

Article

Negative Effect Analysis and Multi-Strategy Coordinated Oscillation Mitigation of Offshore Wind Power via a MMC-HVDC Transmission System

Zaide Xu ^{1,2}, Bingbing Shao ^{1,*} , Yang Yu ¹, Zheng Ni ¹, Liu Liu ² and Zilong Miao ¹¹ School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China² State Grid Jiangxi Electric Power Research Institute, Nanchang 330096, China

* Correspondence: 2021800094@hfut.edu.cn

Abstract

Modular multilevel converter-based high-voltage direct current (MMC-HVDC) transmission systems possess distinctive advantages such as massive transmission capacity and flexible control, making them increasingly popular for offshore wind power integration. However, offshore wind power via a MMC-HVDC transmission (OWPMMC-HVDC) system is highly susceptible to wideband oscillations caused by dynamic control interactions. Although traditional strategies can effectively mitigate oscillations within a specific frequency band, they frequently induce new oscillations in non-target bands—a phenomenon defined herein as the negative effect. To clarify the negative effect mechanism, this study first analyzes the impedance characteristics of the OWPMMC-HVDC system under traditional active and passive mitigation strategies. To reveal the damping drift characteristics across the full-frequency band, a multi-strategy coordinated oscillation mitigation approach based on the damping complementary principle is proposed. Finally, the effectiveness and superiority of the proposed coordinated oscillation mitigation strategy are verified through PSCAD/EMTDC electromagnetic transient simulations based on the 1100 MW/± 400 kV OWPMMC-HVDC system. The analysis results demonstrate that compared with the single-strategy approach, the proposed multi-strategy coordinated control successfully solves the negative effect issue. This comprehensively enhances wideband oscillation damping and the stable operation of the system, thus providing a robust oscillation mitigation strategy for practical engineering applications.

Keywords: MMC-HVDC; oscillation; negative effect; multi-strategy collaboration

Academic Editor: Shoji Nishikata

Received: 24 June 2026

Revised: 19 July 2026

Accepted: 20 July 2026

Published: 4 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Compared with the traditional high-voltage direct current based on line-commutated converter transmission technology (LCC-HVDC), the high-voltage direct current based on the modular multilevel converter (MMC-HVDC) transmission system has the characteristics of larger transmission capacity, longer transmission distance, more flexible control and lower loss, and it has been gradually popularized and applied in recent years [1–5]. However, with the development of the MMC-HVDC system, the stability issues have gradually become prominent, and certain offshore wind power via MMC-HVDC transmission (OWPMMC-HVDC) projects have experienced different oscillation phenomena during commissioning or operation. During the commissioning of the MMC-HVDC project in South Australia, there were sub-synchronous oscillation (SSO) phenomena on both the

AC and DC sides [6,7]. In 2013, the Borwin1 offshore wind power project in Germany experienced a medium-frequency oscillation of 250~350 Hz during operation, and the oscillation current exceeded 40% of the amplitude of the fundamental current, causing the filter capacitor of the offshore platform to burn and the system to be shut down for half a year [8]. In 2015, there was an oscillation of about 1.6 kHz during the operation of the Spanish–French cross-border interconnection flexible project [9]. In 2020, the Zhangbei MMC-HVDC project in China observed a high-frequency oscillation phenomenon of about 1500 Hz at the Kangbao Station, along with near-power-frequency sub-synchronous oscillations [10,11]. At the end of 2021, the Rudong OWPMHC-HVDC project experienced medium-frequency oscillations of 300~350 Hz [12] and high-frequency oscillations of 2 kHz [13].

Fundamentally, the oscillations in the OWPMHC-HVDC system are driven by insufficient system damping at specific oscillation frequencies. To address this, existing mitigation measures generally focus on optimizing controller parameters, adding passive devices, or introducing active damping controllers. Adjusting existing controller parameters or refining control architectures can reshape the impedance characteristics of both the wind turbines and the MMC-HVDC converter, thereby decoupling adverse dynamic interactions. Reference [14] improved AC voltage stability and mitigated oscillations by optimizing the current control and phase-locked loop (PLL) parameters of the wind turbine converter. Alternatively, installing passive devices at the point of common coupling (PCC) can effectively mitigate oscillations. These devices operate on the principle of passing fundamental power-frequency components while blocking oscillation components. As demonstrated in [15], a band-stop filter (BSF) presenting low impedance at the fundamental frequency and high impedance at the sub-synchronous frequency can effectively decouple the interaction between the wind farm and the grid. Similarly, reference [16] utilized a passive damping strategy to address stability issues caused by constant power loads, although its parameter design heavily relies on accurate system modeling and lacks robustness. When the effect of parameter optimization is limited, additional active damping controllers are often employed. References [17–19] indicate that incorporating supplementary damping loops into the machine-side or grid-side converters of wind turbines can effectively mitigate SSOs. However, in practical engineering applications, these traditional single-target mitigation strategies frequently induce other frequency band oscillations.

Reference [20] proposed a high-frequency oscillation mitigation method for MMC-HVDC systems based on nonlinear filtering in the voltage feedforward loop. This method can reshape the impedance characteristics of the MMC-HVDC system in the medium- and high-frequency bands, thereby achieving oscillation mitigation. However, the low-frequency damping characteristics of the MMC-HVDC system are not taken into account. References [21,22] studied the oscillation phenomena in the Luxi back-to-back HVDC project and proposed a mitigation method based on low-pass filtering in the voltage feedforward loop. Although this method can improve the negative damping characteristics of the MMC-HVDC system at high frequencies, it deteriorates the negative damping characteristics in the medium- and low-frequency bands, leading to oscillation shifting from high frequencies to medium- and low-frequencies. In practical engineering applications, these traditional single-target mitigation strategies frequently induce other frequency band oscillations. The Yu'e back-to-back MMC-HVDC transmission project incurred negative effect issues during the operation. A high-frequency oscillation at 1810 Hz was observed on one side of the converter station. While the implementation of a low-pass filter successfully eliminated the targeted 1810 Hz oscillation, it simultaneously excited a new oscillation of 700 Hz [20].

