A Systematic Framework for Grid-Forming Inverter Sizing in Must-Run-Constrained 100% IBR Systems

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Abstract— **High penetration of inverter-based resource (IBR) challenges frequency stability in power systems. In this context, the power system must assess operability under 100% IBR operation. This paper presents a two-stage framework to enable secure 100% IBR operation by grid-forming inverter (GFM) to replace must-run unit commitment (MUC) generators. First, MUC performance -equivalence determines GFM conditions by matching the MUC equivalent characteristics. Second, operational-criteria evaluation computes the required GFM capacity across load and IBR-penetration scenarios so that frequency criteria are met. A case study on the target power system shows that a properly sized GFM ensures frequency criteria during 100% IBR conditions, enabling curtailment reduction and operating-cost savings. The framework offers a transparent planning metric for GFM in high-IBR systems.**

Keywords—Grid-Forming Inverter, Inverter-based Resource Must-run Generator, Frequency Stability

I. INTRODUCTION

The global energy transition toward decarbonization, catalyzed by the Paris Agreement, is driving aggressive deployment of inverter-based resource (IBR) worldwide [1],[2]. Unlike synchronous generator (SG), which provide rotational inertia and governor-based frequency response, grid-following inverter (GFL) operates as current sources and contribute limited dynamic support in weak grids [3],[4]. The challenge is amplified in power systems where must-run unit commitment (MUC) generators impose operational constraints that force IBR curtailment during high-generation periods [5],[6].

Existing remedies include synchronous condenser (SC) for inertia provision and battery energy storage systems (BESS) for fast frequency support [7]. However, synchronous condensers require substantial capital investment and offer limited operational flexibility, while GFL-controlled BESS face challenges in autonomous operation under extremely low short-circuit ratio (SCR) conditions. Grid-forming inverter (GFM), acting as controlled voltage sources with virtual inertia and droop characteristics, have emerged as an alternative [8].

Recent research has advanced GFM technology through control algorithm development and demonstrations [9]–[12]. Various studies have explored critical aspects such as inertia requirements for high-IBR systems under grid code [11], comparative performance analysis between GFM and GFL architectures, and stability assessment under diverse operating scenarios [12]. Despite growing recognition of GFM potential, a systematic framework for determining the required GFM capacity and control parameters to fully replace MUC generators while maintaining equivalent frequency stability performance remains insufficiently developed.

This paper addresses this gap through a two-stage framework. First, a performance-equivalence formulation determines the GFM capacity and associated parameter settings by matching all criteria. Second, an operational-criteria assessment derives the required GFM capacity such that frequency constraints are satisfied under N−1 contingency. The proposed framework is applied to a target system case study to examine its practical applicability. The analysis is validated through multi-day unit-commitment (UC) and economic-dispatch (ED) based simulations, investigating the potential for stable high-IBR operation and curtailment reduction.

The remainder of this paper is organized as follows: Section II describes MUC generators operation and summarizes GFM characteristics. Section III presents the proposed framework for assessing GFM sizing requirements. Section IV provides case study results. Section V concludes with findings and future work.

II. MUC OPERATION AND PATHWAY TO 100% IBR

MUC generators are SGs mandatorily operated to provide system inertia, short-circuit strength, and frequency regulation. These MUC generators play a critical role in securing system short-circuit ratio, ensuring protection coordination through fault current contribution, and maintaining frequency stability of the system. In Korea, particularly on Jeju Island where the number of dispatchable generators is limited, a certain number of MUC generators are operated depending on load demand levels, as described in Table I.

TABLE I. MUC OPERATION STATUS DEPENDING ON LOAD DEMAND IN JEJU ISLAND

Load demand range	Number of MUC
800 ~ 1,020 MW	5
460 ~ 800 MW	4
~ 460 MW	3

However, during the high IBR penetration, MUC generators can lead to curtailment of IBR and increased system operation costs. Therefore, to achieve 100% IBR-based operation while maintaining acceptable operational performance, it is necessary to establish a framework in which IBR can emulate the dynamic characteristics of SGs to preserve the system stability.

