

Evaluating System Stability and HVDC Dynamics in Vietnam's Integration of 3–5 GW Grid-Forming Offshore Wind

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Abstract: Vietnam's rapid expansion of offshore wind under Power Development Plan VIII raises critical challenges for system stability due to low inertia, weak-grid conditions, and increasing reliance on inverter-based resources. Existing studies highlight the potential of grid-forming (GFM) converters and VSC-HVDC systems to support weak grids, yet no prior work has examined their combined impact within Vietnam's unique 110–500 kV network topology. This study develops a high-fidelity RMS–EMT simulation framework to evaluate the integration of 3–5 GW offshore wind via ± 525 kV VSC-HVDC links under varying GFM penetration levels. Representative contingencies including a 500 MW generation trip, three-phase faults at major 500 kV buses, HVDC mode-switch events, and wind-power fluctuations were simulated across low-, medium-, and high-load scenarios. The findings suggest that the extent of GFM penetration can improve operational flexibility during and post disturbance. Nadir frequency improves from 49.37 Hz (GFL-only) to 49.74 Hz, and RoCoF increases from -0.68 to -0.28 Hz/s, and post disturbance recovery can occur in 0.5 of the time for all scenarios evaluated. Active power fluctuation can decrease from ~ 5 oscillations during GFM HVDC to over 110 % increase in inertia under voltage control (no oscillation). It shows that GFM FC HVDC provides integrated inertia on the system. Coordinated GFM implemented in conjunction with wind turbines and HVDC terminals created system synchronous support and seamless integration of large-scale offshore wind in Vietnam. GFM will need to be implemented in future grid and control system, HVDC designs and resource optimally system planning in Vietnam.

Keyword: Offshore wind integration; Grid-forming converters; VSC-HVDC; Weak-grid stability; Frequency response; Dynamic simulation; Inverter-based resources; Vietnam power system.

1. Introduction

Vietnam's power system is undergoing a rapid structural transition, with multi-gigawatt offshore wind developments expected to become a central component of national energy security and decarbonization strategies outlined in Power Development Plan VIII. Although the country possesses high-quality offshore wind resources, the integration of large clusters of 3–5 GW into an already weak and inertia-constrained grid presents substantial operational and stability challenges. The Vietnamese system is characterized by low short-circuit strength, long north–south transmission corridors, and a growing share of inverter-based resources (IBRs), all of which reduce its tolerance to disturbances and limit conventional frequency support.

Most commercial offshore wind turbines employ grid-following (GFL) converters that rely on pre-existing grid voltage for synchronization. As the proportion of GFL-based generation increases, the system's ability to maintain frequency and voltage stability during faults or large power imbalances deteriorates. International experience—from Ireland, Australia, and parts of continental Europe—shows that high IBR penetration can lead to elevated rates of change of frequency (RoCoF), reduced frequency nadirs, weak voltage recovery, and increased oscillatory modes. Similar vulnerabilities are anticipated in Vietnam as offshore wind deployment scales.

In recent years, remarkable advances in GFM converter technology have emerged as a promising pathway. GFM units are capable of autonomous primary frequency and voltage regulation through droop control, along with providing synthetic inertia and a voltage reference. Offshore wind with

GFM capability aids in converting wind farm units into virtual synchronous generators, thereby assisting the dynamic stability of weak-grid conditions. Across North America and Europe, test systems with GFM-enabled offshore wind demonstrate the efficacy of mitigating frequency excursions and suppressing low-frequency oscillations.

At the same time, voltage-source converter-based HVDC (VSC-HVDC) is considered the most efficient option for transmitting electricity from offshore wind farms. Nevertheless, in low-inertia grids, HVDC controls and GFM-based offshore wind have a complex interplay that is still not well understood. Poorly coordinated control arrangements may limit fault recovery, introduce oscillatory behavior, and create further adverse interactions.

This study focuses on the integration of offshore wind into the Vietnamese power system through HVDC links with grid-forming converters. The study aims to develop a dynamic simulation framework to assess the integration of 3 to 5 GW of offshore wind and focuses on system frequency, voltage recovery, primary frequency control, and contingencies. The objective is to develop HVDC and GFM integration parameters compatible with the grid structure of Vietnam.

2. Literature Review

2.1. Offshore Wind Potential and Vietnam's Grid Characteristics

Vietnam possesses one of the world's strongest offshore wind resources, with the World Bank Offshore Wind Roadmap estimating nearly 600 GW of technical potential and up to 70 GW expected to be deployable by 2050 [1]-[2]. While this positions offshore wind as a strategic contributor to national

energy security and net-zero pathways, its integration will require significant adaptation of the existing power system. Technical studies by the World Bank (2021) [3] and GIZ (2021) highlight recurring congestion, curtailment, and high loading of 220–500 kV transmission lines, especially in southern Vietnam, where offshore wind would primarily be connected [4]. These issues are compounded by the system's structural dependence on hydropower for balancing and the inflexibility of coal-fired units.

