

COORDINATED FREQUENCY SUPPORT OF GRID FORMING AND GRID FOLLOWING CONVERTER CLUSTERS

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Abstract: High penetration of inverter-interfaced renewable generation reduces the equivalent inertia of power systems and increases the need for fast frequency support from power-electronic resources. Grid-forming (GFM) converters can provide virtual-inertia and droop responses, whereas grid-following (GFL) converters can contribute additional active power through frequency-dependent control but exhibit different synchronization and response dynamics. This paper develops a reduced-order model for coordinated frequency support of a GFM battery energy storage system (GFM-BESS) cluster and a GFL renewable energy source (GFL-RES) cluster. Particle swarm optimization is used to coordinate the virtual-inertia coefficient and the GFM/GFL active-power support gains. Three strategies, namely Conventional, GFM-only, and Proposed, are compared under a 10 MW load disturbance. Relative to Conventional control, the Proposed strategy reduces the maximum frequency deviation from 0.6084 Hz to 0.4556 Hz and the maximum RoCoF from 0.8331 Hz/s to 0.5188 Hz/s, corresponding to reductions of 25.1% and 37.7%, respectively. Compared with GFM-only control, it reduces the peak GFM support by 18.0% while the GFL cluster provides 2.366 MW of peak support. The results indicate that coordinated GFM/GFL control can improve transient frequency performance while distributing short-term support more effectively between converter clusters.

Keywords: Grid-forming converter; Grid-following converter; Frequency support; Battery energy storage; Coordinated control

1 INTRODUCTION

The growing penetration of wind and photovoltaic generation is replacing conventional synchronous generation with inverter-interfaced resources, reducing system inertia and increasing the sensitivity of frequency dynamics to power disturbances [1]. Grid-forming energy storage can provide frequency regulation and voltage control while using its stored energy and fast power response to support low-inertia systems [2]. Droop-controlled grid-forming inverters have also been shown to mitigate frequency deviations and the rate of change of frequency (RoCoF) through virtual inertia and active frequency support [3]. Converter-based frequency support is therefore becoming an important function in renewable-dominated power systems.

Grid-following (GFL) and grid-forming (GFM) converters achieve synchronization and frequency support through different mechanisms. GFL converters typically rely on a phase-locked loop and exhibit current-source characteristics, whereas GFM converters regulate internal voltage and frequency and can provide active grid support [4]. When the two converter types coexist, their different control strategies and external characteristics introduce additional coupling and complicate hybrid-system dynamics [5]. Frequency-domain analysis further shows that GFM and GFL resources contribute differently across frequency ranges, even when auxiliary frequency control is added to GFL units [6]. Different GFM implementations, including droop, virtual synchronous machine, matching, and dispatchable virtual oscillator control, also exhibit distinct dynamic and stability characteristics [7]. Coordinated support should therefore account for heterogeneous response mechanisms rather than treating converter groups as dynamically equivalent.

Recent studies have improved the frequency-support capability of individual GFM resources and have begun to address multi-type coordination. Adaptive inertia and damping for grid-forming direct-drive wind turbines can reduce disturbance-induced frequency and power oscillations [8]. Disturbance-observer-based sliding-mode control can provide flexible GFM frequency support while improving damping and active-power tracking [9]. Adaptive grid-forming control with tunable virtual inertia and damping has also been shown to reduce frequency deviation, RoCoF, and settling time [10]. For mixed resources, coordinated virtual-inertia control of GFL and GFM energy storage has been developed by considering their different synchronization mechanisms, response delays, and modal characteristics [11]. Hierarchical coordination of GFM and GFL wind turbines has likewise been used to exploit their different frequency-response processes in hybrid wind farms [12]. At the planning level, coordinated configuration of GFM and GFL energy storage has been investigated to combine frequency support with operational objectives [13]. Distributed optimal frequency control has more recently been developed for mixed GFM and GFL inverter-based resources subject to power-capacity and network constraints [14]. These studies demonstrate the value of coordinated control, but many existing methods target detailed stability analysis, planning, or higher-level optimal control.