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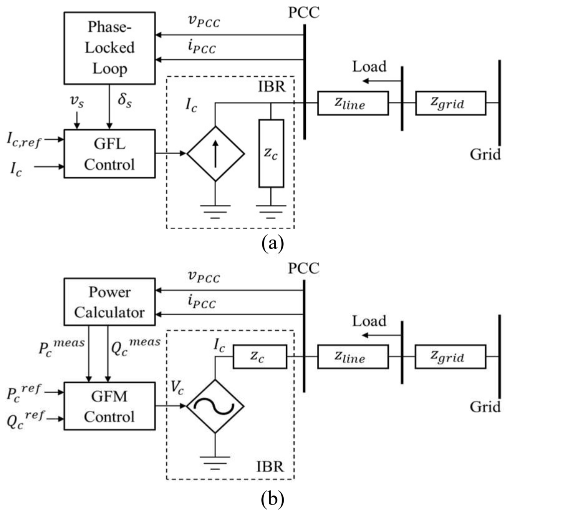

Fig. 1. Conceptual control architectures of IBRs. (a) GFL with PLL acting as a current source. (b) GFM acting as a voltage source.

To substitute the MUC generators, technologies such as SC can be utilized to provide inertia and high fault current for system strength enhancement, while STATCOMs can be employed for voltage support. More importantly, in an IBR-dominated system, inverter control performance becomes the dominant factor determining system behavior. Hence, control technologies employing GFMs are expected to play a pivotal role. Fig. 1. shows a conceptual diagram of inverter types according to their control schemes.

GFLs operate as current sources synchronized via a phase-locked loop (PLL), which results in a rapid degradation of control performance under conditions with no voltage reference or low SCR. In contrast, GFMs operate as voltage sources that directly establish reference voltages, providing virtual inertia and droop-based frequency support even in extremely weak system [13],[14]. This capability positions GFM as the key enabler for 100% IBR operation through MUC replacement while preserving system stability.

III. GFM Capacity Sizing Decision Framework

A. MUC Performance-Equivalent Replacement

This section explains the minimum requirements for reproducing the frequency stability performance provided by MUC generators through GFM, in order to achieve 100% IBR operation in the power system. The main concept is to determine the required GFM capacity (S_{GFM}) and its control parameters—specifically, the inertia constant (H_{GFM}) and droop coefficient (R_{GFM})—based on three aspects: virtual inertia (VI), primary frequency response (PFR), and frequency reserve (FR).

1) Equivalent Inertia Criterion

To maintain the system's rate of change of frequency (RoCoF) performance immediately after a disturbance, the GFM must provide equivalent or greater inertia energy to that of the replaced MUC generators, which are calculated as the product of each generator's inertia constant (H_i) and rated capacity (S_i) shown in (1):

$$H_{GFM} S_{GFM}^{VI} \geq \sum_{i \in MUC} H_i S_i. \quad (1)$$

2) Equivalent Frequency Response Criterion

Even when MUC generators are replaced, the GFM must ensure frequency response capability. Accordingly, the droop-based response capacity of the GFM must be equal to or greater than the total effective frequency response capability provided by the MUC generators, as defined in (2):

$$\frac{S_{GFM}^{PFR} \times \Delta f_{st.}}{R_{GFM} \times f_0} \geq \sum_{i \in MUC} \min\left(\frac{S_i \times \Delta f_{st.}}{R_i \times f_0}, P_{max,i} - P_{gen,i}\right), \quad (2)$$

where, R_i is a droop coefficient. f_0 and $\Delta f_{st.}$ is nominal system frequency and frequency deviation standard from the nominal value, respectively. Also, generator's headroom is calculated by relation on generation output between maximum ($P_{max,i}$) and current ($P_{gen,i}$). Here, The minimum value ensures that each generator's contribution is limited by its available headroom.