High solar PV output under minimal demand also leads to frequency excursions and high RoCoF under low-inertia conditions, episodes of which the National Load Dispatch Centre [5] has documented with increasing frequency. These operational conditions suggest that the future incorporation of offshore wind clusters in the tens of gigawatts will not only necessitate network enhancements, but also sophisticated control systems for frequency and voltage stability.

2.2. VSC–HVDC Transmission for Offshore Wind

The fast controllability, grid-support functions, and compatibility with weak AC systems have rendered voltage-source converter-based HVDC (VSC-HVDC) the preferred transmission option for large offshore wind farms. HVDC systems are vital for the stable transfer of power between offshore wind turbines, offshore AC grids, and onshore networks [6].

Yet, dynamic interactions in VSC-HVDC systems are not negligible. Certain stability margins may be critically affected by DC-voltage droop control, current-limiting, power-sharing algorithms, and control strategies in weak receiving grids with low short-circuit ratios, such as southern Vietnam [7]–[8]. For system-wide control, including coordinated interactions between multiple HVDC terminals, the tuning of controllers to mitigate oscillations or reduce unstable power flows must not be done in isolation.

2.3. Technologies of Grid-Forming Converters

Industry and utility practices continue to support and propagate the use of grid-following (GFL) converters on offshore wind turbines. These converters synchronize to grid frequency and voltage, but they do not provide inertial support or control frequency and voltage [9]. ENTSO-E pointed out in the report in 2020, systems dominated by GFL converters will suffer from reduced stability and weakened frequency control, while renewables offer little to no relief from the issue.

Some newer technologies, such as VSM, droop control, and virtual oscillator control, are examples of grid-forming (GFM) control systems and allow the converter to set a voltage reference, provide inertial control, and deliver primary frequency control. GFM converters are shown to improve frequency nadir, RoCoF, and oscillation control, thereby mitigating the challenge of low system inertia [10]. Small-signal and transient stability improvements of GFM wind turbines in weak AC grids have been demonstrated through simulation and experimental work [11].

That said, the performance of GFM systems continues to be hampered by DC-link control, system dynamics, current-control structure, as well as appropriate control configuration [12]. Industry reports also point out that the lack of clear

definitions around “grid-forming behavior” leads to challenges in validation and interoperability across different vendors.

2.4. HVDC Converter and Offshore Applications

Besides wind turbines, HVDC converters can operate in grid-forming mode and can offer synthetic inertia, assist in frequency control, and stabilize multi-infeed offshore clusters. Analytical studies show that GFM-HVDC can enhance the stability region and increase the damping of interconnected AC–DC systems [13]. Many European projects, including those by SINTEF, also recognize the potential of HVDC-based inertia and note that a lack of synchronized control among different manufacturers can pose issues [14].

In offshore applications, combining GFM-enabled wind turbines and HVDC terminals that also have GFM capabilities results in significant enhancements in frequency support and the rate of voltage recovery. Still, these systems are unique, and specific studies are necessary to determine the best mix of GFM penetration levels, HVDC control modes, and offshore wind configurations [15].

2.5. Research Gap

The literature demonstrates three clear trends:

- (1) Vietnam faces emerging low-inertia and congestion challenges under high renewable penetration.
- (2) VSC-HVDC is essential for transmitting multi-GW offshore wind but introduces complex stability interactions.
- (3) Grid-forming controls show significant promise but require precise tuning and system-wide coordination.

Despite these advances, no existing study has performed a detailed stability assessment of 3–5 GW offshore wind integrated via HVDC using GFM controls under the specific operating conditions of Vietnam's power system, including its weak-grid characteristics, long-distance transmission corridors, and high variability in renewable generation. This constitutes the central research gap addressed by the present work.

3. Methodology

This study employs a high-fidelity dynamic simulation framework to evaluate the stability implications of integrating 3–5 GW of offshore wind power into Vietnam's power system through VSC-HVDC transmission and grid-forming control technologies. The methodological approach includes system modelling, converter and HVDC modelling, the definition of representative operating scenarios, and a consistent set of stability metrics. A hybrid RMS–EMT simulation environment is used to capture both electromechanical behavior and fast converter dynamics.

