Under Different Control Parameters

To further examine the influence of control parameters on the small-disturbance grid-forming capability of the hybrid system, the PLL parameters of the GFL converter and the virtual inertia J , damping coefficient D , and Q - V droop coefficient K_q of the GFM converter are varied. The PLL-estimated frequency, RoCoF, and active power responses are compared. In all simulations, SCR_0 and β are fixed at 2.20 and 20%, respectively, and the remaining parameters are unchanged.

First, to analyze the influence of PLL parameters on the small-disturbance grid-forming capability of the hybrid system, three sets of PLL proportional and integral gains are compared. At $t = 2.0$ s, a 5% three-phase symmetrical voltage sag is applied at the infinite bus and cleared after 10 ms. The PLL-estimated frequency and active power responses of the GFL converter are shown in Figure 7.

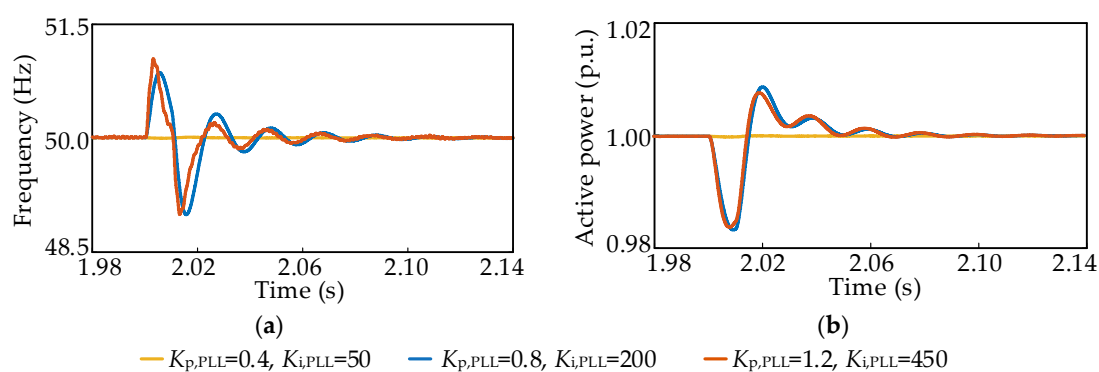


Figure 7. PLL-estimated frequency and active power responses of the GFL converter under different PLL parameters: (a) PLL-estimated frequency response; (b) active power response.

As shown in Figure 7, for the three sets of PLL parameters, the values of Δf_{pk} are 0.014 Hz, 1.007 Hz, and 1.044 Hz, respectively. The corresponding $M_f^{(m)}$ values are 7.047, 0.099, and 0.096. Only the first PLL parameter set satisfies the frequency deviation constraint. The maximum active power deviations are 0.00026 p.u., 0.01676 p.u., and 0.01626 p.u., respectively. Because $\mathcal{A}^{(m)} = \{f\}$, the bottleneck index satisfies $K_{GFM}^{(m)} = M_f^{(m)}$.

The results show that, under weak grid conditions, simultaneously increasing the PLL proportional and integral gains increases the maximum deviation of the PLL-estimated

frequency. Thus, higher PLL gains increase the system sensitivity to voltage disturbances and amplify the PLL-estimated frequency deviation.

Second, to examine the influence of J on frequency support and power recovery, three virtual inertia values are considered. At $t = 2.0$ s, a 0.1 p.u. active power load disturbance is applied at the PCC and removed after 0.2 s. The frequency, RoCoF, and active power responses of the GFM converter are shown in Figure 8.