Although various oscillation mitigation strategies for the OWPMHC-HVDC system have been studied, most existing studies focus on single-strategy approaches designed for

specific target frequency bands. A major limitation of these traditional strategies is the lack of consideration for the negative effects, which induce oscillations in other frequency bands while mitigating a specific frequency band. In highly coupled power electronics-dominated power systems, the damping characteristics across different frequency bands are mutually constrained. While a single active or passive mitigation technique can effectively provide positive damping in the target band, it may reduce the damping margin in non-target frequency bands. This local impedance reshaping inevitably causes a cross-frequency band-damping drift, which can easily excite new oscillations in other frequency ranges. Since current research generally evaluates oscillation mitigation effectiveness without considering wideband interactions, this critical issue remains unresolved. Therefore, to effectively mitigate negative effects and guarantee wideband stability, it is urgent to propose an oscillation mitigation approach that considers full-frequency band damping characteristics.

In summary, although researchers have studied various oscillation mitigation strategies, most of them adopt a single mitigation method without fully considering the negative effects that may be caused by such measures. To address this issue, this paper proposes a multi-strategy coordinated wideband oscillation mitigation method based on the principle of damping complementarity. First, the damping drift law induced by conventional single-strategy mitigation methods across different frequency bands is revealed, and the negative effect mechanism is clearly defined. On this basis, a coordinated oscillation mitigation strategy that includes a virtual impedance control (VIC), BSF, and passive LC filter is proposed. Meanwhile, the feasibility of achieving damping enhancement over the full-frequency band with this coordinated strategy is demonstrated based on the impedance analysis. Finally, the electromagnetic transient simulations are carried out with the Rudong OWPMHC-HVDC project as a case study. The analysis results show that the proposed multi-strategy coordinated method not only eliminates the negative effects caused by single-strategy mitigation, but also significantly improves the system damping characteristics in the full-frequency band, demonstrating excellent engineering adaptability and robustness.

2. Topology and Control of OWPMHC-HVDC System

The OWPMHC-HVDC system topology in this study is based on the Jiangsu Rudong OWPMHC-HVDC project [23], as illustrated in Figure 1. The offshore wind farm (OWF) comprises many direct-drive permanent magnet synchronous generators (PMSGs) with the same structure and parameters. The generated electrical energy is transmitted via high-voltage alternating current (HVAC) submarine cables to the wind farm-side MMC (WFMMC) for AC/DC conversion. Subsequently, the power is transmitted through high-voltage DC submarine cables to the grid-side MMC (GSMMC) for DC/AC inversion, ultimately feeding into the onshore main grid. The OWPMHC-HVDC system possesses the rated transmission capacity of 1100 MW and operates at a rated DC voltage of ± 400 kV. Regarding the control architecture, the WFMMC operates in a constant AC voltage control mode to establish a stable offshore AC grid, while the GSMMC regulates the DC voltage. Furthermore, considering the relatively uniform distribution of offshore wind resources, the OWF cluster is simplified into a single-machine aggregated model. This equivalent aggregation accurately preserves the external dynamic characteristics of the OWF, while significantly alleviating computational burden and improving simulation efficiency [24]. The main electrical circuit parameters and control parameters of the system are shown in Table 1.

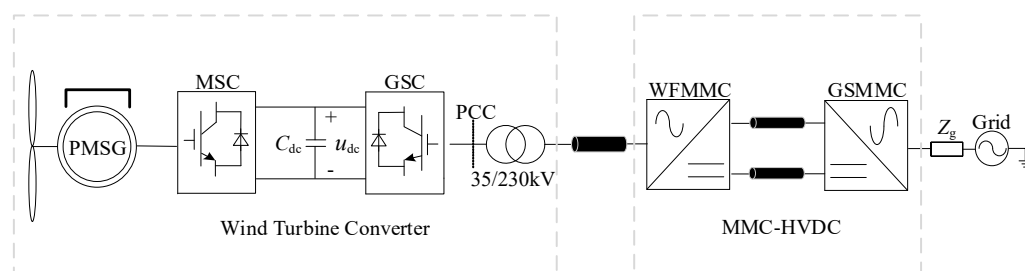


Figure 1. Topology structure of OWPMMC-HVDC system.

Table 1. OWPMMC-HVDC system parameter.

Section	Parameter	Value	Unit
PMSG	Rated power	2.5×440	MW
	Rated voltage	0.69	kV
	DC capacitor	15	mF
	Filter inductor	0.4	mH
	Filter capacitor	0.317	mF
WFMHC and GSMHC	AC voltage	416	kV
	Bridge arm reactance	133	mH
	Submodule rated voltage	2	kV
	Submodule capacitance	9000	μF
	Number of submodules	432	/
DC system	Resistance	0.07050	Ω/km
	Inductive reactance	0.20023	Ω/km
	Capacitive reactance	0.37012	Ω/km
	DC voltage	± 400	kV

The normal operation of an OWF relies on a stable AC power supply. Therefore, the WFMHC converter adopts constant AC voltage control to ensure that the voltage at the PCC remains constant. The GSMHC converter station adopts the closed-loop DC voltage control strategy to achieve system power balance and stable regulation of the DC voltage.

The PMSG includes a machine-side converter (MSC), a grid-side converter (GSC), and a DC link. The MSC utilizes the maximum power point tracking (MPPT) control strategy, thus dynamically adjusting the torque and speed set-points according to real-time wind-speed conditions. The GSC adopts a constant DC voltage control and enables flexible regulation of active and reactive power.

The WFMHC adopts a voltage and frequency control, and its control block diagram is shown in Figure 2. The GSMHC station adopts a constant DC voltage and reactive power control, and its control structure is illustrated in Figure 3. The phase angle θ at the PCC is tracked by the PLL and serves as the reference angle for the dual-loop control. The outer-loop control in the dq -axis regulates the DC voltage and reactive power at the PCC. The outputs of the outer-loop controllers serve as reference values for the inner-loop current controllers. The inner-loop current controllers output the reference wave for the converter modulation.