3) Equivalent Reserve Capability

To enable the GFM to supply the required frequency reserve during dispatch, it must satisfy a minimum capacity requirement that accounts for the available headroom as shown in (3):

$$S_{GFM}^{FR} \geq \frac{\max\left(FR_{reserve}, P_{max,trip}\right)}{\alpha_{Headroom}}, \quad (3)$$

where, $FR_{reserve}$ and $P_{max,trip}$ represents the required frequency reserve to MUC generators, possible maximum generator trip, respectively. Also, $\alpha_{Headroom}$ denotes the utilization ratio of the available headroom.

4) Final Determination of Required GFM Capacity

The required GFM installed capacity that simultaneously satisfies the three aforementioned conditions can be defined as shown in (4):

$$S_{GFM}^{MUC} = \max\{S_{GFM}^{VI}, S_{GFM}^{PFR}, S_{GFM}^{FR}\}, \quad (4)$$

At the same time, the parameters (H_{GFM}, R_{GFM}) must be configured to meet the frequency response constraints of the GFM. Based on these integrated criteria, this study derives the operating envelope for GFM operation within the power system.

B. Operational Criteria-Based Assessment

In this section, a procedure is presented to estimate the required GFM capacity by considering the actual operational constraints required by the power system. Through this process, the minimum GFM capacity required under critical operating conditions to ensure adequate system performance can be determined. The overall assessment procedure is illustrated in the flowchart shown in Fig. 2.

In this process, scenario is first selected, including load level, IBR penetration ratio, and unit status, while the GFM capacity is initially set to zero. Subsequently, under the defined N-1 contingency, frequency performance indicators are calculated. If both criteria — the frequency nadir (f_{nadir}) and RoCoF — are simultaneously satisfied, the corresponding minimum required GFM capacity for that scenario is stored as S_{GFM}^{req}.

Conversely, if either condition is violated, S_{GFM} is incrementally increased by a predefined step ($S_{GFM,step}$), and the

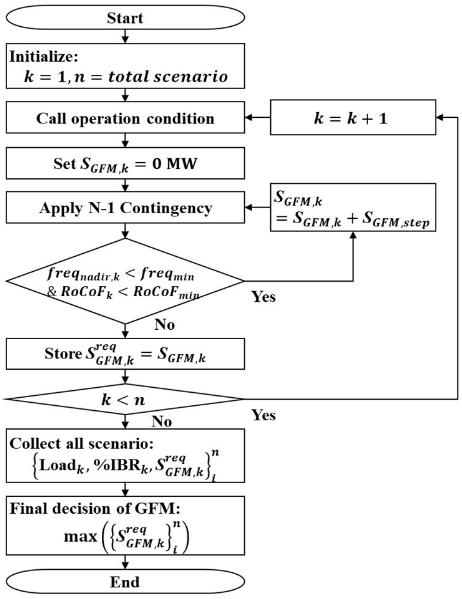

Fig. 2. Flowchart of the GFM requirement evaluation based on operational criteria.

same evaluation process is repeated. This iterative procedure is carried out for all operational scenarios to obtain the set $\{S^{req}_{GFM,k}\}$. By selecting the largest required capacity among all scenarios, system operational stability can be ensured across the entire range of conditions.

Based on this framework, power system operators can conservatively evaluate both (i) the GFM capacity equivalent to the replaced MUC generators and (ii) the GFM capacity required to maintain frequency stability. Through the comparative assessment of these two perspectives, it becomes possible to determine the most advantageous GFM integration strategy for reliable and economically efficient system operation.

IV. Case Study

A. System Configuration

In this case study, an analysis was conducted on the operation of a future power system under conditions characterized by a continuous increase in IBRs and a decrease in the number of synchronous generators. To accomplish that, the study was conducted based on the power system of Jeju Island, in South Korea, for the 2030. Based on the forecasted output of IBR and load demand, operating conditions were established. For the system analysis, the power system simulation engineering (PSS®E) software was utilized. The target power system configuration is shown in Fig. 3.

In this analysis, power exchange and control between the mainland and Jeju Island via the high voltage direct current (HVDC) interconnection line, which is currently in operation, were not considered. This analysis evaluated the operational condition required to achieve 100% IBR operation under the condition of an independently operated power system of the corresponding scale. The power system operating conditions and frequency stability criteria are described in the Table II.