To provide a compact engineering-oriented assessment of transient frequency support, this paper develops a reduced-order renewable-storage system containing a GFM-BESS cluster and a GFL-RES cluster. The GFM group provides virtual-inertia and droop responses, whereas the GFL group provides PLL-based fast active-power support. Particle

swarm optimization coordinates the virtual inertia and the key GFM/GFL support gains. Conventional, GFM-only, and proposed coordinated strategies are compared using maximum frequency deviation, RoCoF, settling time, and converter power sharing, followed by an equivalent-inertia sensitivity analysis. The objective is to quantify how coordinated GFM/GFL responses improve frequency dynamics while reducing excessive concentration of short-term support on the GFM storage group.

2 COORDINATED FREQUENCY-SUPPORT MODEL

2.1 Aggregated System and Converter-Cluster Dynamics

Figure 1 summarizes the proposed framework. A single-area 100 MW renewable-storage system is represented by a GFL-RES cluster, a GFM-BESS cluster, an aggregate load/grid, and a common AC bus. The model is intentionally reduced-order: it is used to compare the main time-domain frequency-support characteristics of the two converter groups rather than to reproduce device-level electromagnetic transients.

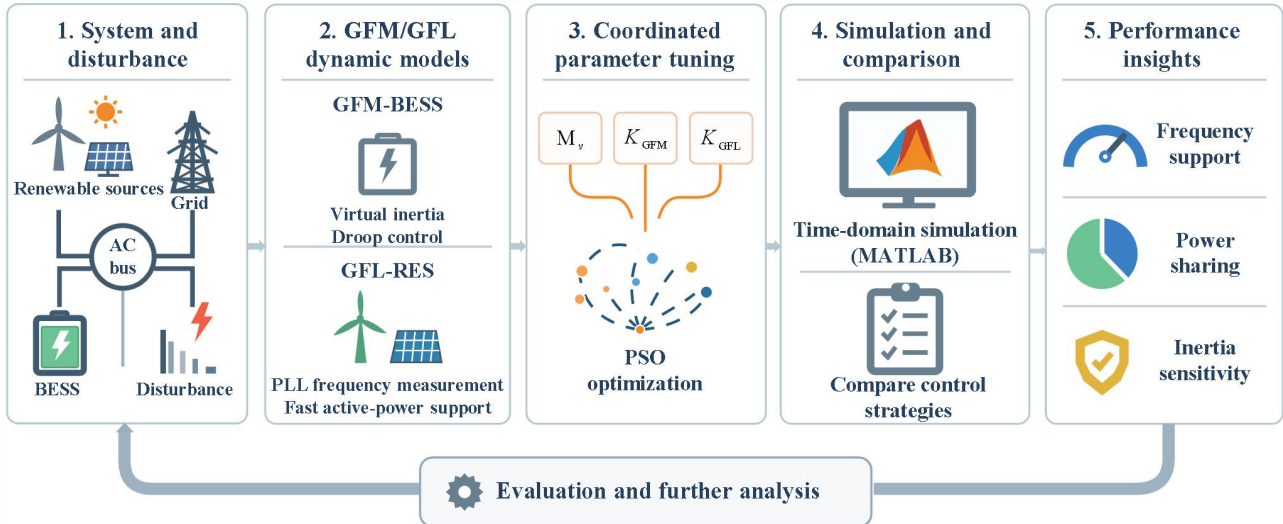


Figure 1 Framework of the Coordinated Frequency-Support Method for GFM/GFL Converter Clusters

Let $\Delta\omega$ denote the per-unit system-frequency deviation. The aggregate frequency dynamics are represented as

$$(2H_{\text{sys}} + M_v) \frac{d\Delta\omega}{dt} = \Delta P_{\text{GFM},d} + \Delta P_{\text{GFL}} + \Delta P_{\text{res}} - \Delta P_d - D_{\text{sys}} \Delta\omega \quad (1)$$

where H_{sys} and D_{sys} are the system inertia and damping, M_v is the equivalent virtual-inertia coefficient, and ΔP_d is the disturbance. The remaining power terms denote the GFM droop contribution, GFL active-power support, and restoration power, respectively.

For the GFM-BESS cluster, the droop component follows a first-order response,

$$T_{\text{GFM}} \frac{d\Delta P_{\text{GFM},d}}{dt} = -\Delta P_{\text{GFM},d} - K_{\text{GFM}} \Delta\omega \quad (2)$$

while the virtual-inertia contribution used for support-power evaluation is reconstructed as

$$\Delta P_{\text{GFM},i} = -M_v \frac{d\Delta\omega}{dt}, \quad \Delta P_{\text{GFM}} = \Delta P_{\text{GFM},d} + \Delta P_{\text{GFM},i} \quad (3)$$

Thus, virtual inertia mainly affects the initial frequency-change rate, whereas droop support develops with the GFM active-power loop. The two components are evaluated together when reporting GFM support power, so the model retains the distinction between inertia-related and droop-related contributions without introducing a detailed converter switching model.