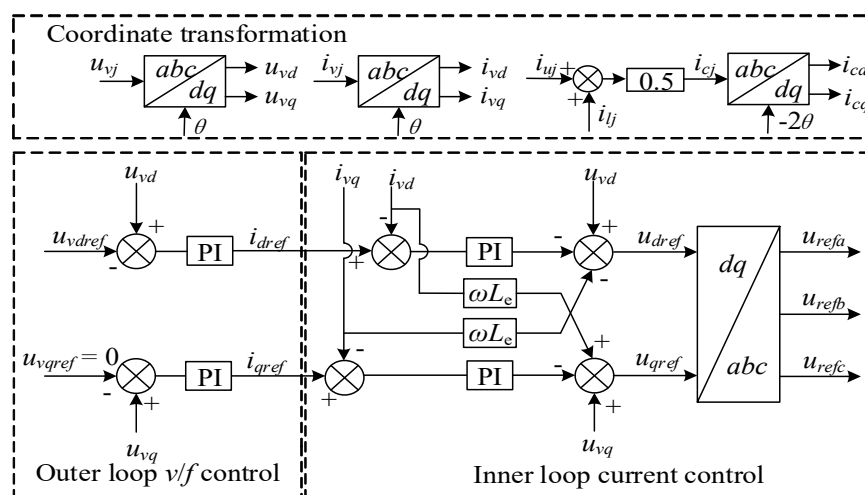


Figure 2. Control diagram of WFMMC.

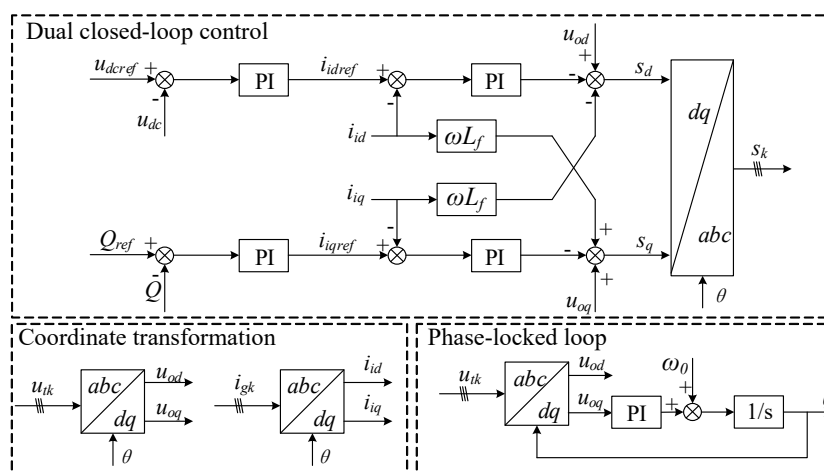


Figure 3. Control diagram of GSMHC.

Within this specific OWPMHC-HVDC topology, the underlying technical root of wideband stability issues lies in the impedance mismatch between the offshore WFMMC converters and the aggregated renewable energy generation source [25]. Specifically, the constant AC voltage control of the WFMMC, when coupled with the dynamics of the submarine cables and the PMSG controller, introduces negative resistance characteristics in specific frequency ranges. These multi-variable control interactions can excite sub-synchronous, medium-frequency, or high-frequency divergent oscillations under practical operational perturbations.

3. Negative Effect Analysis and Damping Reshaping in OWPMHC-HVDC Systems

3.1. Comparison of System Wideband Stability Before and After Applying BSF

Prior to practical commissioning, the OWPMHC-HVDC system must undergo rigorous validation across diverse operating conditions to guarantee comprehensive safety and dynamic stability. The BSF provides the distinct advantage of frequency-selective tunability, enabling the impedance reshaping of the WFMMC impedance within specific target frequency bands. Consequently, a BSF is incorporated into the WFMMC station to actively mitigate oscillations, as shown in Figure 4.

added VIC is shown in Figure 6. The control diagram of the virtual impedance mitigation strategy is shown in Figure 7.

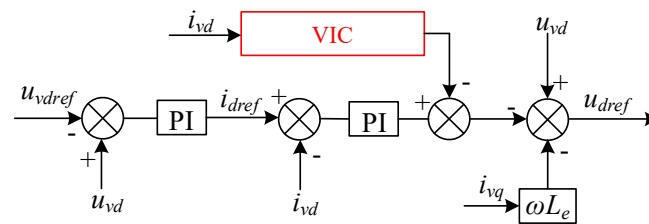


Figure 6. WFMCM converter station control model with an additional VIC.

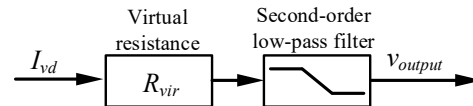


Figure 7. Control block diagram of the virtual impedance control.

As shown in Figure 7, a virtual resistance for active damping control is configured to enhance stability. The function of the virtual resistance is to alter the system impedance characteristics, thereby modifying its impedance magnitude–frequency profile. Consequently, the system oscillation frequency and damping are shifted. The transfer function of the VIC can be expressed as:

$$G_{\text{damr}}(s) = R_{\text{vir}} \frac{(2\pi f_c)^2}{s^2 + 2\zeta_c(2\pi f_c)s + (2\pi f_c)^2} \quad (2)$$

where R_{vir} represents the virtual resistance; f_c and ζ_c are the cutoff frequency and damping ratio of the second-order low-pass filter, respectively.

The VIC parameters are designed with a virtual resistance $R_{\text{vir}} = 0.42$ pu, a cutoff frequency $f_c = 200$ Hz and a damping ratio $\zeta_c = 0.707$ for the second-order low-pass filter. The impedance comparisons of the PMSG and WFMCM converter with and without the VIC are shown in Figure 8.

