Wideband Oscillation Mitigation Using Adaptive New-Type Power System Stabilizers in Converter-Dominated Networks

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Abstract - Traditionally, **synchronous generators** use **Power System Stabilizers (PSSs)** to control and damp **low-frequency oscillations (LFOs)** caused by electromechanical interactions. However, as **modern power systems** increasingly rely on **converter-based technologies**, new types of oscillations known as **wideband oscillations (WBOs)** have become more common. These oscillations arise from the **interactions between converters and their control systems**, posing new stability challenges.

While conventional PSSs have been extensively studied and standardized for synchronous machines, **converter-based devices** lack equivalent stabilizing solutions. To address this gap, this paper introduces the concept of **New-Type Power System Stabilizers (NPSSs)**—control mechanisms designed specifically to mitigate **WBOs** in converter-dominated networks.

The study discusses **design principles**, **tuning methods**, and **implementation techniques** for NPSSs and explores their use not only in **inverter-based renewable sources** (such as Type-3 and Type-4 wind turbines) but also in other **converter-driven technologies** like **FACTS devices, HVDC systems, and battery energy storage inverters**. Several practical case studies are presented to demonstrate the effectiveness of NPSSs. Finally, the paper reviews **current challenges and research opportunities**, offering insights into **future development trends** for stabilizing modern converter-rich power grids.

***Key Words*:** Power System Stabilizer (PSS), New-Type Power System Stabilizer (NPSS), Synchronous Generator, Converter-Based Devices, Wideband Oscillations (WBOs), Low-Frequency Oscillations (LFOs), Converter-Dominated Power Systems, HVDC, FACTS Controllers, Battery Energy Storage, Wind Turbine Inverters, Reactive Power Control, System Stability, Oscillation Damping, Control Interaction.

1.INTRODUCTION

Modern power systems are rapidly evolving from traditional setups dominated by synchronous generators to advanced networks with a high share of power electronic converters across generation, transmission, distribution, and utilization levels. In conventional systems, oscillations mainly arise from the electromechanical dynamics of synchronous generators, causing local or interarea low-frequency oscillations (LFOs). However, in converter-dominated systems, the fast control actions and multiple dynamic time scales of converters have led to the emergence of electromagnetic wideband oscillations (WBOs) globally.

To address this, there is a growing need for **new-type power system stabilizers (NPSSs)**—analogous to classical PSSs but specifically designed for converter-based devices. These NPSSs can provide active damping to suppress WBOs across various operating conditions without affecting the converters' primary functions. Unlike traditional damping methods focused on local LCL resonance or harmonic issues, NPSSs target system-wide oscillations caused by converter-control interactions.

This paper first reviews classical PSS applications for damping LFOs and subsynchronous resonance (SSR) in synchronous generator-based systems. It then explores the challenges introduced by converter-based devices and the necessity of NPSSs. The proposed NPSS framework can be integrated into various converter-interfaced systems—such as type-3/4 wind turbines, PV inverters, SVCs, STATCOMs, BESS, and HVDC converters. The paper further presents NPSS design strategies, real-world applications, and implementation examples, along with a discussion of ongoing challenges and future research opportunities in this emerging area.

II. Problem Statement.

A.Power System Oscillations and System Stability

A power system inherently exhibits self-sustaining oscillations at its fundamental frequency, typically 50 or 60 Hz. However, various system dynamics—such as mechanical, electromagnetic, or coupled multi-time-scale interactions—can introduce oscillations at other frequencies, collectively known as **power system oscillations**. These oscillations can disrupt normal operation, compromise stability, affect power quality, and even threaten equipment safety.

Based on their frequency characteristics, power system oscillations are broadly divided into two categories:

1. **Power or fundamental frequency oscillations**, which are essential for the normal functioning of AC systems, and
2. **Non-power or non-fundamental frequency oscillations**, which must be suppressed to maintain system stability and are often treated as a stability concern.

From the perspective of dynamic interactions, non-fundamental oscillations can be further classified into:

- **Electromechanical oscillations**, typically arising from interactions involving synchronous machines, and
- **Electromagnetic oscillations**, primarily linked to converter-based systems such as Type-3 or Type-4 wind turbines.

Understanding the origins of these oscillations and developing effective mitigation strategies is a vital area of research to ensure the **safe, stable, and reliable operation** of modern power systems.

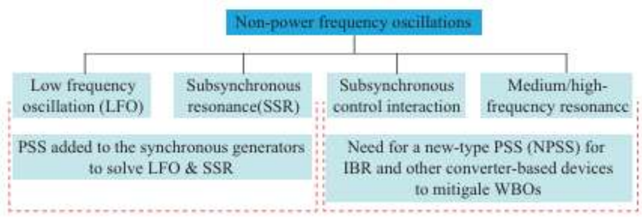

Fig. 1. Classification of power system oscillations.

