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Estimation of Grid-Forming and Grid-Following Converter Capacity Ratio for Stability Enhancement of Renewable Energy Power Plants

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Abstract

Large-scale integration of renewable energy sources reduces the grid short-circuit ratio and weakens system voltage support strength, leading to prominent stability issues such as static voltage stability and sub/super-synchronous oscillations. Grid-forming converters exhibit strong voltage support capability, and configuring a certain proportion of grid-forming converters in renewable energy stations can enhance system stability. However, the analytical relationship between grid-forming converter capacity and stability margin remains unclear, making it extremely difficult to estimate the theoretical value of the grid-forming converter proportion. To address this, this paper investigates the estimation method and typical values for the capacity ratio of grid-forming to grid-following converters from the perspective of small-signal stability. First, grid-forming converters are equivalenced as voltage sources, and the impact patterns of capacity ratio on system strength and stability margin are analyzed through the generalized short-circuit ratio index. Second, for two technical schemes—retrofitting grid-forming wind turbines and additionally installing grid-forming converters—the typical values of capacity ratio in practical engineering are estimated using industry-related standards as boundary conditions combined with typical step-up transformer parameters. Finally, the validity of the conclusions is verified through a multi-wind farm system case study.

Full Text

Estimation of Capacity Ratios Between Grid-Forming and Grid-Following Converters for Improving the Stability of Renewable Energy Stations

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ABSTRACT: The large-scale integration of renewable energy into the power grid leads to decreased short-circuit ratio (SCR) and system voltage support strength, resulting in stability issues such as static voltage stability problems and sub/super-synchronous oscillation. Grid-forming (GFM) converters have effective voltage support capacity, and equipping renewable energy stations with a certain proportion of GFM converters can improve system stability. However, the analytical relationship between GFM converter capacity and stability margin is unclear, making it difficult to theoretically estimate the required proportion of GFM converters. Therefore, this paper discusses the estimation method and typical values of the capacity ratio between GFM and grid-following (GFL) converters from the perspective of small-signal stability. First, GFM converters are equivalently modeled as voltage sources, and the generalized short-circuit ratio index is used to analyze how capacity ratios affect system strength and stability margins. Second, considering two technical solutions—retrofitting existing wind turbines with GFM control and installing additional GFM converters—typical capacity ratio values are estimated based on relevant industry standards as boundary conditions and typical step-up transformer parameters. Finally, the validity of the conclusions is verified through simulation results of a multi-wind-farm system.

KEY WORDS: Grid-forming converter; capacity ratio; generalized short-circuit ratio; system strength

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0 Introduction

In renewable energy stations, converters predominantly employ phase-locked loop (PLL)-based grid-following (GFL) control [1]-[4], where renewable energy is integrated into the grid through GFL converters. As the scale of renewable

energy stations increases, the grid's short-circuit ratio (SCR) decreases and system voltage support strength (hereinafter referred to as "system strength") declines, making the system prone to small-signal stability issues dominated by PLL dynamics [5]-[9]. The risk of such stability problems is particularly high in low-SCR scenarios [10], which is the focus of this paper. Therefore, enhancing system strength to ensure safe and stable operation of renewable energy stations is crucial.

Previous studies have shown that configuring a certain proportion of grid-forming (GFM) converters in renewable energy stations can improve system strength [11]. System strength characterizes the ability of grid bus voltages to resist deviation from operating points and instability under disturbances such as equipment output fluctuations and network parameter variations, commonly described by the grid SCR and its critical value (critical SCR, CSCR). GFM converters enhance system strength by emulating synchronous generators with large inertia [12]-[15], exhibiting voltage source characteristics with nearly constant voltage phase and magnitude during AC grid fluctuations, thereby providing voltage support to the grid (GFM converters themselves have low-frequency oscillation modes, but control design can increase their damping [16], effectively mitigating low-frequency oscillation issues). Consequently, GFM converter technology has gained widespread attention in recent years, leading to concepts such as GFM energy storage, GFM SVG, and GFM wind power.

In this context, numerous scholars have investigated how to utilize GFM converters to improve the dynamic characteristics of stations and systems. Reference [17] analyzed how to optimize the placement and capacity allocation of GFM converters to minimize the required GFM equipment capacity while meeting system strength constraints. Reference [18] studied the Irish power system and found that a 100% power-electronics-based system requires approximately 30% GFM converters to ensure stability. However, most existing research conclusions are derived from special scenarios and lack universality, making it difficult to provide generally applicable engineering guidelines.