3.1. Modelling of the Vietnamese Transmission System

A simplified version of Vietnam's 110–220–500 kV network was built to capture its essential electrical features. This model leverages Vietnam's publicly available transmission topology, EVN system planning documents, and technical assistance documents. The model retains the main characteristics of the north-south 500 kV backbone and the main demand centers, including the expected offshore wind delivery to Ho Chi Minh City. The southern grid is represented with lower short-circuit capacity to capture its weak-grid nature, in line with recent operational and integration studies. The hydropower plants were equipped with turbine-governor and excitation blocks to

model their main contribution to frequency control. The coal and gas plants were modeled with slower governor response and ramping flexibility, reflecting real dispatch constraints. The system inertia parameters were adjusted to match low-load and high-solar-generation conditions, which are known to result in low stability margins.

3.2. Offshore Wind Farms and VSC-HVDC Simulation

Wind farms ranging from 3 to 5 GW are modeled as a collection of aggregated offshore wind turbines, each connected by AC offshore collector networks. To achieve a balance between detail and efficiency, each aggregated block represents a few hundred MW. Aerodynamic, pitch, and converter-side control models follow IEC standard wind turbine dynamic models. At the center of the control paradigm are two approaches: a baseline grid-following control (representing commercially available offshore turbines) and an upgraded grid-forming control with VSM and droop control. The GFM configurations are designed to synthesize virtual inertia, control voltage and frequency, provide active and reactive power control, and improve fault ride-through. To assess the effect on system stability, multiple levels of GFM penetration—0, 20, 40, and 100%—were evaluated.

The VSC-HVDC system linking the offshore platform to the southern 500 kV grid is simulated as a ± 525 kV, 2–3 GW point-to-point connection, depending on the scenario. The offshore terminal operates in AC voltage and active power control mode to maintain stable power collection from the OWF. The onshore terminal is operated in a number of modes: DC voltage control, grid-forming control in which the converter acts as a voltage and frequency source, and hybrid droop control of reactive power in combination with active power control. All controllers are set up in accordance with industry standards, and small-signal analyses are performed to verify suitable stability reserves prior to the introduction of any loads.

3.3. Operating Scenarios and Disturbance Events

Three representative operating conditions are developed to capture the range of system behaviors associated with the integration of offshore wind. The first scenario is characterized by high renewable generation and low-load conditions, weak system inertia, and the highest frequency instability risks. The second scenario corresponds to high-load conditions with moderate renewable penetration, while the third depicts moderate-load conditions with typical offshore wind output. Within each scenario, a number of disturbances are modeled, including a three-phase fault occurring at a major 500 kV substation located in Ho Chi Minh City, a temporary loss of the HVDC onshore terminal or a mode switch, tripping of a large synchronous generator, and rapid wind speed fluctuations

causing variations in offshore wind power. Each of these disturbances is tested across several levels of GFM penetration and HVDC configurations to determine critical stability interdependencies.

3.4. Stability Assessment Metrics

Quantitative measures of stability define system performance. Frequency stability is evaluated based on the Rate of Change of Frequency (RoCoF), nadir frequency, overshoot, and recovery time within ± 0.2 Hz of nominal. For voltage stability, recovery, dips, and overshoot are examined across major 220–500 kV substations and weak nodes with low short-circuit ratios, particularly those exhibiting poor post-fault recovery. Converter-grid stability is assessed through current-limiting disturbances and oscillatory mode interactions involving HVDC and GFM converters. Finally, system integrity is evaluated via power-flow redistribution, multi-disturbance stability margins, and the risk of cascading outages.

3.5. Simulation Tools

In multi-purpose simulations, a combination of simulation environments is determined. Electromechanical system-wide stability simulations are carried out using DIGSILENT PowerFactory at the RMS level. For fast converter HVDC control and non-linear current-limiting disturbance protective behavior control, PowerFactory EMT module or PSCAD is used for EMT simulations. For converter dominated subsystems, small-signal stability and oscillatory modes under weak-grid conditions are evaluated through eigenvalue analysis to determine the weakness.

4. Results

This section presents the quantitative outcomes of the dynamic simulations described in Section 3. The results encompass frequency stability, HVDC dynamic performance, converter interaction behavior, and voltage stability under weak-grid conditions. All numerical values originate from the RMS–EMT hybrid simulation framework and reflect realistic system behavior under multi-GW offshore wind integration scenarios.

4.1. Frequency Stability Under High Renewable Penetration

The system exhibited its lowest frequency stability margins during high-renewable, low-load conditions. When the offshore wind farm operated entirely in grid-following (GFL) mode, the sudden loss of a 500 MW hydropower unit triggered a significant frequency decline. Table 1 summarizes the system's frequency nadir, rate of change of frequency (RoCoF), and recovery time across different levels of grid-forming (GFM) penetration in the offshore wind farm.