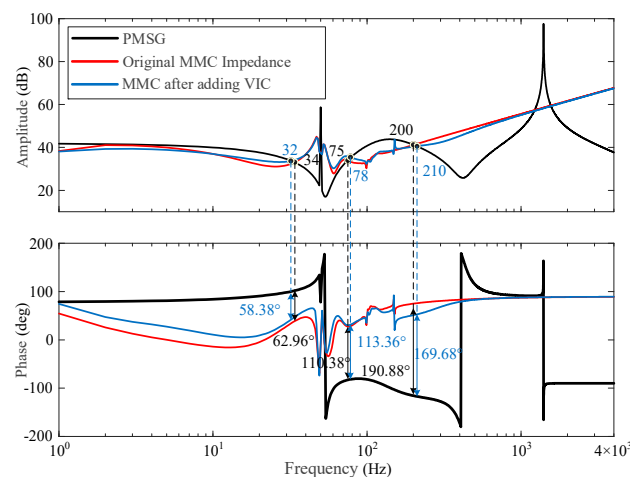


Figure 8. System impedance amplitude–frequency curve before and after adding VIC.

As shown in Figure 8, the sub-synchronous oscillation frequency decreases from 34 Hz to 32 Hz after applying VIC, and the phase margin increases from 117.04° to 121.62° . In the super-synchronous frequency band, the oscillation frequency increases from 75 Hz to 78 Hz, and the phase margin reduces from 69.62° to 66.64° . In the medium-frequency band, the 200 Hz oscillation with a negative phase margin of -10.88° shifts to 210 Hz oscillation

with a positive phase margin of 10.32° , indicating effective medium-frequency oscillation mitigation. The oscillation frequency and damping in the high-frequency band remain nearly unchanged. Overall, the VIC transfers the damping from the super-synchronous frequency band to the sub-synchronous and medium-frequency bands.

3.3. Comparison of System Wideband Stability Before and After Applying LC Filter

After adding the LC filter, the structure of the OWPMHC-HVDC system is shown in Figure 9.

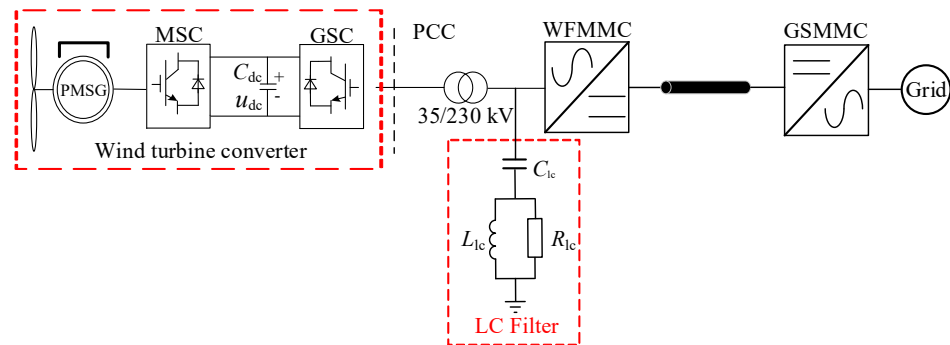


Figure 9. System structure diagram after applying a LC filter.

This section considers the method of connecting a parallel LC filter to the AC bus of OWPMHC-HVDC system, which aims to modify the impedance characteristics of the WFMMC station. The impedance expression of the LC filter is:

$$Z_{lc}(s) = \frac{1}{sC_{lc}} + \frac{sR_{lc}L_{lc}}{R_{lc} + sL_{lc}} \quad (3)$$

After adding the LC filter, the impedance of the WFMMC station is reshaped as follows:

$$Z_{MMC}^1 = Z_{MMC} \parallel Z_{lc} \quad (4)$$

where Z_{MMC} is the impedance of the WFMMC station, Z_{lc} is the impedance of the passive LC filter, and Z_{MMC}^1 is the impedance of the WFMMC station after impedance reshaping.

The LC filter parameters are designed with a filter resistance $R_{lc} = 58.6 \, \Omega$, a filter inductance $L_{lc} = 0.084 \, \text{H}$, and a filter capacitance $C_{lc} = 20.4 \, \mu\text{F}$. The impedance comparisons of the PMSG and WFMMC converter with and without the LC filter are shown in Figure 10.

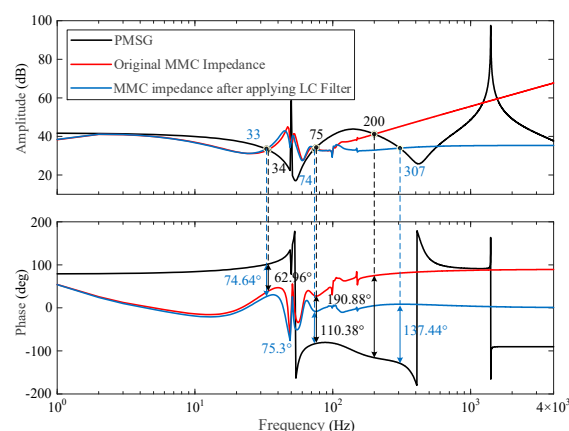


Figure 10. System impedance amplitude–frequency curve after adding a LC filter.

As shown in Figure 10, the sub-synchronous oscillation frequency decreases from 34 Hz to 33 Hz after applying LC filter, and the phase margin reduces from 117.04° to

105.36°. In the super-synchronous frequency band, the oscillation frequency decreases from 75 Hz to 74 Hz, and the phase margin increases from 69.62° to 104.7°. In the medium-frequency band, the 200 Hz oscillation with a negative phase margin of −10.88° shifts to 307 Hz oscillation with a positive phase margin of 42.56°, indicating effective mitigation of medium-frequency oscillations. Overall, the LC filter transfers the damping from the sub-synchronous frequency band to the super-synchronous and medium-frequency bands.

4. Multi-Strategy Coordinated Oscillation Mitigation Strategy

4.1. Coordinated Configuration Scheme

The analysis results in Section 3 show that incorporating the BSF transfers the damping from the sub-synchronous frequency band to the super-synchronous and medium-to-high frequency bands. After applying the BSF, the damping in the sub-synchronous frequency band reduces, while the damping in the super-synchronous and medium-to-high frequency bands increases. The VIC transfers the damping from the super-synchronous frequency band to the sub-synchronous and medium-frequency bands. After applying VIC, the damping in the sub-synchronous and medium-frequency bands increases, while the damping in the super-synchronous frequency band decreases. The LC filter transfers the damping from the sub-synchronous frequency band to the super-synchronous and medium-frequency bands, thus reducing sub-synchronous oscillation damping and increasing the damping in the other two frequency bands.