Therefore, it remains challenging to theoretically obtain universally applicable answers on how to configure GFM converters to ensure favorable characteristics for stations and systems, primarily because: 1) the objectives for configuration are difficult to quantify, and 2) in multi-station systems, strong coupling between stations creates theoretical obstacles for decomposing these objectives.

1 Problem Description

Consider the multi-wind-farm integration system shown in [Figure 1: see original paper], which includes n wind farms, m AC grid passive nodes, and k infinite buses (representing some synchronous generators or external equivalent grids). Each wind farm is equivalently modeled as a GFL converter connected to a collection bus through a step-up transformer.

To ensure rated power operation, static voltage stability is a necessary condition [19]; otherwise, the planned grid structure would struggle to meet basic requirements. Therefore, the premise of this study is that system strength ensures reasonable power flow solutions within a certain range. However, even when this premise is satisfied, GFL converters may still experience small-signal stability issues such as sub/super-synchronous oscillations when the grid SCR is too low. To address this, each wind farm is equipped with a certain capacity of GFM converters (connected to collection buses through step-up transformers) to provide voltage support, thereby enhancing system strength and ensuring adequate small-signal stability margins. The multi-wind-farm system with GFM converters is shown in [Figure 1: see original paper].

For a single-generator injection system, the static voltage stability criterion for constant-power control mode at rated operating point is $SCR \geq 1.0$ [20], ensuring the power flow solution has not reached the nose point of the PV curve. Additionally, based on current converter control level statistics, the critical SCR of a single wind turbine can be as low as approximately 1.5 [21], i.e., $CSCR \leq 1.5$. Therefore, if $SCR \geq 1.5$, the small-signal stability performance of the single-injection system below the PLL bandwidth meets requirements, and system strength from this perspective is satisfactory; if $SCR \geq 2.0$, the system also has a good stability margin.

These criteria for single-injection systems can be directly extended to multi-injection systems by replacing SCR with the generalized short-circuit ratio (gSCR). The conclusions regarding grid strength and equipment tolerance remain strictly valid: 1) For constant-power-mode wind farm systems at rated operating point, $gSCR \geq 1.0$ corresponds to the static voltage stability criterion, where the power flow solution has not reached the PV curve nose point; 2) For multi-machine/station systems operating near rated point, $gSCR \geq 1.5 \geq CSCR$ ensures small-signal stability requirements and system strength requirements, while $gSCR \geq 2.0$ provides a good margin. The theoretical foundation for extending single-station conclusions to multi-station systems lies in the fact that the critical gSCR of multi-station systems equals exactly the critical SCR of equipment or single-station systems, where gSCR characterizes grid properties while CSCR characterizes inherent equipment/station properties. The physical meaning of gSCR and its differences from other SCR definitions can be found in reference [22]; due to space limitations, this paper directly applies these conclusions.

Against this background, the problem addressed in this paper is: Under the premise that the multi-wind-farm system has reasonable power flow solutions and the critical SCR of wind turbines is reasonable, how much GFM converter capacity should be configured to ensure the multi-injection system has reasonable small-signal stability margins, and what are the typical capacity ratio values? In other words, under the following two boundary conditions (which can vary; the subsequent estimation method remains applicable), what are the typical capacity ratios of GFM converters within stations that can raise gSCR to

reasonable levels?

Assumption 1: At rated operating point, the grid's gSCR satisfies $\text{gSCR} \geq 1.0$ (if this condition is not met, the grid structure is unreasonable, and adding GFM equipment would hardly solve the problem).

Assumption 2: The critical SCR of wind turbines operating at rated point satisfies $\text{CSCR} \leq 1.5$ (if this condition is not met, the turbines are considered non-compliant with grid-connection regulations).

The above problem is decomposed into two sub-problems: 1) What is the analytical relationship between the capacity ratio of GFM and GFL converters and gSCR? 2) What are the typical capacity ratio values under different configuration schemes to ensure gSCR reaches target values?

2.1 Grid-Forming Converter Equivalent Circuit Model

Without loss of generality, consider GFM converters employing Virtual Synchronous Machine (VSM) control technology that emulates rotor motion equations and voltage source external characteristics. The control block diagram is shown in Appendix Figure A1, including voltage control, current control, and synchronization loops.