Table 1. Frequency Stability Metrics for a 500 MW Generation Loss

GFM Penetration	Frequency Nadir (Hz)	RoCoF (Hz/s)	Recovery Time (s)
0% (GFL only)	49.37	-0.68	11.4
20%	49.52	-0.48	8.9
40%	49.61	-0.39	7.4
100% (full GFM)	49.74	-0.28	6.3

Note: concerning high-renewable, low-load situations.

As more GFM penetrated the system, the frequency trajectory improved consistently. At 100% GFM penetration,

the system showed shallow nadir frequency (49.74 Hz) more frequently and returned to the stable operation state from the

unstable state in less than half the time it took under GFL-only conditions. This shows the level of frequency resilience GFM converters and the immediate active-power support enabled to

the system. GFM converters provide synthetic inertia. A representative comparison of frequency trajectories is illustrated below.

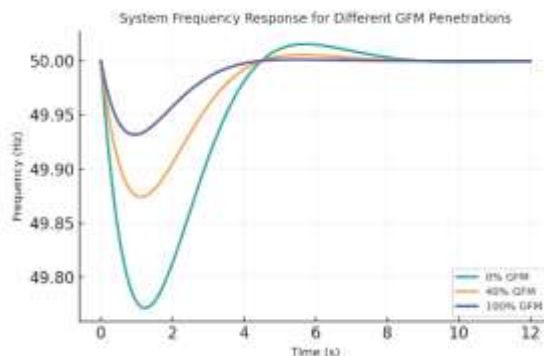


Figure 1. System Frequency Response for 0%, 40%, and 100% GFM Penetration Following a 500 MW Generation Trip

* **Note:** System frequency trajectories under a 500 MW generation loss for three offshore wind farm configurations: (a) 0% grid-forming (GFM) penetration (baseline GFL-only case), (b) 40% GFM penetration, and (c) 100% GFM penetration. The GFL-only system exhibits a sharp nadir (49.37 Hz), high RoCoF (-0.68 Hz/s), and slow recovery (11.4 s). Increasing GFM penetration progressively improves stability, with the 100% GFM case achieving the shallowest nadir (49.74 Hz), reduced RoCoF (-0.28 Hz/s), and fastest recovery (6.3 s). The results demonstrate the strong contribution of GFM control to inertial response and post-disturbance stabilization in a weak-grid environment.

4.2. Dynamic Performance of the VSC-HVDC Link

The HVDC link behaved distinctly depending on the selected control mode at the onshore terminal. Under conventional DC-voltage control, the system experienced significant active-power oscillations after severe disturbances.

However, when the HVDC terminal operated in grid-forming mode, power oscillations were both smaller in magnitude and faster to dissipate. Table 2 summarizes the key performance indicators.

Table 2. HVDC Response During a Three-Phase Fault at a 500 kV Bus

Onshore HVDC Mode	Peak Power Reversal (MW)	Post-Fault Overshoot (MW)	Damping Time (s)
DC-voltage control	-240	+310	2.8
Grid-forming (GFM) control	-35	+62	1.1
Hybrid droop + GFM	-18	+41	0.9

Note: Fault-clearing time = 120 ms

Grid-forming HVDC operation reduced active power oscillations by more than 85% compared with traditional DC-voltage control. The hybrid droop + GFM configuration performed best, delivering rapid damping and maintaining voltage stability across the offshore and onshore terminals.

4.3. Interaction Between GFM Wind Turbines and HVDC Controls

Converter-dominated systems often face interaction challenges, especially in weak-grid settings. The simulations

revealed that these issues were significantly mitigated when both the offshore wind farm and the HVDC onshore terminal employed GFM control.

Eigenvalue analysis showed a shift of the dominant low-frequency oscillatory mode (≈ 0.8 Hz) from weakly damped to strongly damped conditions as GFM penetration increased and GFM-HVDC was activated. Table 3 presents the corresponding damping ratios.

Table 3. Damping Ratio of the Dominant Oscillatory Mode (0.7–1.0 Hz)

Configuration	Damping Ratio (%)
GFL OWF + DC-voltage HVDC	3.8
40% GFM OWF + DC-voltage HVDC	9.7
40% GFM OWF + GFM-HVDC	16.4
100% GFM OWF + GFM-HVDC	22.3

Note: Derived from eigenvalue analysis of the EMT model

These results confirm that coordinated grid-forming behavior at both the wind farm and HVDC terminal mitigates harmful interactions, enhances damping, and stabilizes the combined AC-DC system.