Although the installed capacity of IBR exceeds the peak load demand, the intermittent nature and low capacity factor of IBR

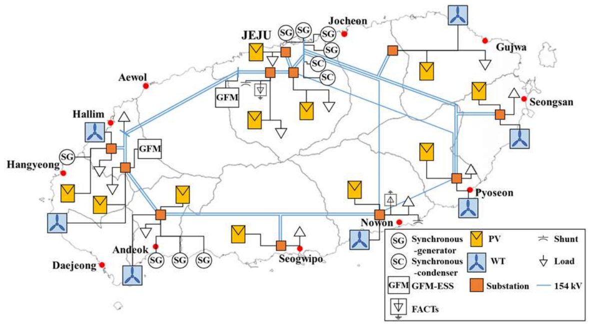

Fig. 3. System diagram of target power system.

TABLE II. System Operational Condition and Criteria

Index	Parameter	Value
System Operating Condition	Load demand	- Peak: 1,330 MW - Median: 807 MW - Off-peak: 562 MW
	IBR capacity	PV: 1,220 MW / WTG: 877 MW
	Number of SGs	8
	UFLS	58.8 Hz (1st stage)
Operation Criteria	Number of MUC	3 units (97 / 97 / 130 MVA)
	MUC total inertia	2109.95 MVAs
	MUC total PFR	112.35 MW
	Frequency nadir	59.0 Hz (with 0.2 Hz of margin above UFLS)
	RoCoF	-1.0 Hz/s
	Contingency	N-1 (largest unit: 185 MW)

still necessitate the dispatch of SGs. However, this case study primarily aims to examine whether an operational point can be identified that enables 100% IBR-based operation while maintaining power system stability.

The modeling of IBR was carried out using the generic models provided in the PSS®E library [15]. Parameter settings were referenced from the WECC and UNIFY guidelines, as summarized in Table III [16],[17]. For the GFM model, a virtual synchronous machine (VSM)-based model, REGFMB1U, was applied. However, for photovoltaic (PV) and wind turbine generator (WTG) resources, GFL average models were adopted, which do not provide frequency response.

TABLE III. Dynamic Model for IBR

IBR Resource	Inverter type	Applied model	Ref.
PV	GFL	RECGA1 + REECA1 + REPCA1	[16]
WTG	GFL	RECGA1 + REECA1 + REPCA1	[16]
GFM-ESS	GFM	REGFMB1U	[17]

B. GFM Replacement for MUC Generators

To achieve 100% IBR operation, it is first necessary to establish operating conditions that can replace the MUC generators. For this purpose, the analysis was conducted based on the previously described MUC replacement framework.

- Case A: Operation condition maintains MUC
- Case B: MUC replacement condition with GFM

The fundamental objective is to identify operating conditions under which the power system can deliver response performance equivalent to that observed when MUC generators are online. Using the dynamic parameters of the three MUC generators operating in the target power system, the MUC replacement framework was applied.

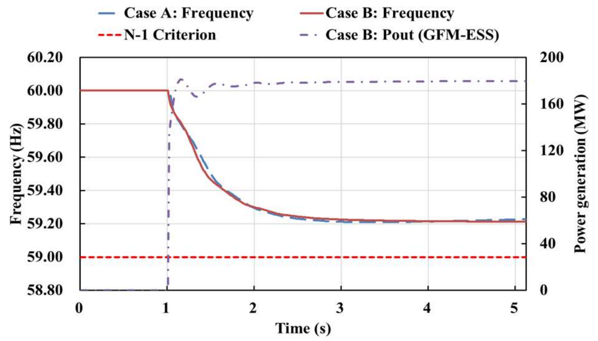

Fig. 4. GFM equivalent replacement for MUC generators.