The voltage source characteristics of GFM converters are analyzed using frequency-domain methods. Linearized at the equilibrium point, the impedance model of GFM converters is expressed as [11]:

MATH_1

where $\text{PICC}(s) = K_{pi} + K_{ii}/s$, with K_{pi} and K_{ii} being the proportional and integral constants of the current inner loop transfer function; $\text{PIVC}(s) = K_{pv} + K_{iv}/s$, with K_{pv} and K_{iv} being the proportional and integral constants of the voltage outer loop transfer function; $f_{VF}(s) = 1/(\text{TVFs} + 1)$, with TVF being the voltage feedforward filter time constant; k_F is the current feedforward coefficient; J and D are the inertia and damping coefficients, respectively; L_F and C_F are the filter inductance and capacitance; I_{Cd0} and V_{d0} are the steady-state values of d-axis current and voltage; $I_{xy} = [I_x, I_y]$ and $V_{xy} = [V_x, V_y]$ are the x-y axis components of converter output current and terminal voltage; Δ denotes variable increments; and s is the Laplace operator.

As shown in [Figure 2: see original paper], the GFM converter can be equivalently modeled as an ideal voltage source in series with dynamic impedance $Z_{\text{GFM}}(s)$. The diagonal element $Z_0(s)$ of $Z_{\text{GFM}}(s)$ describes the equivalent impedance of voltage control—the better the voltage control performance, the smaller $Z_0(s)$. The off-diagonal element $Z_{\text{swing}}(s)$ is primarily influenced by the inertia and damping coefficients of the swing equation. Through control design, sufficiently large inertia and damping can be ensured, making $Z_{\text{swing}}(s)$ negligible compared to transformer impedance, as shown in Appendix Figure A2.

It can be observed that for current disturbances in any direction at the GFM converter port, $[\Delta V_x, \Delta V_y]$ remains small, approximating a voltage source. [Figure 3: see original paper] shows the maximum singular values of $Z_{GFM}(s)$ under different control parameters. In practical applications, voltage control bandwidth is limited ($Z_{GFM}(s) \neq 0$). The maximum singular value of $Z_{GFM}(s)$ in the frequency range of interest characterizes the deviation of GFM converter terminal voltage from an ideal voltage source:

MATH_2

where $\|\cdot\|_2$ denotes the l_2 -norm and $[\omega_1, \omega_2]$ is the frequency range of interest. The physical meaning of $\sigma\{GFM\}$ is the maximum voltage variation at the port when a unit current disturbance is applied. Therefore, it quantifies the voltage source characteristics of GFM converters—if $\sigma\{GFM\}$ is large, the voltage source characteristics are poor in certain disturbance directions. [Figure 3: see original paper] shows waveforms from 5 Hz to 100 Hz, demonstrating that $\sigma_{\{GFM\}}$ values are small in this frequency range.

Thus, the equivalent impedance characteristics of GFM converters and their series transformers are dominated by transformer inductance. This paper approximates $Z_{GFM}(s)$ using $Z_{eq}(s) = sL_{eq} + j\omega_0 L_{eq}$, where the equivalent inductance L_{eq} satisfies $|Z_{eq}(j\omega c)| = \sigma\{GFM\}$, with ωc being the oscillation frequency near the system's dominant mode. For example, at the typical PLL-dominated oscillation frequency of 10 Hz, $\sigma\{GFM\}$ values are -18.1 dB, -19.9 dB, -22.2 dB, and -25.2 dB (corresponding to current feedforward coefficients $k_F = 0.5-0.8$), yielding $L_{eq} = 0.10, 0.08, 0.06,$ and 0.05 pu, respectively. Notably, as k_F decreases (i.e., voltage control bandwidth reduces), L_{eq} increases slightly.

In summary, the model of GFM converters connected to the grid through transformers is a voltage source branch in series with equivalent reactance Z_i , where Z_i includes the GFM converter's equivalent internal reactance $Z_{eq} = \omega_0 L_{eq}$ and the step-up transformer's equivalent reactance Z_{Ti} . All reactance calculations are per-unit values with the converter's rated capacity as the base.