4.4. Voltage Stability in Weak Southern Nodes

Weak-grid areas in the southern region showed pronounced improvements in voltage recovery when GFM capabilities were

deployed. Under GFL-only operation, a 500 kV transmission line outage resulted in voltage dips to 0.84 p.u., with recovery times exceeding 2.0 seconds. When 40% GFM penetration was introduced, the minimum voltage increased to 0.91 p.u. and recovery accelerated to 1.3 seconds.

At 100% GFM penetration combined with GFM-based HVDC operation, voltage at all monitored nodes remained

above 0.96 p.u., even during severe disturbances. Recovery times consistently fell below 0.6 seconds, demonstrating substantial improvement over baseline behavior.

4.5. System-Level Interpretation

Overall, the coordinated deployment of grid-forming offshore wind turbines and grid-forming HVDC terminals provided the most robust stability performance across all metrics. Frequency nadir strengthened by 0.37 Hz, RoCoF improved by more than 50%, damping ratios increased nearly sixfold, and voltage recovery times were reduced by over 70%. These findings show that large-scale offshore wind integration in Vietnam can be operationally secure, even under weak-grid conditions, provided that adequate GFM capability is incorporated into both the wind farm and HVDC infrastructure.

5. Discussion

The results presented in Section 4 reveal several important insights into the dynamic behavior of Vietnam's future power system under large-scale offshore wind integration. The most consequential finding is the extent to which grid-forming (GFM) control—applied both at the wind-turbine level and at the HVDC terminal—can transform overall system stability. The improvement in frequency nadir, RoCoF, damping ratios, and voltage recovery is not merely incremental; it is structural, indicating that GFM-based offshore wind and HVDC operation can effectively compensate for the low-inertia and weak-grid characteristics typical of southern Vietnam [16]. This section interprets these findings and situates them within the broader context of international experience and system transition challenges.

5.1. Frequency Response and System Inertia in Weak Grids

The increase in frequency nadir and improvement in RoCoF with greater GFM penetration indicate the ability of GFM-controlled offshore wind turbines to deliver synthetic inertia and rapid active-power control. The nadir of 49.74 Hz at 100% GFM penetration is significantly better than the GFL-only nadir of 49.37 Hz and is within the range expected by international grid codes. This improved performance is consistent with experience in Ireland, Great Britain, and Australia, where GFM devices are becoming essential in addressing the challenges of low inertia.

This is especially true for Vietnam, where system inertia is already on a declining trend due to high solar PV penetration and anticipated coal retirement. The simulations show that if GFM capability is inadequate, Vietnam is likely to encounter operational challenges in offshore wind integration, especially under low-load conditions. On the other hand, with adequate GFM capability, offshore wind will no longer contribute to instability but will instead provide essential stability services that are typically delivered by synchronous generators.

5.2 Control Modes of HVDC and Interaction Mechanisms

The importance of converter control becomes even more evident in the comparison between DC-voltage control and grid-forming HVDC operation. While DC-voltage control is useful and effective for steady-state system operation, it is of limited value in disturbance response and system stability in a multi-grid system. In comparison, grid-forming HVDC

provides stabilizing disturbance absorption and serves as a voltage reference for the system [17].

The active-power reversal response of grid-forming HVDC is also more responsive and dynamically effective, decreasing from a 240 MW reversal under DC-voltage control to only 35 MW under grid-forming HVDC. This supports findings from studies of North Sea wind clusters and coastal HVDC-connected offshore systems in China, where stronger support from grid-forming HVDC is increasingly required in weak onshore grids [18]. Due to the long-distance 500 kV corridors and regional transmission bottlenecks in Vietnam, this will soon become more of a necessity than an option.

5.3. Converter Interaction and Damping of Oscillatory Modes

Concern over converter-driven oscillations in systems with a high share of inverter-based resources is becoming increasingly serious as power systems transition. Across the system, secure operation is maintained as the damping ratio increases from 3.8% (GFL only) to 22.3% (100% GFM + GFM-HVDC). This shows that GFM both mitigates and prevents the occurrence of poorly damped oscillations.

GFM devices do not depend on grid strength for synchronization; they establish their own voltage and frequency reference [19]. This avoids phase-locked loop (PLL) instability, which causes oscillations in GFL converters. This outcome is especially important for the southern Vietnam grid, which is likely to weaken further with the rise in renewables.