B. Oscillation Associated with Synchronous Generators and the Role of Power System Stabilizers

1) Low-Frequency Oscillation (LFO)

Low-Frequency Oscillation (LFO) was first observed in 1964 during the early stages of the Western Power Grid interconnection project in the United States [3]. When the Northwest and Southwest grids were connected, continuous fluctuations in torque, speed, and output power were detected in several generating units, oscillating around 0.1 Hz. These oscillations posed a serious threat to the secure operation of the system. The frequency of LFOs is primarily determined by the inertia time constant and the equivalent stiffness coefficient of the system. Due to the large inertia of steam turbine generators, the oscillation frequency generally remains low—typically between 0.01 Hz and 2.5 Hz.

A cost-effective approach to suppressing LFOs is to enhance generator excitation systems through Power System Stabilizers (PSSs), which act as supplementary damping controllers [4]–[6]. Introduced in the 1970s, the PSS has become a standard control feature in synchronous generators, with well-established models such as PSS1A, PSS2B, PSS3B, and PSS4B [7].

Subsynchronous Resonance (SSR) or Subsynchronous Oscillation (SSO) arises due to mechanisms like Torsional Interaction (TI), the Induction Generator Effect (IGE), and Torque Amplification (TA). This phenomenon first gained attention in the 1970s after several SSR-related incidents were reported at the Navajo and San Juan power plants in the United States. With the growing adoption of series compensation and HVDC transmission systems in countries such as China, India, and Brazil, SSR/SSO issues re-emerged in the early 21st century, prompting extensive theoretical and practical research. The frequency of SSR/SSO typically lies between 10 Hz and 45 Hz, depending on system configuration, shaft dynamics of synchronous generators, and the degree of series compensation.

Since classical SSR/SSO phenomena are also linked to synchronous machines, they can be mitigated by modifying the excitation system of these generators [8]–[10]. Several standardized control strategies have been developed over time to effectively suppress SSR/SSO and enhance system stability.

C. Converter Associated Oscillations and Need for NPSS 1) Emerging Converter Control Interactions

Modern power systems are increasingly dominated by converter-based technologies, including inverter-based renewable resources such as wind and solar energy, as well as FACTS controllers, HVDC transmission systems, and battery energy storage systems (BESS). Due to their multi-time-scale dynamic behavior, these converter-based devices and their associated control systems often interact with one another and with traditional power system components. Such interactions have led to the emergence of electromagnetic oscillations, which have drawn significant global attention because of their potential to cause system instability or physical damage to power equipment.

These oscillations can grow rapidly, leading to instability or component failure. Their magnitude and frequency depend on several factors, including generation dispatch conditions, control parameters, and grid strength. Unlike subsynchronous resonance (SSR) or subsynchronous oscillations (SSO) found in systems dominated by synchronous machines, the oscillations observed in converter-based systems can occur across a wide frequency spectrum—from a few tenths of a hertz to several kilohertz.

Over the past decade, numerous oscillatory incidents have been reported across the world, such as in the ERCOT grid in Texas (USA), First Solar's plants in California, the Southeast and West Murray regions in Australia, Hornsea offshore wind farms in the UK, and China's Guyuan, Hami, NanAo, LuXi, and ZhangBei HVDC systems [1]. These events highlight the growing risk of oscillatory instability driven by control interactions among various power system components as the share of converter-based devices continues to rise.

Some of the major interaction mechanisms contributing to such instability include:

1. Interactions between type-3 wind turbines and series-compensated transmission networks.
2. Interactions between type-4 wind turbines and weak AC grids, where oscillations may propagate and excite torsional vibrations in nearby synchronous machines.
3. Interactions between photovoltaic (PV) plants and weak grids.
4. Interactions among type-3 wind farms and multi-terminal HVDC systems.
5. Control-based coupling between type-3/type-4 wind turbines and HVDC converters, often aggravated by control delays.

These wideband oscillations (WBOs) caused by converter control dynamics are fundamentally different from traditional low-frequency oscillations (LFOs) or SSR phenomena observed in synchronous generator systems. Consequently, the classical definition of power system stability has been expanded—now encompassing converter-driven stability and non-fundamental component stability as described in [11], [12]. Addressing this emerging oscillatory stability challenge is crucial for ensuring the secure and reliable operation of future power systems with high renewable and converter penetration.