Based on the damping complementary principle across different frequency bands where the damping deterioration in a specific band caused by one mitigation strategy can be compensated by another strategy that improves the damping in that band, the multi-strategy coordinated oscillation mitigation strategy can be proposed for the OWPMMC-HVDC system. In this paper, two multi-strategy coordinated oscillation mitigation methods are proposed: VIC combined with BSF control, and VIC combined with BSF control and passive LC filter.

4.1.1. VIC Combined with BSF Control

The VIC parameters are set to $L_{vir} = 0.8$ and $f_n = 20$ Hz, and the BSF control parameters are set to $\zeta_{bf} = 0.707$ and $f_0 = 150$ Hz. The impedance comparisons of the PMSG and WFMMC converter with and without the coordinated control strategy are shown in Figure 11.

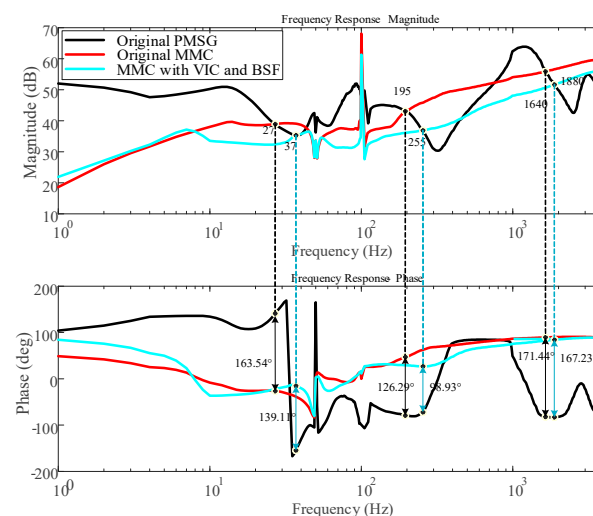


Figure 11. System impedance magnitude–frequency curve before and after simultaneously adding VIC and BSF.

As shown in Figure 11, in the low-frequency band (1 Hz–100 Hz), the oscillation frequency shifts from 27 Hz to 37 Hz after applying the coordinated control strategy, and the phase difference at the oscillation point changes from 163.54° to 139.11° , which means that the phase margin changes from 16.46° to 40.89° . Therefore, by applying the proposed coordinated control strategy, the low-frequency oscillation damping is enhanced. In the medium-frequency band (100 Hz–1000 Hz), the oscillation frequency shifts from 195 Hz to 255 Hz after applying the coordinated control strategy, and the phase difference at the oscillation point changes from 126.29° to 98.93° , which means that the phase margin changes from 53.71° to 81.07° . Therefore, by applying the proposed coordinated control strategy, the medium-frequency oscillation damping is enhanced. In the high-frequency band (1000 Hz–4000 Hz), the oscillation frequency shifts from 1640 Hz to 1880 Hz after applying the coordinated control strategy, and the phase difference at the oscillation point changes from 171.44° to 167.23° , which means that the phase margin changes from 8.56° to 12.77° . Therefore, by applying the proposed coordinated control strategy, the high-frequency oscillation damping is enhanced.

In conclusion, the combined implementation of VIC and BSF can achieve the damping enhancement across a wide frequency range in the OWPMMC-HVDC, which demonstrates that the synergy of the two mitigation strategies is effective.

4.1.2. VIC Combined with BSF Control and LC Filter

The VIC parameters are set as $L_{vir} = 0.8$ and $f_n = 20$ Hz; the BSF control parameters are set as $\xi_{bf} = 0.707$ and $f_0 = 150$ Hz; the passive LC filter parameters are set as $R_{lc} = 160 \Omega$, $L_{lc} = 42$ mH, and $C_{lc} = 0.72 \mu\text{F}$. The impedance comparisons of the PMSG and WPMVC converter with and without the coordinated control strategy are shown in Figure 12.

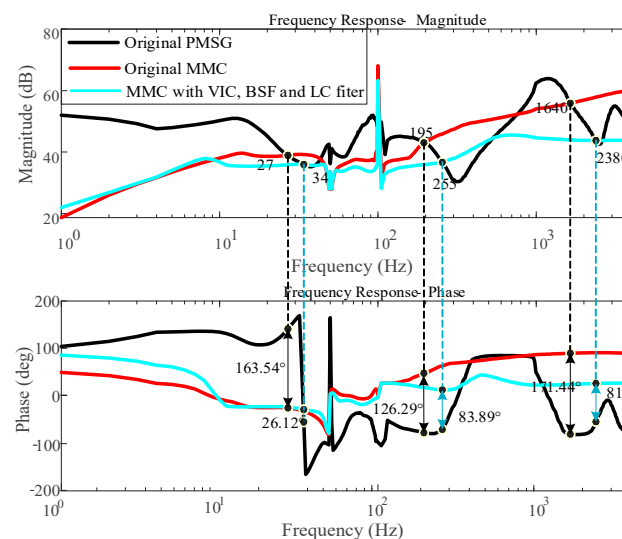


Figure 12. Frequency response curves of system impedance before and after simultaneously applying VIC, BSF, and LC filter.

As shown in Figure 12, in the low-frequency band (1 Hz–100 Hz), the oscillation frequency shifts from 27 Hz to 34 Hz after applying the coordinated control strategy, and the phase difference at the oscillation point changes from 163.54° to 26.12° , which means that the phase margin changes from 16.46° to 153.88° . Therefore, by applying the proposed coordinated control strategy, the low-frequency oscillation damping is enhanced. In the medium-frequency band (100 Hz–1000 Hz), the oscillation frequency shifts from 195 Hz to 255 Hz after applying the coordinated control strategy, and the phase difference at the oscillation point changes from 126.29° to 83.89° , which means that the phase margin

changes from 53.71° to 96.11° . Therefore, by applying the proposed coordinated control strategy, the medium-frequency oscillation damping is enhanced. In the high-frequency band (1000 Hz–4000 Hz), the oscillation frequency shifts from 1640 Hz to 2380 Hz after applying the coordinated control strategy, and the phase difference at the oscillation point changes from 171.44° to 81° , which means that the phase margin changes from 8.56° to 99° . Therefore, by applying the proposed coordinated control strategy, the high-frequency oscillation damping is enhanced.