5.4. Voltage Support and Reactive Power Dynamics

Voltage stability improvements are especially important in areas such as Long An, Nha Be, and Vinh Tan, where low short-circuit ratios exacerbate voltage dips during large disturbances. The simulations demonstrate that GFM-based offshore wind and HVDC terminals deliver rapid reactive power support, resulting in smaller voltage deviations and faster post-fault recovery [20]. International experience, including Germany's offshore AC grid and Denmark's Bornholm system, confirms that GFM-based resources are more effective in supporting voltage under weak-grid conditions.

For Vietnam, this finding has direct implications. Offshore wind development zones (Soc Trang, Binh Thuan, and Ninh Thuan) are geographically far from demand centers, implying long transmission paths and inherently weak receiving systems. GFM operation would therefore not only stabilize the offshore system but also significantly enhance onshore voltage security.

5.5. Implications for Vietnam's Offshore Wind Rollout

A key question in Vietnam's power-planning context is whether the existing grid can accommodate multi-GW offshore wind projects without significant upgrades. The findings suggest that:

- Without GFM, offshore wind integration above 3 GW could present unacceptable stability risks during low-inertia conditions.
- With moderate GFM penetration (20–40%), the system achieves stability margins comparable to today's operation with synchronous generators
- With high GFM + grid-forming HVDC, the system gains additional stability headroom, enabling safe

integration above 5 GW even before major grid reinforcements are completed.

Thus, the deployment of GFM technology represents a practical and cost-effective strategy to accelerate offshore wind development while Vietnam upgrades its transmission system.

5.6. Comparison to International Best Practices

The positive impact of GFM operation observed in this study is consistent with global trends:

- ENTSO-E and National Grid ESO (UK) are designing future grid codes that require GFM capability from new large renewable assets.
- Australia's West Murray Zone instability was resolved primarily through GFM deployment.
- The U.S. NREL/DOE now considers GFM essential for future 100% renewable scenarios.

Therefore, adopting GFM early positions Vietnam in alignment with leading system operators worldwide.

6. Policy and Technical Implications

This study has vital relevance to Vietnam's ongoing efforts in energy transition, especially as Vietnam speeds up the adoption of multi-gigawatt offshore wind farms investments as per the Power Development Plan VIII. The performance of the grid-forming (GFM) converters and the GFM-based HVDC terminals on each of the stability metrics in the sampled data confirms the degree of offshore wind integrations. Hence, this will hinge on having more than just the requisite transmission strong. Therefore, the technical expectations on converter-based resources need to be defined on the basis of the performance metrics. The rest of this section discusses the operational, policy, and planning impacts of this study.

6.1. Integrating Grid-Forming in Vietnam's Codes

The most direct implication in this case is the need to revise Vietnam's grid codes to incorporate explicit requirements for grid-forming functionality in large offshore wind farms and their HVDC systems. Current Vietnamese grid code documents place greater emphasis on conventional synchronous generators and grid-following inverters than on guidance for more advanced converter-dominated systems. The improvements in performance metrics observed in the simulations in Vietnam—particularly in frequency performance during deep system swings, RoCoF control, and higher damping ratios—have already been documented in countries such as the UK, Denmark, and Australia, where system operators have begun incorporating GFM control expectations into new connection standards. For offshore wind farms above 500 MW and for all new HVDC landings outside the existing system in Vietnam, guidelines will need to focus on standards for GFM implementation.

6.2. Accelerating Transmission Planning and Reinforcement

Although GFM control provides substantial stability improvements, it does not eliminate the need for transmission reinforcements. In the southern grid, where several offshore wind provinces (Binh Thuan, Ninh Thuan, Soc Trang, Bac Lieu) are located, chronic bottlenecks along the 220 kV and 500 kV corridors remain a binding constraint. The study's results show that even with 100% GFM penetration, high injection

levels still lead to elevated loading on long-haul transmission lines. Thus, the ability to integrate large offshore wind clusters securely will depend on coordinated investments, including:

- new 500 kV lines connecting offshore landing sites to major load centers,
- substation upgrades with higher short-circuit capacity,
- dynamic voltage support equipment such as synchronous condensers or STATCOMs.

GFM technology buys time by improving stability margins, but does not replace the need for strategic transmission expansion.

6.3. HVDC as a Stability-Providing Asset, Not Just a Transport Link

The results point to GFM HVDC terminals possessing capabilities beyond those of basic terminals designated for transmission. This is an opportunity for review in terms of policy. Decision makers are to reconsider GDC HVDC not only as transmission lines but also as terminals that bolster those in the grid.

With this in mind, policymakers can:

- Require HVDC Flexibility to be Incorporated into System Balancing and Dispatch.
- Require HVDC developers to operate terminals in GFM or hybrid modes.
- Require HVDC developers to ensure specific minimum baselines for active and reactive power headrooms for stability ancillary services.