2) Existing Mitigation Methods

Wideband oscillations (WBOs) pose a serious threat to the stability of modern converter-dominated power systems, creating an urgent need for the development of generalized and effective countermeasures to suppress them. Several mitigation strategies have been proposed in existing research, including retuning of control parameters, modification of converter control structures through the addition of supplementary damping lo

2. Body of Paper ops, integration of auxiliary control mechanisms in FACTS devices, and the use of specialized shunt current generators [13].

A number of studies have explored both generator-side and grid-side methods to alleviate WBO-related instability [13], [14]. For instance, a novel BESS/STATCOM configuration was introduced in [15] to enhance grid stiffness and effectively dampen subsynchronous oscillations (SSO) arising from interactions between type-4 wind farms and weak AC networks. Similarly, [16] examined how incorporating a feedforward voltage filter and a feedback current filter can improve the damping of high-frequency resonance (HFR) in modular multilevel converters (MMCs) connected to the grid. In [17], researchers proposed an additional voltage controller within the outer control loop of a VSC-HVDC system to mitigate HFR issues in both VSC-HVDC links and wind farm systems.

Despite these advancements, existing solutions are often case-specific and limited in general applicability. Therefore, there remains a strong need for systematic and universally applicable approaches to thoroughly understand, control, and suppress WBOs in complex converter-based power networks.

III. NEW-TYPE POWER SYSTEM STABILIZERS

A. Fundamental Principles

Just as conventional power system stabilizers (PSS) are designed to suppress low-frequency oscillations (LFOs) in synchronous generators, the wideband oscillations (WBOs) that occur in converter-based devices can also be effectively mitigated by integrating a new-type power system stabilizer (NPSS) within the device's control or excitation system. Incorporating NPSS enhances the damping characteristics within the oscillation frequency range of each converter unit, thereby improving the overall dynamic stability of the power grid. The primary objective is to achieve active damping of WBOs through an appropriately designed NPSS while ensuring the system retains sufficient control bandwidth and robustness margins for reliable operation.

B.Linear and Nonlinear NPSS

Just like traditional PSS used for synchronous generators, the new-type power system stabilizer (NPSS) for converter-based devices can be designed using either linear or nonlinear control techniques. Linear NPSS designs assume the system operates near a steady-state point, allowing small-signal linearization. Common linear approaches such as lead–lag, proportional-derivative (PD), linear quadratic regulator (LQR), and H-infinity control have been widely applied to suppress wideband oscillations.

Conversely, nonlinear NPSS designs consider the inherent nonlinear dynamics of the power system and may use techniques like feedback linearization or sliding mode control. While nonlinear controllers offer improved precision, they are generally more complex and computationally demanding.

In practical power converter applications, the industry tends to favor simpler linear control strategies (e.g., P, PI, PD, PID) due to their ease of implementation and stability. Adaptive features can also be integrated to handle the time-varying nature of wideband oscillations. Hence, this study focuses solely on linear NPSS design and its real-world implementations, and the term *NPSS* hereafter refers specifically to linear NPSS.

The design of a **linear NPSS** depends on several key factors, including the **primary control objectives**, the capabilities and control philosophies of the **converter-based devices**, the **control structure**, and the characteristics and mechanisms of the **wideband oscillations (WBOs)**.

A typical NPSS structure, illustrated in **Figure 2**, generally comprises four main modules:

1. **Prefiltering Module:** Cleans the input control signal by removing unwanted components, such as high-frequency noise or the fundamental frequency component.
2. **Cascaded Filtering Module:** Extracts the targeted oscillation mode. This usually involves multiple **band-stop filters** to suppress undesired modes and a **band-pass filter** to allow the target mode to pass.
3. **Control/Filtering Block:** Acts as a digital filter or controller to further process the input signal. Common implementations include **proportional-derivative controllers** or second-order **low-pass, band-pass, or band-stop filters**.
4. **Gain & Phase Shifting Block:** Compensates for gain and phase changes introduced by earlier modules, ensuring proper alignment and stability of the control action.

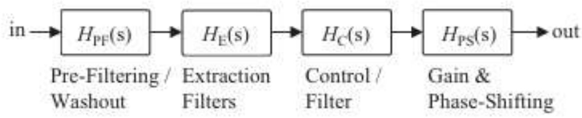

Fig. 2. General structure of a linear NPSS.