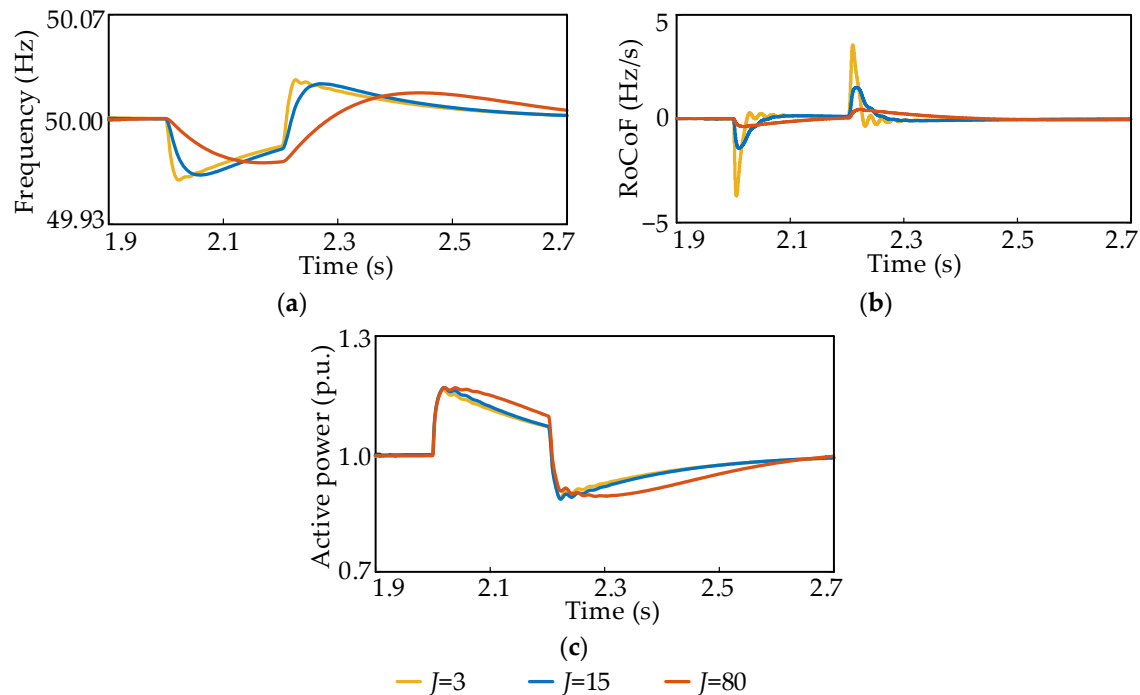


Figure 8. GFM output responses for different virtual inertia values: (a) frequency response; (b) RoCoF response; (c) active power response.

As shown in Figure 8, for $J = 3, 15$, and 80 , the values of Δf_{pk} are 0.040 Hz, 0.037 Hz, and 0.029 Hz, respectively. All three values are below the 0.100 Hz limit. The corresponding $M_f^{(m)}$ values are 2.470, 2.695, and 3.463. The values of $R_{f,max}$ are 3.714 Hz/s, 1.501 Hz/s, and 0.454 Hz/s, respectively. The corresponding $M_R^{(m)}$ values are 0.539, 1.333, and 4.408. The values of ΔP_{pk} are 0.164 p.u., 0.169 p.u., and 0.169 p.u., respectively. The corresponding bottleneck index values $K_{GFM}^{(m)}$ are 0.539, 1.333, and 3.463. At $J = 3$, the RoCoF margin determines the bottleneck index, which is below unity and therefore does not satisfy the constraint. At $J = 15$ and 80 , all applicable indices satisfy their respective constraints.

These results show that, within the specified parameter range, increasing J substantially reduces the RoCoF and improves frequency support but also slows active power recovery. The results quantitatively reveal the tradeoff between inertial support and active power recovery speed.

Third, to examine the influence of D on oscillation damping and active power recovery, three damping coefficients are considered. At $t = 2.0$ s, a 0.1 p.u. active power load disturbance is applied at the PCC and removed after 0.2 s. The frequency, RoCoF, and active power responses of the GFM converter are shown in Figure 9.

As shown in Figure 9, for $D = 200, 800$, and 1600 , the values of Δf_{pk} are 0.111 Hz, 0.037 Hz, and 0.013 Hz, respectively. The corresponding $M_f^{(m)}$ values are 0.902, 2.693, and 7.821. The values of $R_{f,max}$ are 2.620 Hz/s, 1.501 Hz/s, and 1.152 Hz/s, respectively. The corresponding $M_R^{(m)}$ values are 0.763, 1.332, and 1.736. At $D = 200$, neither the frequency deviation index nor the RoCoF index satisfies its constraint. At $D = 800$ and 1600 , both

indices satisfy their respective constraints. The values of ΔP_{pk} are 0.225 p.u., 0.170 p.u., and 0.165 p.u., respectively. The corresponding bottleneck index values $K_{GFM}^{(m)}$ are 0.763, 1.332, and 1.736. For all three values of D , the RoCoF margin determines the bottleneck index.