The GFL-RES cluster measures frequency through a first-order PLL and uses the measured deviation to generate a fast active-power command. Its reduced-order dynamics are

$$T_{\text{PLL}} \frac{d\Delta\omega_{\text{PLL}}}{dt} = \Delta\omega - \Delta\omega_{\text{PLL}} \quad (4)$$

$$\Delta P_{\text{GFL}}^* = -K_{\text{GFL}} \Delta\omega_{\text{PLL}} \quad (5)$$

$$T_{\text{GFL}} \frac{d\Delta P_{\text{GFL}}}{dt} = -\Delta P_{\text{GFL}} + \Delta P_{\text{GFL}}^* \quad (6)$$

with $|\Delta P_{\text{GFL}}| \leq P_{\text{GFL}}^{\text{max}}$. The limit represents renewable-side active-power headroom reserved for short-term frequency support. This structure preserves the main distinction between immediate GFM inertia-related response and the PLL/power-loop-mediated GFL response while keeping the model compact. Because the GFL command is generated from the measured frequency deviation, its contribution naturally develops later than the reconstructed GFM inertia component. This difference in response timing is the main physical basis for coordinating the two converter groups.

A fixed slow restoration loop is applied identically to all strategies to recover the nominal frequency:

$$\frac{d\Delta P_{\text{res}}}{dt} = -K_{\text{res}} \Delta\omega \quad (7)$$

This restoration component is excluded from the optimization so that the comparison focuses on converter-cluster frequency support.

2.2 Coordinated Parameter Optimization

The coordinated parameter vector is $\mathbf{x}=[M_v, K_{\text{GFM}}, K_{\text{GFL}}]$. The search ranges are $M_v \in [0.5, 5.0]$ s, $K_{\text{GFM}} \in [2, 8]$, and $K_{\text{GFL}} \in [0, 4]$. Candidate parameters are assessed using a normalized weighted objective,

$$J=0.45\bar{J}_{\Delta f}+0.20\bar{J}_{\text{RoCoF}}+0.15\bar{J}_{t_s}+0.10\bar{J}_u+0.10J_{\text{reg}}, \quad (8)$$

where $\bar{J}_{\Delta f}$, $\bar{J}_{\text{RoCoF}}$, and $\bar{J}_{t_s}$ are the maximum frequency deviation, maximum RoCoF, and settling time normalized by the Conventional case; $\bar{J}_u$ is the normalized converter control effort; and J_{reg} is a mild parameter regularization term used to avoid unnecessarily extreme gains. A compact particle swarm optimization (PSO) with 20 particles and 30 iterations is adopted. The performance terms are normalized by the Conventional case before weighting, which prevents indices with different physical units from dominating the search. The optimization is intentionally limited to three parameters so that the resulting settings remain interpretable and the computational procedure is suitable for an engineering-oriented reduced-order study.

The control-effort term is calculated from the time integral of the squared per-unit GFM and GFL support powers and normalized by the Conventional case. The regularization term applies weights of 0.25, 0.45, and 0.30 to the squared normalized values of M_v , K_{GFM} , and K_{GFL} , respectively. Thus, the objective penalizes excessive converter action and unnecessarily large gains while keeping frequency deviation, RoCoF, and settling time as the dominant criteria. The same normalization is used for all candidate particles, making the objective dimensionless over the search.

Three strategies are evaluated. Conventional uses $M_v=1.0$ s, $K_{\text{GFM}}=4.0$, and $K_{\text{GFL}}=0$. GFM-only optimizes M_v and K_{GFM} while fixing $K_{\text{GFL}}=0$. Proposed jointly optimizes all three parameters. This arrangement separates the benefit of GFM parameter tuning from the additional effect of coordinated GFL participation.

3 CASE STUDY AND RESULTS

3.1 Simulation Setup

The test system uses a 100 MW power base and a nominal frequency of 50 Hz. A 10 MW load increase (0.10 p.u.) is applied 1 s after the start of the simulation. The time-domain model is solved in MATLAB using a fixed-step fourth-order Runge–Kutta method with a 0.01 s step over a 15 s horizon. The system inertia and damping are set to 2.5 s and 1.0 p.u., respectively. The GFM, PLL, and GFL time constants are 0.12, 0.12, and 0.15 s, respectively; the restoration gain is fixed at 3.0 s^{-1} ; and the GFM and GFL power limits are 25 and 10 MW, respectively.