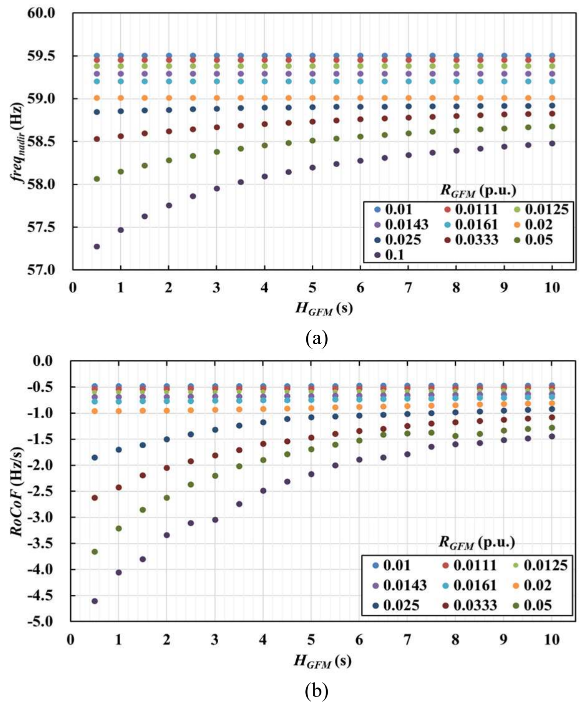

Fig. 5. Frequency nadir and RoCoF versus H_{GFM} for different droop characteristic: (a) f_{nadir}; (b) $RoCoF$.

As a result, the equivalent inertia was determined to be 2,110 MVAs, the required PFR was 112.35 MW, the FR was 123 MW, and the $P_{max,trip}$ was 185 MW. Based on these characteristics, it was confirmed that, according to the MUC equivalence criteria, a minimum GFM capacity of 200 MVA is required to meet all specified performance. Under this condition, the GFM control parameters of H_{GFM} = 9.17 s and R_{GFM} = 0.0161 were identified as a feasible combination that satisfies an equivalent level of inertia. The corresponding results are illustrated in Fig. 4, while the impact of variations in the (H_{GFM}, R_{GFM}) parameters on the power system operational performance is presented in Fig. 5.

From these results, it was confirmed that by securing the required control performance of the GFM, the MUC generators can be effectively replaced while providing equivalent dynamic performance to the power system. Based on this outcome, a further assessment was conducted in the following section to determine the required GFM capacity for maintaining operational performance under various operating scenarios.

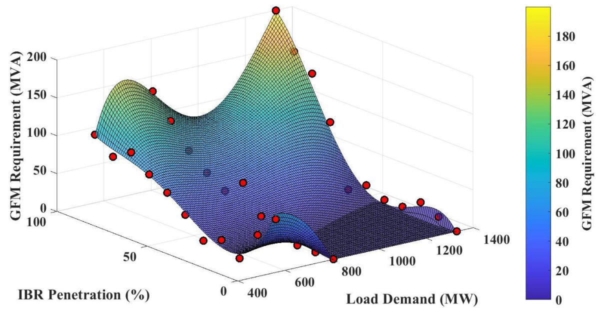

Fig. 6. Required GFM capacity versus load demand and IBR penetration under N-1 contingency

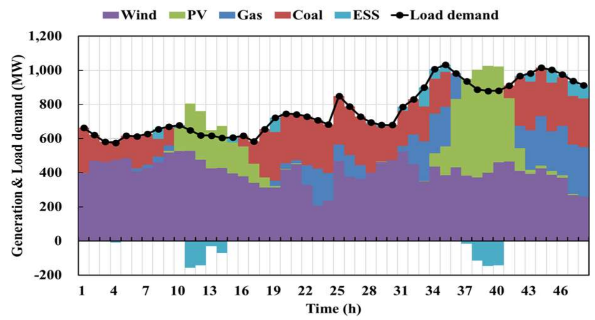

Fig. 7. Operating profile including 100% IBR operating condition.

C. Evaluation of Required GFM Capacity

In this section, the required GFM capacity was derived to ensure frequency stability of the power system under different operating conditions. For this purpose, boundary conditions were established based on three load conditions and corresponding IBR penetration levels, as summarized in Table II. Using this database, the required GFM capacity was calculated according to the procedure in Fig. 2. The resulting analysis results are shown in Fig. 6.