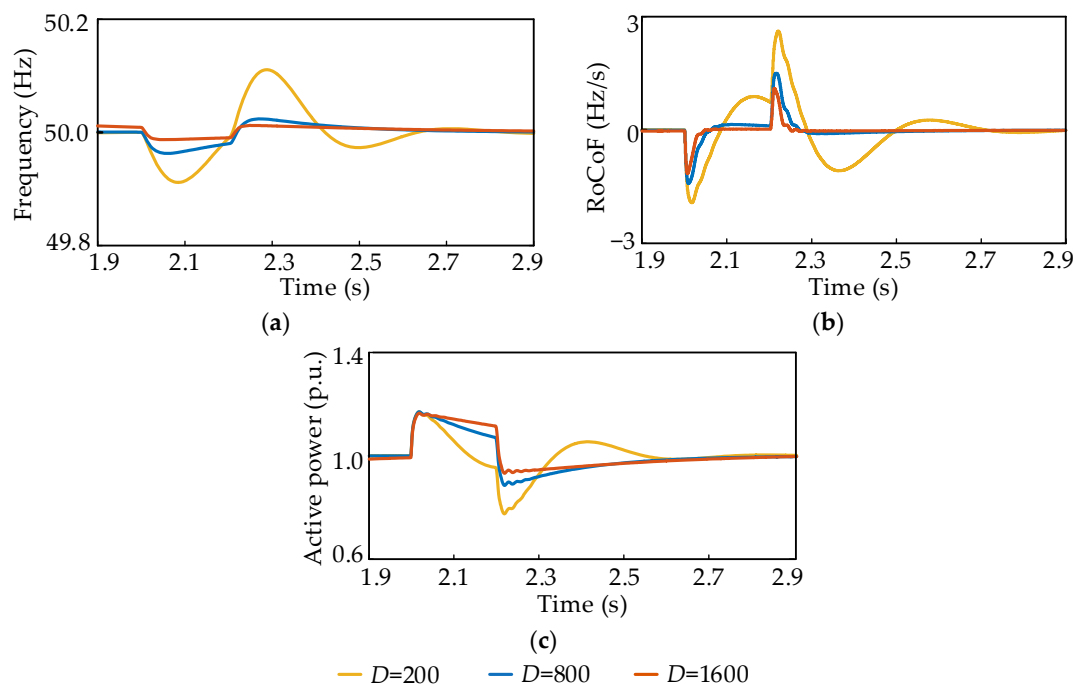


Figure 9. GFM output responses for different damping coefficients: (a) frequency response; (b) RoCoF response; (c) active power response.

These results show that increasing the damping coefficient markedly suppresses frequency and active power oscillations and increases both the frequency deviation and RoCoF margins. However, as D increases, the active power takes progressively longer to enter the allowable steady-state error band, indicating a tradeoff between enhanced damping and active power recovery speed.

Finally, the influence of the Q – V droop coefficient K_q is assessed under the voltage sag condition. The values $K_q = 0.0025, 0.0050$, and 0.0100 are considered. Over the investigated range, the PCC voltage magnitude and GFM converter reactive power response exhibit only marginal variations.

In summary, within the specified parameter range, the PLL parameters of the GFL converter primarily affect synchronization dynamics and the magnitude of power oscillations. The virtual inertia of the GFM converter mainly affects the RoCoF and inertial support capability. The damping coefficient primarily determines the attenuation of post-disturbance oscillations. Proper coordination of the GFL and GFM converter control parameters is therefore essential for improving the small-disturbance grid-forming capability of the hybrid system.

6. Conclusions

This paper proposes a GFM converter capacity ratio estimation method and a grid-forming capability assessment framework for a hybrid GFL and GFM converter system with a fixed total installed capacity. The main conclusions are as follows.

- (1) By combining the CSCR of the GFL converter with the terminal impedance of the GFM converter, a relationship between the GFM converter capacity ratio and gSCR is established. This relationship yields a continuous lower bound on the GFM converter capacity ratio that satisfies both the small-signal stability and target grid strength

requirements. In the case study, the capacity ratio lower bound required for small-signal stability is 1.53%. For target gSCR values of 5.00 and 10.00, the required capacity ratios are 17.97% and 37.90%, respectively. Under the selected operating conditions, the stability results obtained using the generalized Nyquist criterion are consistent with the capacity ratio estimates.

- (2) Normalized margins and the bottleneck index are used to assess system strength, oscillation damping, frequency support, and settling time. The framework determines whether each index satisfies its requirement and identifies the factor that limits system performance. In the case study, increasing the GFM converter capacity ratio increases the equivalent gSCR, improves oscillation damping, reduces the peak power deviation, and shortens the settling time. Increasing the external grid strength increases the system strength and oscillation damping margins but slightly increases the peak power deviation immediately after a disturbance. Thus, neither the capacity ratio nor gSCR alone can fully characterize the dynamic performance of the system.
- (3) The control parameters affect the dynamic response of the hybrid system in different ways. Higher PLL gains increase the sensitivity of the GFL converter to voltage disturbances and amplify the PLL-estimated frequency deviation. Increasing virtual inertia reduces the RoCoF but slows active power recovery. Increasing the damping coefficient suppresses frequency and active power oscillations, but higher damping may also slow active power recovery. The GFM converter capacity ratio and control parameters should therefore be coordinated with grid strength and dynamic performance requirements.