3.2 Frequency Response and Converter Power Sharing

Figure 2 compares the system-frequency responses. Conventional control reaches a minimum frequency of 49.3916 Hz, corresponding to a maximum deviation of 0.6084 Hz. Optimizing only the GFM parameters raises the minimum frequency to 49.5374 Hz and reduces the maximum deviation to 0.4626 Hz. The Proposed strategy further raises the minimum frequency to 49.5444 Hz and reduces the maximum deviation to 0.4556 Hz. The additional nadir improvement over GFM-only is therefore limited, which indicates that the value of GFL participation should not be judged only by the frequency minimum. The trajectory also shows that both optimized strategies arrest the initial frequency decline more rapidly than Conventional control and recover toward the nominal value within the simulation horizon.

Table 1 provides the main quantitative comparison. Relative to Conventional, Proposed reduces the maximum frequency deviation by 25.1% and the maximum RoCoF by 37.7%. The settling time decreases from 9.13 s to 6.81 s, a reduction of 25.4%. GFM-only already achieves a settling time of 6.71 s, slightly shorter than Proposed; therefore, the coordinated strategy does not outperform GFM-only in every metric. Its additional advantage appears more clearly in RoCoF and converter power sharing. In particular, the Proposed strategy reduces the initial frequency-change rate while avoiding the larger GFM peak produced by the GFM-only tuning. This trade-off is consistent with the optimization objective, which considers both frequency indices and converter control effort rather than minimizing the nadir alone.

Table 1 Dynamic Performance under Different Coordination Strategies

Strategy	M_v / s	K_{GFM}	K_{GFL}	Max. deviation / Hz	Max. RoCoF / (Hz/s)	Settling time / s	Peak GFM / MW	Peak GFL / MW
Conventional	1.000	4.000	0	0.6084	0.8331	9.13	4.844	0
GFM-only	3.883	6.000	0	0.4626	0.5628	6.71	5.899	0
Proposed	4.637	3.520	2.616	0.4556	0.5188	6.81	4.835	2.366

Figure 3 shows the active-power contributions of the two converter clusters under Proposed control. The GFM cluster responds first through the equivalent virtual-inertia and droop mechanisms, while the GFL contribution develops after PLL measurement and the active-power loop. The peak GFL support reaches 2.366 MW. Compared with GFM-only, the GFM peak decreases from 5.899 MW to 4.835 MW, corresponding to an 18.0% reduction. Meanwhile, the maximum RoCoF is further reduced by 7.8% relative to GFM-only. These results indicate that GFL participation does not replace

GFM support; instead, it shares part of the short-term active-power requirement and reduces the concentration of peak support on the storage-side GFM cluster. The different peak times also reflect the intended complementarity: GFM provides the earliest response, while the GFL group contributes after its measurement and power-control dynamics have developed.

The power-sharing result also clarifies the functional separation between the two converter groups. The GFM-BESS cluster provides the earliest short-term support through virtual inertia and then continues through droop control, whereas the GFL-RES cluster contributes after frequency measurement and active-power command formation. The coordinated setting therefore does not simply transfer the entire support burden from storage to renewable generation. Instead, it uses the available GFL headroom to complement the early GFM response, which reduces the storage-side peak while preserving the frequency-response benefit obtained from GFM control.