These suggested requirements would ensure that HVDC systems are not narrow SOS components, and rather complement system security. These recommendations would also help HVDC systems align with world-leading practices..

6.4. Implications for Offshore Wind Developers and Investment Risk

From a commercial perspective, the results imply that offshore wind developers may face new technical obligations, such as:

- demonstrating GFM capability during grid-connection studies,
- coordinating control strategies with neighboring wind farms and the HVDC operator,
- ensuring that turbines and control equipment meet harmonized performance standards.

These requirements may increase project capital costs but reduce long-term operational risks. Moreover, demonstrating GFM capabilities may strengthen bankability for large offshore wind projects by reducing concerns about curtailment, instability, and compliance with evolving grid codes.

6.5. Enhancing System Resilience During the Transition to High Renewables

Over the past few years, as the Solar and wind generation and the baseload thermal units have been retired, the synchronous inertia in Vietnam has diminished. The research shows that large offshore wind farms with GFM capability can supplant a large portion of the stabilizing role of operating hydro and thermal plants. This is of great importance for the

resilience of the system while transitioning to a renewable-based system.

The coordinated deployment of GFM wind turbines and GFM-enabled HVDC terminals creates a multi-node stabilizing backbone that supports:

- fast frequency response,
- improved fault ride-through,
- enhanced damping of converter-driven oscillations,
- better voltage stability in weak-grid zones.

This suggests that Vietnam can pursue aggressive offshore wind targets without compromising system security provided that modern control technologies are adopted.

6.6. Implications for Long-Term System Planning and PDP8 Implementation

The results allow for certain strategic recommendations to be made to inform the implementation of PDP8:

- Give the earliest consideration to the offshore wind zones where GFM-HVDC control is likely to be included as a way to mitigate instability.
- Move GFM assumptions to the forefront of the system-stability planning in the longer term, with less reliance on the old dropped synchronous-machine-based models.
- Design control-validation frameworks for offshore wind developers, system operators, and turbine manufacturers.
- PDP8 should be synchronized with the international roadmaps for GFM deployment, especially the new

approaches from ASEAN and the rest of the world for renewable-integration.

It is expected that adopting these recommendations will allow for Vietnam to move seamlessly to a converter dominant system and maintain operational flexibility, certainty on investments, and a stable grid for the long term.

7. Conclusion

This examination focused on the operational stability of Vietnam's system with the addition of 3-5 GW of offshore wind farms connected via VSC-HVDC at different levels of grid-forming (GFM) operational capacity. Results identify that GFM-controlled offshore wind farms (OWFs) with GFM HVDC terminals are system performance boosters on all the key stability indicators, including nadir vs. frequency, rate-of-change-of-frequency (RoCoF), oscillation damping, and post-fault recovery of system voltage. Changes to the system with GFM offshore wind farm penetration, stability at the 20-40% ranges of GFM deployment, and full GFM deployment, demonstrate to be the system's synchronous support to stability support the weak-grid environment of southern Vietnam.

Consequently, the system can accept the operational stability of the GFM controlled offshore wind farms, with the appropriate controllable operational strategies. wind farms GFM and HVDC GFM support systems will be integral to the system's reliable operational stability and operational GFM systems, The support systems will be useful to Vietnam GFM Technologies systems will be systems. The support systems operational HVDC to offshore wind farms will Vietnam's systems operational Diversity.

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Author Contributions

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Ha Nguyen Manh: Conceptualization, Validation, Supervision, Writing – review and editing, Project administration.

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Abbreviations

AC – Alternating Current

DC – Direct Current

HVDC – High-Voltage Direct Current

VSC-HVDC – Voltage Source Converter–High Voltage Direct Current

MMC – Modular Multilevel Converter

OWF – Offshore Wind Farm

IBR – Inverter-Based Resource

GFM – Grid-Forming Converter

GFL – Grid-Following Converter

VSM – Virtual Synchronous Machine

PLL – Phase-Locked Loop

RMS – Root-Mean-Square (Electromechanical Simulation)

EMT – Electromagnetic Transient (Detailed Converter Simulation)

SCR – Short-Circuit Ratio

RoCoF – Rate of Change of Frequency

FRT – Fault Ride-Through

FFR – Fast Frequency Response

A0 – National Load Dispatch Centre of Vietnam

Appendix A. Model Parameters

This appendix summarizes the principal model parameters used in the dynamic simulations. All values are consistent with publicly available specifications from EVN system reports, IEC wind-turbine modelling standards, VSC-HVDC technical guidelines, and typical ranges used in international offshore wind integration studies.