The proposed method and framework link preliminary GFM converter capacity ratio estimation with grid-forming capability assessment and can provide guidance for capacity planning and control parameter design in hybrid renewable energy plants. This study adopts a single-infeed equivalent model and focuses primarily on small-disturbance conditions. Future work will examine the framework under multi-infeed configurations and broader disturbance conditions. It will also validate the proposed approach through controller-hardware-in-the-loop testing and experimental studies.

7. Patents

The following Chinese invention patent applications have resulted from the work reported in this manuscript:

- (1) Zhu, L.; Wu, M.H.; Guo, L.; Li, X.L.; Liu, Y.X.; Jia, N.J.; Cao, J.C.; Zeng, G.M.; Liu, Y.Y.; Zhu, Y.H.; Tang, Y.H.; Luo, C. Capacity Proportioning Method for a Hybrid System of Grid-Following and Grid-Forming Converters for Renewable Energy Stations. Chinese Invention Patent Application No. 202610884535.2, filed on 18 June 2026 (pending).
- (2) Zhu, L.; Wu, M.H.; Guo, L.; Li, X.L.; Liu, Y.X.; Cao, J.C.; Jia, N.J.; Zeng, G.M.; Tang, Y.H.; Zhu, Y.H.; Liu, Y.Y.; Luo, C. Grid-Forming Capability Evaluation Method Based on System Strength, Control Dynamics, and Disturbance Response. Chinese Invention Patent Application No. 202610884534.8, filed on 18 June 2026 (pending).

Author Contributions: Conceptualization, M.W. and L.Z.; methodology, M.W., L.Z. and X.L.; software, M.W. and J.C.; validation, J.C.; formal analysis, M.W. and J.C.; investigation, X.L.; resources, L.Z.; data curation, M.W.; writing—original draft preparation, M.W. and J.C.; writing—review and editing, L.Z., X.L. and L.G.; visualization, M.W. and J.C.; supervision, L.Z., X.L. and L.G.; project administration, L.Z., X.L. and L.G.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

GFL	Grid-following
GFM	Grid-forming
PLL	Phase-locked loop
gSCR	Generalized short-circuit ratio
CSCR	Critical short-circuit ratio
RoCoF	Rate of change of frequency
PWM	Pulse-width modulation
PCC	Point of common coupling
AC	Alternating current
dq	Direct-quadrature
PI	Proportional-integral
SCR	Short-circuit ratio
p.u.	Per unit

Appendix A

Table A1. Simulation parameters of the hybrid GFL and GFM converter system.

Category	Parameter	Symbol	Value
Circuit parameters	Total installed capacity	S_{total}	2 MVA
	Fundamental system frequency	f_0	50 Hz
	AC grid inductance	L_g	0.4225 p.u.
	GFL 35 kV connection branch inductance	L_1	0.2 mH
	GFM 35 kV connection branch inductance	L_2	0.1 mH
	Leakage reactance per winding of the converter and grid step-up transformers	$X_{T,c}, X_{T,g}$	0.04 p.u.
	Filter inductance and capacitance	L_f, C_f	35 μH , 150 μF
Control parameters	GFL PLL PI gains	$K_{p,PLL}, K_{i,PLL}$	0.8, 200
	GFL outer active power loop PI gains	$K_{p,P,GFL}, K_{i,P,GFL}$	0.001, 0.14
	GFL outer reactive power loop PI gains	$K_{p,Q,GFL}, K_{i,Q,GFL}$	0.001, 0
	GFL inner current loop PI gains	$K_{p,C,GFL}, K_{i,C,GFL}$	5, 500
	GFM virtual inertia	J	15 $\text{kg}\cdot\text{m}^2$
	GFM damping coefficient	D	800 $\text{N}\cdot\text{m}\cdot\text{s}/\text{rad}$
	GFM outer voltage loop PI gains	$K_{p,V,GFM}, K_{i,V,GFM}$	66, 800
	GFM inner current loop PI gains	$K_{p,C,GFM}, K_{i,C,GFM}$	10, 100
	Q–V droop coefficient	K_q	0.005

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