In conclusion, the combined implementation of VIC, BSF and LC filter can achieve the damping enhancement across a wide frequency range in the OWPMHC-HVDC, which demonstrates that the synergy of the three mitigation strategies is effective. Meanwhile, it can be known from Figures 11 and 12 that the synergy of the three mitigation strategies performs better than the synergy of the two mitigation strategies.

4.2. Simulation of the Collaborative Configuration of Oscillation Suppression Strategies

In the PSCAD/EMTDC V5 simulation software, a simulation model of the OWPMHC-HVDC system is established. The proportional coefficient of the inner loop for d-axis AC voltage control of the WFMMC is changed from 5 to 0.55 at 1.5 s. At 2 s, two coordinated oscillation mitigation strategies in Sections 4.1.1 and 4.1.2 are respectively applied. The d-axis AC voltage waveforms of the WFMMC are shown in Figures 13 and 14.

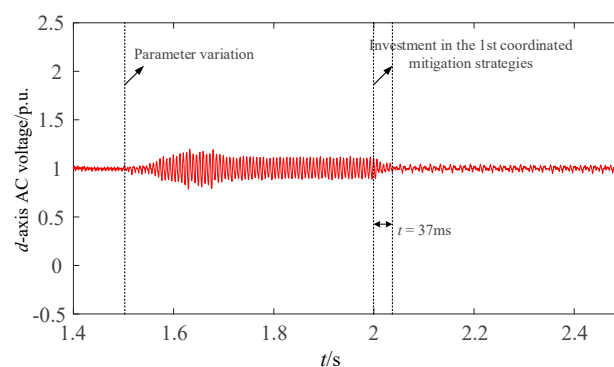


Figure 13. AC voltage waveform of the d-axis at the WFMMC after the implementation of the VIC combined with BSF control.

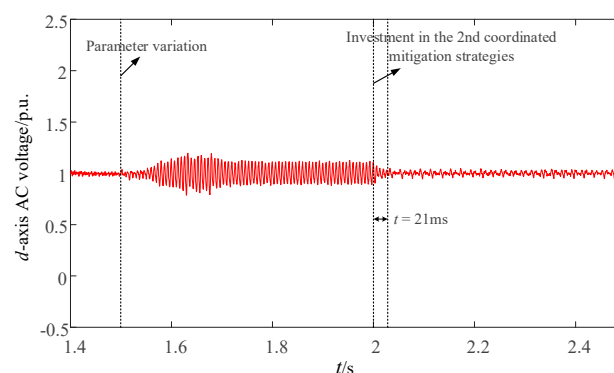


Figure 14. AC voltage waveform of the d-axis at the WFMMC after the implementation of the VIC combined with BSF control and LC filter.

As can be seen from Figures 13 and 14, after the parameter changes at 1.5 s, the d-axis AC voltage of the WFMMC exhibits diverging oscillations with a frequency of approximately 150 Hz. It can be known from Figure 13 that when both the VIC and BSF control are applied at 2 s, the time from oscillation decay to system stabilization is 37 ms. This verifies the effectiveness of the coordinated oscillation mitigation strategy

under the VIC and BSF control. In Figure 14, when the VIC, BSF, and passive LC filter are simultaneously applied at 2 s, the time from oscillation decay to system stabilization is 21 ms. This verifies the effectiveness of the coordinated oscillation mitigation strategy under the VIC, BSF, and passive LC filter. Table 2 summarizes the advantages, limitations, economic feasibility, and applications of existing oscillation mitigation strategies in comparison with the proposed synergetic framework.

Table 2. Comparison of different oscillation mitigation strategies.

Mitigation Strategy	Advantages	Limitations	Economic Feasibility	Applications
Passive filtering Devices	Clear physical meanings and intuitive mechanism	Large footprint and cost; prone to inducing negative effects in non-target bands	Poor	Medium- or high-frequency oscillations
Active damping control	Fast dynamic response; high control flexibility.	Easily triggers cross-frequency damping drift in complex systems	Good	Single resonance mode
VIC + BSF	No negative effect; broadens wideband damping margin	High-frequency damping enhancement is slight	Good	Engineering scenarios balancing low cost and wideband damping
VIC + BSF + LC	No negative effects; ultra-fast oscillation mitigation	Requires installation space for LC hardware	Poor	Large-scale offshore wind power projects demanding strong stability and robustness

5. Discussions

5.1. Negative Effects of the Single Oscillation Mitigation Strategy

Through frequency-domain impedance analysis, this paper confirms that in the OWPMHC-HVDC system, a single oscillation mitigation strategy easily disrupts the full-frequency band damping balance. Specifically, although the BSF mitigates the medium-frequency oscillations, it leads to the damping decrease in the sub-synchronous frequency band. The VIC can enhance sub-synchronous oscillation damping, but it triggers a negative effect of damping decrease in the super-synchronous frequency band. Similarly, the passive LC filter improves the medium-frequency oscillation damping while decreasing sub-synchronous oscillation damping. While facing the medium-frequency oscillations, the phase margin improvement of the passive strategies (especially the LC filter) is superior to that of the active strategies. These non-monotonic and cross-frequency drift phenomena during impedance reshaping fully demonstrate that a single strategy cannot achieve comprehensive stability improvement across wide-frequency band, which highlights the necessity of multi-strategy coordination.