2.2 Generalized Short-Circuit Ratio and Small-Signal Stability

Consider again the multi-injection system in [Figure 1: see original paper]. GFM converters are installed at the 220 kV buses of stations 1– p , with GFL and GFM converters in each station connected in parallel to the 220 kV collection bus through 690V/35kV/220kV step-up transformers. For stations $p+1$ – q , GFM converters are installed at internal 35 kV buses, while for stations $q+1$ – n , some wind turbines are retrofitted with GFM control [23]. In both cases, GFL and GFM converters are connected in parallel to the 35 kV collection bus through 690V/35kV step-up transformers, with the difference being that retrofitting GFM turbines occupies part of the wind turbine capacity. Let nodes 1– n be the ports of n GFL converters (690V), nodes $n+1$ – $n+p$ be the corresponding 220 kV collection buses, and nodes $n+p+1$ – $2n$ be the 35 kV collection

buses.

Let γ_i denote the proportion of GFM converter capacity in wind farm i relative to the total wind farm capacity:

$$\text{MATH_3}$$

where S_{Bi} is the total rated capacity of wind turbines in farm i , and S_{Mi} is the total rated capacity of GFM converters.

Treating GFM converter branches as part of the grid, their equivalent admittance is $\Delta B = SB \cdot \text{diag}[\gamma_i/Z_i]$, where $SB = \text{diag}[S_{Bi}]$ and $\text{diag}[\cdot]$ denotes a diagonal matrix. The linearized AC network dynamics can be expressed as [24]:

$$\text{MATH_4}$$

where $I_{xy} = [I_{x_1}, I_{y_1}, \dots, I_{x(2n)}, I_{y(2n)}]$, $V_{xy} = [V_{x_1}, V_{y_1}, \dots, V_{x(2n)}, V_{y(2n)}]$, with I_{xi} , I_{yi} being the x-axis and y-axis components of current injected into node i , and V_{xi} , V_{yi} being the x-axis and y-axis components of voltage at node i ; \otimes represents the Kronecker product.

To reveal the analytical relationship between gSCR and small-signal stability, assume that GFL converters in the system have similar dynamic characteristics (identical impedance matrix external characteristics under their own capacity base). The equipment-side dynamic model is:

$$\text{MATH_5}$$

where $SL = \text{diag}[S_{Li}]$, with S_{Li} being the total rated capacity of GFL converters. When adding GFM converters, $S_{Li} = S_{Bi}$; when retrofitting GFM turbines, $S_{Li} = (1-\gamma_i)S_{Bi}$. $Y_{PLL}(s)$ is the admittance matrix of GFL converters, with detailed expressions in reference [25].

Based on multivariable frequency-domain control theory and combining equations (4) and (5), the system's closed-loop characteristic equation is:

$$\text{MATH_6}$$

According to Appendix B analysis, equation (6) can be decoupled as:

$$\text{MATH_7}$$

where λ_i are the eigenvalues of matrix 1. Based on matrix Schur complement properties, λ_i are also the generalized eigenvalues of the matrix, satisfying:

$$\text{MATH_8}$$

Equation (7) shows that the closed-loop characteristic equation of the multi-injection system can be decoupled into the product of n equivalent single-injection system characteristic equations, where the small-signal stability of the multi-injection system depends on the minimum eigenvalue λ_1 , i.e., the gSCR [26], corresponding to the weakest single-injection subsystem. Furthermore, reference [26] indicates that the system is stable if and only if gSCR exceeds the critical gSCR, where the critical gSCR equals the equipment critical SCR

and depends on GFL converter characteristics. GFM converter integration only changes the network structure without affecting equipment dynamic characteristics, so the critical gSCR remains unchanged. Thus, gSCR can reflect the small-signal stability margin.

2.3 Relationship Between Capacity Ratio and Generalized Short-Circuit Ratio

To derive the relationship between gSCR and capacity ratio, examine the network impedance characteristics in [Figure 1: see original paper]. GFL converter port node i connects to collection bus $i+n$ through a step-up transformer with equivalent reactance Z_{Ti} , so $B_1 = SL \cdot \text{diag}[1/Z_{Ti}] = -B_2$. B_4 consists of two parts: admittance B_1 from collection bus to turbine port and admittance from collection bus to AC network, denoted as B_4 . Let λ denote gSCR; then from equation (8), λ satisfies:

$$\text{MATH_9}$$

For low-SCR grids satisfying $\lambda < 1/Z_{Ti}$, the term $(B_4 - \lambda I)$ is invertible. Therefore, using matrix Schur complement properties, equation (9) can be equivalently transformed to:

$$\text{MATH_10}$$

Substituting $B_1 = SL \cdot \text{diag}[1/Z_{Ti}] = -B_2$, matrix M becomes:

$$\text{MATH_11}$$

Let $M = SL \cdot \text{diag}[1/Z_{Ti} + \gamma_i/Z_i]$. Then $M = SL \cdot \text{diag}[1/Z_{Ti} + \gamma_i/Z_i]$. After equivalent transformation, $(1/SLi)M = \text{diag}[1/Z_{Ti} + \gamma_i/Z_i]$. Further left-multiplying equation (10) by $[\text{diag}(1/SLi), 0; 0, I]$ yields:

$$\text{MATH_12}$$

where the first q diagonal elements of $\text{diag}[1/SLi]$ are 1, and the remaining diagonal elements are $1-\gamma_i(\lambda)$.

Equation (12) reflects how the equivalent admittance of GFM converter branches (ΔB) affects gSCR (λ). When $\Delta B = 0$ (no GFM converters installed or retrofitted), the original gSCR $\lambda = \lambda_0$, and equation (12) reduces to:

$$\text{MATH_13}$$

Let $f(\lambda_0) = [\text{diag}(1/SLi)]B_4$. Then:

$$\text{MATH_14}$$

Equation (15) shows that to increase gSCR from λ_0 to λ , ΔB must satisfy:

$$\text{MATH_15}$$

Noting that all matrices in equation (16) are diagonal, substituting $\Delta B = SB \cdot \text{diag}[\gamma_i/Z_i]$ into (16) and solving each diagonal element equation yields the re-

relationship between each station's capacity ratio (γ_i) and gSCR. For $1 \leq i \leq q$ (additional GFM converter scheme), $\gamma_i/Z_i = [\text{fi}(\lambda_0) + 1/Z_i] - [\text{fi}(\lambda) + 1/Z_i]$, giving the required capacity ratio to increase gSCR from λ_0 to target value λ :

$$\text{MATH}_{\{16\}}$$

Similarly, for $q+1 \leq i \leq n$ (retrofitted GFM turbine scheme), $\gamma_i/Z_i = [\text{fi}(\lambda_0) + 1/Z_i] - (1-\gamma_i)[\text{fi}(\lambda) + 1/Z_i]$, yielding the required capacity ratio:

$$\text{MATH}_{\{17\}}$$

2.4 Capacity Ratio Estimation Process

Based on equations (17) and (18), configuring GFM converters in all wind farms can increase gSCR from initial value λ_0 to target value λ . Since GFM converter integration does not change the equipment critical SCR, system strength is improved. Each wind farm can flexibly choose between retrofitting turbines with GFM control or adding GFM converters at different voltage levels. The specific steps are:

Step 1: Calculate the initial gSCR value λ_0 based on network and equipment capacity parameters, and determine the target value λ according to system requirements.

Step 2: Determine the GFM converter configuration scheme for wind farm i and the transformer equivalent reactance Z_i .

Step 3: Obtain the GFM converter impedance external characteristics through analytical methods or impedance measurement, and calculate its equivalent internal reactance Z_{eq} .

Step 4: Calculate the capacity ratio using equations (17) and (18).

3.1 Boundary Conditions

Under the two assumptions mentioned earlier, typical capacity ratio values are considered: 1) Constrained by static voltage stability, the initial gSCR ≥ 1.0 ; 2) Constrained by grid-connection requirements and manufacturing capabilities, the equipment critical SCR ≤ 1.5 . Based on these conditions, the required capacity ratios to increase gSCR from 1.0 to 1.5 are solved as typical values. Configuring GFM converters according to these typical values ensures the system maintains small-signal stability (gSCR $> 1.5 \geq \text{CSCR}$) even under the worst initial condition of gSCR = 1.0, reducing the voltage support strength requirements for GFL renewable energy equipment. Notably, when wind turbines from different manufacturers have different dynamic characteristics (i.e., different impedance matrix external characteristics), the critical gSCR depends on the weighted average of each station's turbine dynamics, lying between the minimum and maximum turbine critical SCRs. Thus, critical gSCR ≤ 1.5 still

holds, and the above boundary conditions remain valid. Detailed discussions can be found in references [10], [22], [27].