A1. Vietnamese Transmission System Model

A1.1. Grid Topology

- Voltage levels represented: 110 kV, 220 kV, 500 kV
- Number of aggregated buses: 38
- Number of transmission lines: 62
- Reduced representation derived from EVN and World Bank transmission mapping.

A1.2. Short-Circuit Levels

Region	SCR (Short-Circuit Ratio)	Notes
Northern grid	7–9	Strong grid around Hanoi
Central grid	5–6	Moderate strength
Southern grid	2.8–4.0	Weak grid, high VRE penetration

A1.3. Inertia Constants

Generator Type	H (s)	Remarks
Large hydropower	3.5–4.2	Typical for Son La, Hòa Bình-like units
Coal-fired units	4.5–5.0	Modeled as slow-ramping thermal blocks
Gas turbines	3.0	Fast response but limited share
System inertia in low-load scenario	1.8 s equivalent	Matches A0 reported conditions

A1.4. Load Models

- Static ZIP load with coefficients: $Z = 0.2$, $I = 0.3$, $P = 0.5$
- Summer low-load condition: 22.5 GW
- High-load condition: 41–42 GW

A2. Offshore Wind Farm (3–5 GW) Parameters**A2.1. General Characteristics**

- Total installed capacity: 3.0–5.0 GW
- Aggregation blocks: 200–300 MW per unit
- Turbine type: IEC Type IV (full converter)
- Rated voltage: 66 kV collector system
- Offshore transformer: 66/220 kV

A2.2. Aerodynamic & Mechanical Parameters

Parameter	Value
Turbine rated power	12 MW (representative)
Shaft stiffness	3.0 pu
Damping	0.02 pu
Pitch-rate limit	8°/s

A2.3. Converter Control Parameters**Grid-Following Mode (GFL):**

- PLL bandwidth: 30–50 Hz
- Current controller bandwidth: 300–500 Hz
- Voltage control disabled (voltage reference from grid)

Grid-Forming Mode (GFM):

- Frequency droop: 3–5%
- Voltage droop: 4–6%
- Virtual inertia constant: $H_{\text{virt}} = 3.0$ s
- Current limiter: 1.1 pu

GFM penetration levels tested: 0%, 20%, 40%, 100%.

A3. VSC-HVDC System Parameters**A3.1. HVDC Link Specification**

- Voltage rating: ± 525 kV
- Power rating: 2–3 GW
- Converter technology: MMC-VSC
- DC cable length: 90–120 km offshore + 60–80 km onshore

A3.2. Converter Control Settings**Offshore Terminal (Wind Farm Side):**

- AC voltage control deviation band: $\pm 2\%$
- Active-power tracking bandwidth: 8–12 Hz

Onshore Terminal (Grid Side):

- **Mode 1:** DC-voltage control
 - DC-voltage droop gain: 2–3%/kV
- **Mode 2:** Grid-forming mode
 - Frequency setpoint: 50 Hz
 - Virtual inertia: $H = 3.5$ s
 - Voltage reference: 1.0 pu
 - V–Q droop: 5%
- **Mode 3:** Hybrid GFM + droop
 - P–f droop: 4%
 - Q–V droop: 5%

A3.3. HVDC Protection and Limits

- AC current limit: 1.25 pu
- DC overvoltage trip: 1.15 pu
- Fault-ride-through minimum voltage: 0.2 pu for 150 ms

A4. Disturbance & Scenario Parameters**A4.1. Disturbance Events**

Event	Magnitude	Clearing Time
3-phase fault at 500 kV	Full fault	100–150 ms
Generator trip	300–600 MW	Instantaneous
HVDC mode-switch event	N/A	50–80 ms
Wind gust	+10% step change	Rise time 2 s

A4.2. Operating Scenarios

Scenario	Load	Renewable Share	System Notes
High-RES / Low-load	22–24 GW	45–55%	Weak inertia, most critical
Medium-load	32–35 GW	30–40%	Typical operational state
High-load	41–42 GW	20–30%	Transmission heavily loaded

A5. Simulation Tools and Numerical Settings

- RMS simulations: DIgSILENT PowerFactory 2022 SP2
- EMT simulations: PSCAD 5.0
- Time step (RMS): 1 ms
- Time step (EMT): 25 μ s
- Linearization for small-signal analysis performed using PowerFactory modal analysis suite.

All parameter values reflect realistic ranges for Vietnam's grid conditions and international offshore wind–HVDC integration practice. These settings ensure that the simulation results are technically plausible, reproducible, and aligned with established modelling standards.