5.2. Distinction of the Damping Complementary Principle from the Existing Literature

To further position the state-of-the-art of the proposed framework, it is critical to distinguish the damping complementary principle from conventional coordinated mitigation methods. Traditional methods focus on independent band allocation, assuming that the frequency response of an active damping loop does not conflict with a passive dampener. However, as demonstrated by the frequency-domain impedance analysis in Section 3, single-target strategies easily disrupt the full-frequency band damping. The core

scientific contribution of proposed damping complementary principle lies in treating the negative effects not as an unavoidable system constraint, but as a design degree-of-freedom for mutual cancelation. By utilizing the distinct damping transfer pathways of the VIC, BSF, and LC filter, the proposed framework establishes a synergetic multi-layered defense spectrum across the low-frequency, mid-frequency, and high-frequency ranges simultaneously. This systematic coordination completely avoids the risk of oscillation shifting commonly found in traditional single or simple additive mitigation methods.

5.3. Engineering Implementation and Practicality

While the proposed multi-strategy coordinated framework demonstrates superior wideband damping performance, its practical deployment in real-world offshore MMC-HVDC systems necessitates a thorough evaluation of engineering implementation aspects.

(1) **Parameter Tuning Procedure:** The tuning of the coordinated framework follows a systematic, constrained iterative approach. For the active VIC, the virtual inductance is determined through an iterative process to strictly satisfy a minimum phase margin of 30° for the interconnected system. For the passive LC filter, to prevent grid impact, the capacitance is designed to ensure that the reactive power compensation remains strictly below 5% of the rated system active power. Subsequently, the resistance and inductance are calculated by ensuring the reshaped AC impedance phase is confined within $[-90^\circ, 90^\circ]$, while constraining the active power loss to under 5%.

(2) **Controller Implementation Requirements:** In large-scale offshore wind power projects, modifying the control algorithms of hundreds of individual wind turbines involves extensive commissioning and high operational risks. To facilitate practical installation and debugging, the active mitigation strategies (VIC and BSF) are deployed centrally at the offshore MMC sending-end station.

(3) **Computational Complexity:** The active components of the coordinated strategy impose negligible computational burden. The VIC utilizes a second-order low-pass filter to eliminate high-frequency amplification, and the BSF is similarly implemented as a low-order digital filter. The discretized implementation of these transfer functions requires only basic arithmetic and delay operations, which can be effortlessly executed by commercial DSP or FPGA platforms typically equipped in modern MMC valves without requiring hardware processor upgrades.

(4) **Practical Deployment Challenges:** Real-world deployment dictates a trade-off between mitigation performance and physical constraints. The dual-strategy configuration (VIC + BSF) is highly advantageous as a software-only upgrade with zero physical footprint, making it ideal for offshore platforms where space and weight are strictly limited. Conversely, although the triple-strategy configuration (VIC + BSF + LC) achieves the fastest attenuation (decaying in 21 ms), its deployment is challenged by the extra capital expenditure, the physical space required for the LC hardware, and the minor steady-state active power dissipation introduced by the filtering resistance.

5.4. Limitations and Future Work

While the proposed multi-strategy coordinated framework successfully validates the damping complementary principle under standard operating profiles, its comprehensive deployment in complex industrial environments still presents certain limitations that require further investigation.

Firstly, the current study primarily focuses on revealing the fundamental mechanisms of wideband impedance reshaping and cross-frequency damping neutralization based on representative engineering parameters (e.g., the Rudong MMC-HVDC project). An exhaustive scalability analysis evaluating its applicability across diverse offshore wind farm

capacities, different MMC-HVDC topologies, and varied base-converter control structures has not been fully covered in this theoretical scope.

Secondly, in real-world offshore deployments, extreme non-ideal factors—such as severe weak-grid conditions (extremely low short-circuit ratios), discrete-time communication delays in the supplementary loops, signal-to-noise ratio degradation due to sensor measurement noise, and extreme wind power intermittency—may introduce un-modeled dynamics and phase-shift deviations. Exhaustively testing these multi-variable uncertainties, particularly those involving complex discrete-time hardware behaviors, exceeds the accurate evaluation boundaries of offline electromagnetic transient simulations. Therefore, immediate future work will focus on two main directions: conducting a generalized scalability analysis across diverse grid configurations and capacity ratios; and utilizing controller-hardware-in-the-loop experimental platforms to systematically evaluate the hardware-level robustness of the proposed framework against the aforementioned industrial disturbances, thereby bridging the gap between theoretical wideband damping control and ultimate industrial application.

6. Conclusions

This paper proposes a multi-strategy coordinated wideband oscillation mitigation strategy for the OWPMHC-HVDC system to address the negative effect issues of cross-frequency damping drift induced by traditional single-target strategies. With the impedance analysis, it is verified that relying on isolated active or passive mitigation measures inevitably disrupts the damping equilibrium across the broad frequency spectrum. By strategically coordinating active control algorithms, such as VIC, with passive hardware components, like LC filters, the proposed framework effectively compensates for the inherent damping deficiencies of individual methods. This active-passive coordinated configuration not only reduces the risk of exciting oscillations in non-target bands, but also comprehensively enhances system damping across the entire frequency range, delivering a highly robust and practical engineering solution for wideband stability.

Author Contributions: Conceptualization, Z.X., B.S. and Y.Y.; methodology, B.S., Y.Y. and Z.M.; software, L.L.; validation, Z.X.; formal analysis, Y.Y. and Z.M.; investigation, Z.N.; resources, Z.N.; data curation, Z.M. and L.L.; writing, B.S., Z.M. and Z.X.; visualization, Z.X.; supervision, Y.Y.; project administration, Z.M.; funding acquisition, Z.X. and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the State Grid Corporation of China Technology Project (B7182025Z044).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Zaide Xu and Liu Liu were employed by the company State Grid Jiangxi Electric Power Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from State Grid Corporation of China. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

References

1. Li, Q.; Yu, W.S.; Zhao, J.Y. Key technologies for the safe operation of wind and solar power generation equipment in support of the “peak CO₂ emissions and carbon neutrality” policy. *High Volt. Eng.* **2021**, *47*, 3047–3060.
2. Meng, W.; Le, X.; Lin, C. A study on the impact of wind farm spatial distribution on power system sub-synchronous oscillations. *IEEE Trans. Power Syst.* **2016**, *31*, 2154–2162. [[CrossRef](#)]