As a result, it was confirmed that under low IBR conditions, system operation can be maintained within criteria using only synchronous generators. However, under high IBR conditions, a significant amount of GFM capacity is required due to the shortage of available frequency response and inertia. The GFM capacity required to satisfy all criteria was determined to be approximately 200 MVA. Applying this capacity ensures that the minimum transient frequency and RoCoF in each operating scenario remain within the specified limits.

D. Verification of Required GFM Capacity

To validate the derived 200 MVA of GFM capacity under operating conditions, a 48-hour unit commitment and economic dispatch operating profile was developed using system asset information, load and IBR forecasts, and operational parameters. The PyPSA tool was applied for generating the operational profile, and the resulting operating profile is shown in Fig. 7.

A time-series database for each hour was constructed using the operating profile, and N-1 contingency simulations were performed. The corresponding results are presented in Fig. 8, and the frequency response evaluation results for the time periods operated under 100% IBR conditions are summarized in Table IV.

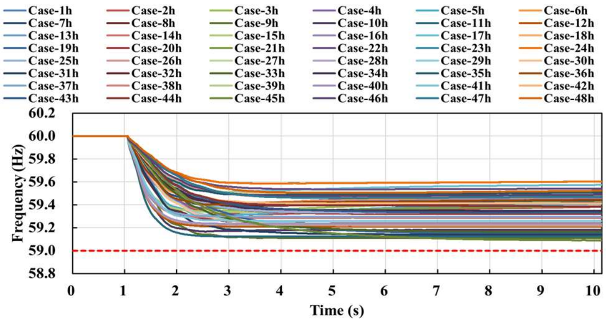

Fig. 8. Frequency stability trends according to operating profiles

TABLE IV. DETAILED FREQUENCY STABILITY RESULTS UNDER 100% IBR OPERATING CONDITION

Index	Case									
	10h	*11h*	*12h*	*13h*	*14h*	*15h*	*37h*	*38h*	*39h*	*40h*
$RoCoF$ (Hz/s)	-0.80	-0.84	-0.76	-0.68	-0.69	-0.64	-0.67	-0.75	-0.74	-0.74
$freq_{nadir}$ (Hz)	59.17	59.12	59.21	59.29	59.29	59.34	59.30	59.22	59.23	59.23

The results demonstrate that, with the application of 200 MVA GFM capacity, all operational criteria were satisfied. Notably, even during 100% IBR operating periods, compliant response characteristics were maintained, thereby validating the effectiveness of the proposed operating-criteria-based GFM capacity sizing determination framework.

These results indicate that applying the proposed GFM capacity enables a reduction in IBR curtailment and operating costs compared to conventional MUC-dependent operation, while simultaneously ensuring frequency stability. This confirms that transitioning from MUC to GFM operation can serve as a practical pathway toward achieving 100% IBR operation in future power systems.

V. CONCLUSION

This paper presented a systematic framework for determining GFM capacity sizing to achieve 100% IBR operation in isolated grids through MUC generator replacement. Two complementary approaches—performance-equivalent design and operational-criteria-based assessment—provide comprehensive GFM capacity determination considering frequency stability requirements.

Jeju Island case study demonstrates that 200 MVA of GFM with proper H_{GFM} and R_{GFM} successfully replaces MUC generators inertia and response characteristic while maintaining frequency nadir and RoCoF under N-1 contingency. Boundary condition analysis and 48-hour time-series validation confirm stable operation during 100% IBR periods, enabling significant IBR curtailment reduction and operational cost savings.

The proposed framework provides power system operators with practical methodology for GFM deployment planning. This framework is directly applicable to other island grids and weakly-connected systems pursuing high renewable penetration with minimal conventional generation. Future work includes extending the framework to voltage-reactive power criteria, GFM/GFL ratio optimization, and economic analysis incorporating curtailment reduction benefits and investment costs.

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