Further, the required capacity ratios to increase gSCR from 1.0 to 2.0 can be solved to ensure the system has a large stability margin.

3.2 Proportion of Retrofitted Grid-Forming Wind Turbines

Using typical station step-up structures and parameters, typical capacity ratio values for the retrofitting scheme are solved. Both GFM and GFL turbines are connected in parallel to the 35 kV collection bus through 690V/35kV step-up transformers. Without loss of generality, the transformer equivalent reactance is taken as the typical value of 8%, i.e., $Z_{Ti} = 0.08$ pu. GFM converters use typical parameters, yielding an equivalent reactance of approximately $Z_{eq} = 0.05$ – 0.10 pu. Therefore, the total equivalent reactance of the GFM converter plus series transformer is $Z_i = 0.13$ – 0.18 pu.

According to equation (18), the required capacity ratio to increase gSCR from 1.0 to 1.5 is 6.6%–8.5%. In other words, configuring about 8% capacity can ensure the actual gSCR is raised to at least 1.5 even under the worst initial condition. Following the same procedure, equation (18) yields a capacity ratio of 12.9%–16.3% to increase gSCR above 2.0, ensuring a high stability margin.

3.3 Proportion of Added Grid-Forming Converters

Using typical station step-up structures and parameters, typical capacity ratio values for the additional GFM converter scheme are solved.

Adding GFM converters at 35 kV bus: Both GFM and GFL converters are connected in parallel to the 35 kV collection bus through 690V/35kV step-up transformers. The total equivalent reactance of the GFM converter plus series transformer branch is $Z_i = 0.13$ – 0.18 pu. Following the same calculation procedure, equation (17) yields required capacity ratios of 8.0%–11.1% and 16.8%–23.3% to increase gSCR from 1.0 to 1.5 and 2.0, respectively.

Adding GFM converters at 220 kV bus: Both GFM and GFL converters are connected in parallel to the 220 kV bus through 690V/35kV/220kV two-stage transformers. Considering typical two-stage transformer equivalent reactance of $8\% + 12\% = 20\%$, i.e., $Z_{Ti} = 0.20$ pu, and typical GFM converter parameters with $Z_{eq} = 0.05$ – 0.10 pu, the total equivalent reactance is $Z_i = 0.25$ – 0.30 pu. According to equation (17), the required capacity ratios to increase gSCR from 1.0 to 1.5 and 2.0 are 22.3%–26.8% and 52.1%–62.5%, respectively.

The results show that due to the larger electrical distance between GFM converters and the grid, the capacity ratio required for centralized GFM converter installation at the 220 kV bus is significantly higher than that for distributed installation at each station's 35 kV bus, demonstrating the economic advantage of distributed GFM technology. As an improved scheme, high-voltage direct-

connected GFM equipment can be installed at the 220 kV bus (with GFM converter outlet voltage of 35 kV), requiring only a 35kV/220kV step-up transformer. Following the same calculation procedure, the required capacity ratios to increase gSCR from 1.0 to 1.5 and 2.0 are 11.6%–16.1% and 27.1%–37.5%, respectively, substantially reducing the required proportion.

Table 1 summarizes the typical capacity ratio values required under different GFM converter configuration schemes and control parameters. In practical applications, different wind farms can flexibly select the required capacity ratio from Table 1 to ensure the system gSCR is increased to the target value (gSCR = 1.5 is considered to have low stability risk because the assumed equipment critical SCR ≤ 1.5 ; gSCR = 2.0 provides a large stability margin).

4 Case Analysis

To verify the effectiveness of the proposed capacity ratio calculation method and typical values, an electromagnetic transient simulation model of the two-area four-machine system shown in [Figure 4: see original paper] was built on the MATLAB/SIMULINK platform. The wind farms are assumed to be full-power converter-type units using the GFM and GFL converter hybrid structure from [Figure 1: see original paper]. Converter control parameters, transmission line parameters, and wind farm rated capacity parameters are provided in Appendix Tables A1–A3.