3. Li, X.Y.; Zeng, Q.; Wang, Y.H.; Zhang, Y.M. Control strategies of voltage source converter based direct current transmission system. *High Volt. Eng.* **2016**, *42*, 3025–3037.
4. Lei, Y.; Li, G.H.; Wang, W.S. Comparison of impedance characteristics and oscillation mechanism for grid following and grid forming renewable energy. *Proc. CSEE* **2025**, *45*, 150–163.
5. Lv, X.J.; Wang, J.L.; Zhang, Z.C.; Liu, Z.W.; Li, Z.X. Adaptive active inertia control strategy of MMC-HVDC systems for flexible frequency support. *Electronics* **2023**, *12*, 4288. [[CrossRef](#)]
6. Yin, C.; Xie, X.; Xu, S. Review of Oscillations in VSC-HVDC Systems Caused by Control Interactions. *J. Eng.* **2019**, *16*, 1204–1207.
7. Lv, J.; Dong, P.; Shi, G.; Cai, X.; Li, X.L. Subsynchronous oscillation and its mitigation of MMC-based HVDC with large doubly-fed induction generator-based wind farm integration. *Proc. CSEE* **2015**, *35*, 4852–4860.
8. Feng, J.J.; Zou, C.Y.; Yang, S.F.; Zhao, X.B.; Fu, C.; Li, Y.; Xu, S.K. Accurate impedance modeling and characteristic analysis of VSC-HVDC system for mid- and high-frequency resonance problems. *Proc. CSEE* **2020**, *40*, 4805–4820.
9. Saad, H.; Fillion, Y.; Deschanvres, S.; Vernay, Y.; Denetiere, S. On resonances and harmonics in HVDC-MMC station connected to AC grid. *IEEE Trans. Power Deliv.* **2017**, *32*, 1565–1573. [[CrossRef](#)]
10. Du, Z.Y.; Yang, Y.X.; Ji, K.; Zhou, X.; Hu, Y.H. High frequency harmonic resonance and suppression in Zhangbei project. *Power Syst. Technol.* **2022**, *46*, 3066–3075.
11. Ma, X.D.; Lu, Y.; Wang, N.N. Mechanism and mitigation strategy of near-power-frequency sub-subsynchronous oscillation in Zhangbei VSC-HVDC project. *Glob. Energy Interconnect.* **2025**, *8*, 489–496.
12. Gao, L.; Lv, J.; Cai, X. Analysis of mid-frequency oscillation characteristics in Rudong MMC-HVDC system for offshore wind farms. *Power Syst. Technol.* **2023**, *47*, 3495–3509.
13. Yuan, B.; Li, X.; Yin, C.Q.; Liu, R.T. Mechanism and suppression strategy of high-frequency oscillation caused by integration of islanded renewable energy station into MMC-HVDC system. *Autom. Electr. Power Syst.* **2023**, *47*, 133–141.
14. Liu, H.; Sun, J. Voltage stability and control of offshore wind farms with AC collection and HVDC transmission. *IEEE J. Emerg. Sel. Top. Power Electron.* **2014**, *2*, 1181–1189. [[CrossRef](#)]
15. Wang, S.; Xu, Z.; Wang, S. New findings on bypass damping filter in increasing subsynchronous resonance damping of series compensated system. *IET Gener. Transm. Distrib.* **2015**, *9*, 1718–1726. [[CrossRef](#)]
16. Cespedes, M.; Xing, L.; Sun, J. Constant-power load system stabilization by passive damping. *IEEE Trans. Power Electron.* **2011**, *26*, 1832–1836. [[CrossRef](#)]
17. Faried, S.; Unal, I.; Rai, D.; Mahseredjian, J. Utilizing DFIG-based wind farms for damping subsynchronous resonance in nearby turbine-generators. *IEEE Trans. Power Syst.* **2013**, *28*, 452–459. [[CrossRef](#)]
18. Maghsoud, M.; Javad, K.; Daryoosh, N. Sub-synchronous resonance damping via doubly fed induction generator. *Int. J. Electr. Power Energy Syst.* **2013**, *53*, 876–883. [[CrossRef](#)]
19. Zhang, Y.; Lin, W.X.; Deng, C.B.; Liu, H.J.; Liu, P.; Gao, T. Low-frequency oscillation mechanism and suppression strategy of Flexible HVDC transmission system. *Power Syst. Technol.* **2021**, *45*, 3134–3146.
20. Guo, X.S.; Liu, B.; Mei, H.M. Analysis and suppression of resonance between AC and DC systems in Chongqing-Hubei back-to-back HVDC project. *Autom. Electr. Power Syst.* **2020**, *44*, 157–164.
21. Guo, Q.; Guo, H.P.; Huang, L.B. Effect of grid voltage feedforward on VSC-HVDC stability in weak power grid. *Autom. Electr. Power Syst.* **2018**, *42*, 139–144.
22. Zou, C.; Rao, H.; Xu, S.; Li, Y.; Li, W.; Chen, J.; Zhao, X.; Yang, Y.; Lei, B. Analysis of resonance between a VSC-HVDC converter and the AC grid. *IEEE Trans. Power Electron.* **2018**, *33*, 10157–10168. [[CrossRef](#)]
23. Zeni, L.; Robert, E.; Spyridon, G. Power oscillation damping from VSC-HVDC connected offshore wind power plants. *IEEE Trans. Power Deliv.* **2016**, *31*, 829–838. [[CrossRef](#)]
24. Lv, J.; Cai, X.; Zhang, Z.K.; Chi, Y.N. Impedance modeling and stability analysis of MMC-based HVDC for offshore wind farms. *Proc. CSEE* **2016**, *36*, 3771–3781.
25. Wang, H.B.; Zhou, N.C.; Huang, P.; Duan, X.C.; Huang, R.L. Mechanism analysis and suppression strategy of continuous high-frequency oscillation in MMC-HVDC system. *Electronics* **2022**, *11*, 3555. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.