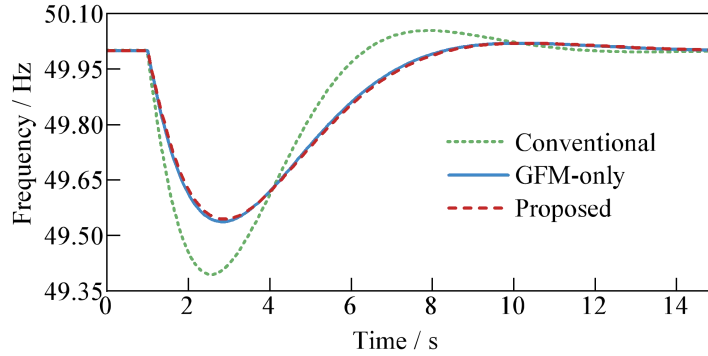


Figure 2 Frequency Responses under Different Coordination Strategies

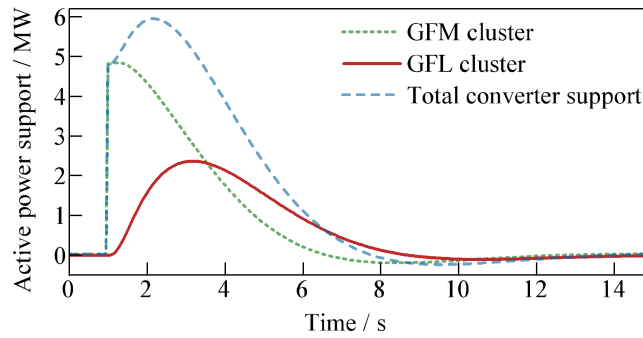


Figure 3 Coordinated Active-Power Responses of GFM and GFL Converter Clusters

3.3 Equivalent-Inertia Sensitivity

To examine whether the comparison depends strongly on the baseline inertia, H_{sys} is varied from 1.5 s to 4.0 s while the optimized parameters are kept unchanged. As shown in Figure 4, lower system inertia increases the maximum frequency deviation for all three strategies. At $H_{\text{sys}}=1.5$ s, the maximum deviations of Conventional, GFM-only, and Proposed are 0.6745, 0.4911, and 0.4834 Hz, respectively. At $H_{\text{sys}}=4.0$ s, the corresponding values decrease to 0.5446, 0.4304, and 0.4243 Hz. Proposed maintains the lowest maximum deviation at every tested inertia level, while the margin over GFM-only remains moderate. This trend supports the interpretation that coordination improves the dynamic response without relying on a single baseline inertia condition.

The optimized parameters are not retuned at each inertia level. Therefore, this sweep evaluates whether a single coordinated setting preserves its comparative advantage when the background system inertia changes, rather than presenting a separate optimization for every operating point.

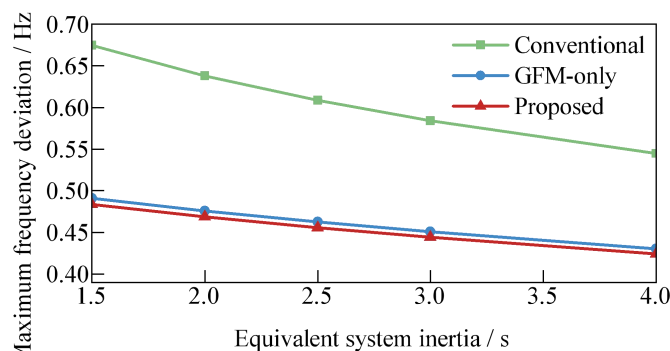


Figure 4 Maximum Frequency Deviation under Different Equivalent System Inertia Levels

As an auxiliary check, 5, 10, and 15 MW disturbances produce maximum frequency deviations of approximately 0.2278, 0.4556, and 0.6834 Hz under Proposed control. The approximately proportional change confirms that the reduced-order model maintains a consistent response trend over the tested disturbance range; this test is used only as a supplementary model check and is not treated as a separate robustness proof.

4 CONCLUSION

This paper presented a reduced-order coordinated frequency-support model for a renewable-storage system containing GFM-BESS and GFL-RES converter clusters. The model distinguishes the fast virtual-inertia and droop response of the GFM cluster from the PLL-mediated active-power response of the GFL cluster, and PSO is used to coordinate M_v , K_{GFM} , and K_{GFL} . Under the 10 MW load disturbance, the Proposed strategy reduces the maximum frequency deviation and maximum RoCoF by 25.1% and 37.7%, respectively, relative to Conventional control. Compared with GFM-only, the frequency-deviation improvement is modest, but the maximum RoCoF is further reduced and the GFM peak support decreases by 18.0% as the GFL cluster contributes 2.366 MW of peak support. The inertia-sensitivity results show the same comparative trend over $H_{sys}=1.5-4.0$ s, and the auxiliary disturbance sweep produces a consistent change in maximum frequency deviation. These results indicate that coordinated GFM/GFL control can improve transient frequency performance while distributing short-term support more effectively between heterogeneous converter groups. The main benefit is therefore not an across-the-board improvement of every index, but a better balance between RoCoF suppression, frequency recovery, and peak support sharing. The present model is intended for aggregated dynamic assessment; detailed electromagnetic-transient interactions, device-level current limits, and network-dependent interactions can be investigated in future work.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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REFERENCES