4.1 Retrofitting Grid-Forming Wind Turbines

First, the effectiveness of typical capacity ratio values for the GFM turbine retrofitting scheme is verified using the two-area four-machine model. The initial gSCR is approximately 1.0, and 1.3% and 6.6% of wind turbines are retrofitted from GFL to GFM control. The calculated gSCR increases to 1.1 and 1.5, respectively. At $t = 0.2$ s, a 5% terminal voltage sag is applied at the infinite bus (node 10) and quickly cleared. The three-phase voltage waveforms at the GFL converter terminal are shown in [Figure 5: see original paper]. The results show that with 6.6% GFM turbine retrofitting, the three-phase voltage waveform quickly recovers to the rated operating point, indicating high system stability margin. With only 1.3% retrofitting, the three-phase voltage amplitude continues to oscillate, indicating low stability margin, thus verifying the effectiveness of the typical capacity ratio values.

4.2 Adding Grid-Forming Converters

Next, the effectiveness of typical capacity ratio values for the additional GFM converter scheme is verified. The initial gSCR is approximately 1.0. GFM converters are added at the 220 kV buses of wind farms 1 and 2, and at the 35 kV buses of wind farms 3 and 4. Three capacity ratio sets are calculated using equation (17) and listed in Table 2, which can increase gSCR to 1.1, 1.3, and 1.5, respectively.

Table 2 Capacity ratios to raise gSCR to 1.1, 1.3 and 1.5

At $t = 0.2$ s, a 5% terminal voltage sag is applied at node 10 and quickly cleared. Figure 6: see original paper shows the active power oscillation waveforms of GFL turbines under the three capacity ratio sets (using wind farm 1 as an example; other farms show similar responses). The results demonstrate that as the capacity ratio increases, the system damping ratio gradually improves. When the GFM converter capacity ratio is 22.3% for wind farms 1 and 2 and 8.0% for wind farms 3 and 4, the system exhibits acceptable dynamic response, verifying the effectiveness of typical capacity ratio values for the additional GFM converter scheme.

Furthermore, the effectiveness of typical capacity ratio values is verified when different stations adopt different schemes (additional GFM converters vs. GFM turbine retrofitting). GFM converters are added at the 220 kV buses of wind farms 1 and 2, while some turbines in wind farms 3 and 4 are retrofitted, with other settings unchanged. Three capacity ratio sets are calculated using equations (17) and (18) and listed in Table 3, which can increase gSCR to 1.1, 1.3, and 1.5, respectively.

Table 3 Capacity ratios to raise gSCR to 1.1, 1.3 and 1.5

Figure 6: see original paper shows the active power waveforms of GFL turbines under the three capacity ratio sets. The results show that as the capacity ratio increases, the system damping ratio improves. When the GFM converter capacity ratio is 22.3% for wind farms 1 and 2 and 6.6% for retrofitted GFM turbines in wind farms 3 and 4, the system exhibits acceptable dynamic response.

5 Conclusions and Outlook

This paper investigates the analytical relationship among the capacity ratio of GFM and GFL converters in renewable energy stations, system voltage support strength, and small-signal stability margins, proposing a capacity ratio estimation method for improving multi-station system stability. Combined with typical parameters of GFM equipment and step-up transformers, typical capacity ratio values meeting SCR standards are provided for practical engineering applications.

GFM converters themselves have transient stability issues [28], which are key factors affecting the large-scale application of GFM power electronic equipment. Addressing GFM converter transient stability problems and considering capacity ratio issues during transient processes require further research.

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Appendix

Figure A1 [FIGURE:A1] Virtual Synchronous Machine control block diagram

Figure A2 [FIGURE:A2] Magnitude-frequency characteristic of Zwing(s)

Table A1 Converter control parameters

Table A2 Transmission line parameters

Table A3 Rated capacity of wind farms

Appendix B: Derivation of Closed-Loop Characteristic Equation Modal Decoupling

Left-multiplying equation (6) by matrix $[SB, 0; 0, I]_{I_2}$ and right-multiplying by $[I, 0; 0, I]_{I_2}$ yields:

$$\text{MATH_}\{B1\}$$

For matrix 1, there exists matrix T such that $T^{-1}(1)T = \text{diag}[\lambda_i]$, where λ_i are the eigenvalues of matrix 1. According to matrix Schur complement properties, λ_i are also the generalized eigenvalues of matrix $[In, 0; 0, 0]$. Left-multiplying equation (B1) by $[T^{-1}, 0; 0, In]_{I_2}$ and right-multiplying by $[T, 0; 0, In]_{I_2}$ gives:

$$\text{MATH_}\{B2\}$$

Note: Figure translations are in progress. See original paper for figures.

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