- [1] Valikhany Mina, Astero Poria, Lehtonen Matti, et al. A review on the suitability of virtual inertia strategies for the next generation of low-inertia power systems. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, 2025, 14: 101131. DOI: 10.1016/j.prime.2025.101131.
- [2] Li Yalou, Zhao Fei, Fan Xuejun. Review of Grid-Forming Energy Storage and Its Applications. *Power Generation Technology*, 2025, 46(2): 386-398. DOI: 10.12096/j.2096-4528.pgt.24052.
- [3] Guzman Gilberto, Madrigal Manuel, Melgoza-Vazquez Enrique. Grid-Forming Inverters for Frequency Support in Power Grids. *Electricity*, 2025, 6(4): 65. DOI: 10.3390/electricity6040065.
- [4] Liu Hui, Yu Siqi, Sun Dawei, et al. An Overview of Control Technologies and Principles for Grid-forming Converters. *Proceedings of the CSEE*, 2025, 45(1): 277-297. DOI: 10.13334/j.0258-8013.pcsee.232479.
- [5] Wang Guanqi, Pei Wei, Xiong Jiawang, et al. Stability Analysis Method for Hybrid Systems of Grid-following and Grid-forming Inverters. *Proceedings of the CSEE*, 2025, 45(1): 25-37. DOI: 10.13334/j.0258-8013.pcsee.240374.
- [6] Wang Zhen, Shan Yu, Zhu Yue, et al. Spatio-Temporal Frequency Distribution Analysis in Systems With Grid-Forming and Grid-Following Inverters: A New Perspective From Frequency Domain. *IEEE Access*, 2025, 13: 87999-88011. DOI: 10.1109/ACCESS.2025.3571481.
- [7] Mohammed Nabil, Ahmed Shehab, Konstantinou Charalambos. Comparative frequency- and time-domain analysis of four grid-forming inverters: Droop, VSM, matching, and dVOC. *International Journal of Electrical Power & Energy Systems*, 2025, 172: 111302. DOI: 10.1016/j.ijepes.2025.111302.
- [8] Liu Zunzhu, Cheng Zhijiang, Wang Weiqing, et al. Active frequency support control strategy for grid-forming direct-drive wind turbines. *Electric Power Engineering Technology*, 2025, 44(2): 23-33. DOI: 10.12158/j.2096-3203.2025.02.003.
- [9] Wang Weiyu, Wu Gongping, Ke Fei, et al. A power disturbance observer-based sliding mode frequency controller for grid-forming converters. *International Journal of Electrical Power & Energy Systems*, 2025, 170: 110696. DOI: 10.1016/j.ijepes.2025.110696.
- [10] Ndirangu Julius, Nderu John, Irungu George. Adaptive Grid-Forming Controller With Virtual Inertia and Damping for Enhanced Frequency Stability in Renewable Energy Systems. *Journal of Electrical and Computer Engineering*, 2026, 2026: 4351705. DOI: 10.1155/jece/4351705.
- [11] Yu Hengning, Yao Liangzhong, Liang Shuai, et al. Coordinated control of grid-following and grid-forming energy storage for virtual inertia response considering frequency modal characteristics. *International Journal of Electrical Power & Energy Systems*, 2025, 168: 110686. DOI: 10.1016/j.ijepes.2025.110686.

- [12] Zong Qihang, Yao Wei, Zhou Hongyu, et al. Hierarchical optimal frequency support scheme of wind farm with both grid-forming and grid-following wind turbines. *International Journal of Electrical Power & Energy Systems*, 2025, 165: 110463. DOI: 10.1016/j.ijepes.2025.110463.
- [13] Wei Che, Pei Wei, Qiu Yinfeng, et al. A co-configuration method of grid-forming/grid-following energy storage for grid frequency support and wind power consumption in offshore oil and gas fields. *Advanced Technology of Electrical Engineering and Energy*, 2025, 44(11): 58-71. DOI: 10.12067/ATEEE2501020.
- [14] Wang Xiaoyang, Chen Xin. Distributed Coordination of Grid-Forming and Grid-Following Inverters for Optimal Frequency Control in Power Systems. *IEEE Transactions on Power Systems*, 2026, 41(5): 3831-3846. DOI: 10.1109/TPWRS.2026.3684791.