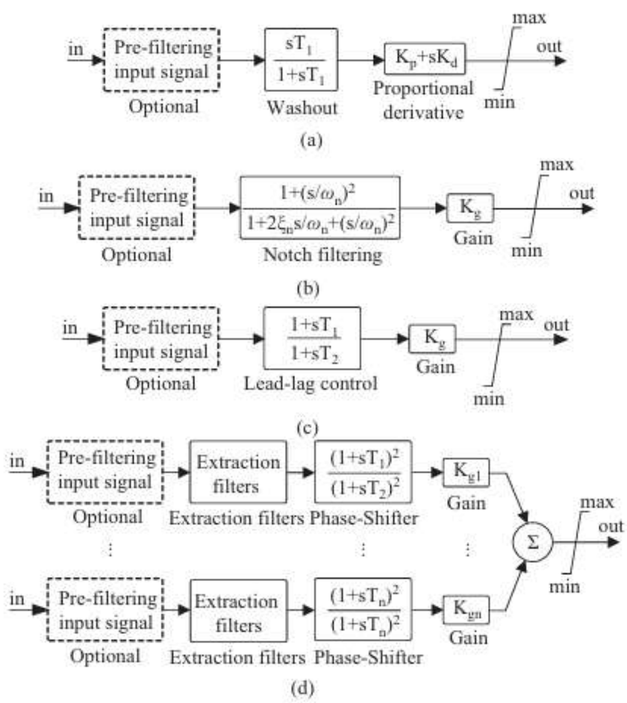

Fig. 3. Design structures of new-type power system stabilizer for converter-based devices. (a) NPSS-1. (b) NPSS-2. (c) NPSS-3-. (d) NPSS-4.

The **proportional-derivative (PD) module** provides the main control action, effectively processing and driving the input control signal. This design enhances the **overall stability** of the converter control system while **preserving the steady-state performance** of the system. The **input-to-output transfer function** of the NPSS-1 is expressed as follows:

$$H_{\text{NPSS-1}}(s) = \left(\frac{sT_w}{1+sT_w}\right)(K_p + sK_d) \tag{1}$$

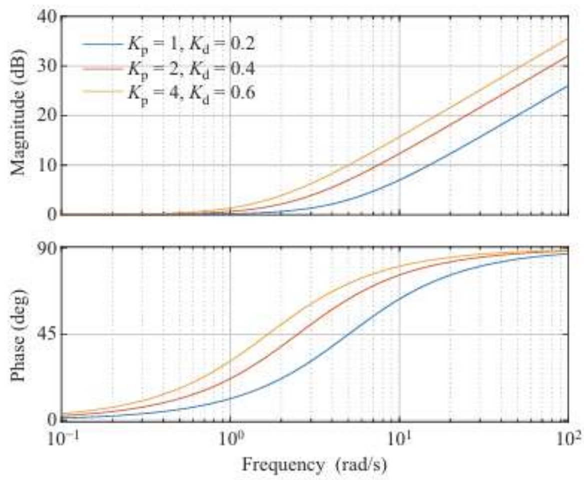

Fig. 4. Bode plots of NPSS-1 for different Kp and Kd values.

$$H_{\text{NPSS-2}}(s) = \frac{1+\left(\frac{s}{\omega_n}\right)^2}{1+2\zeta\left(\frac{s}{\omega_n}\right)+\left(\frac{s}{\omega_n}\right)^2} \tag{2}$$

In this context, ζ represents the **damping factor**, while **n** denotes the **natural frequency** of the notch filter, which is chosen based on the target oscillation frequency. The **depth** and **bandwidth** of the notch filter are determined by its damping factor and bandwidth settings. **Figure 5** illustrates the **Bode plots of NPSS-2** for oscillation frequencies of 40 Hz, 600 Hz, and 1200 Hz.

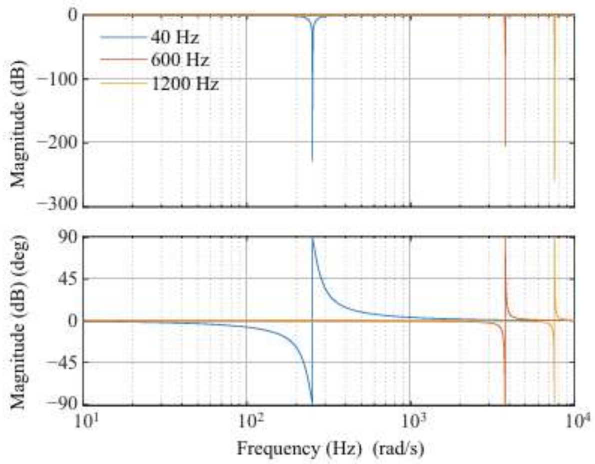

Fig. 5. Bode plots of NPSS-2 for different oscillation frequencies.

$$H_{\text{NPSS-3}}(s) = K_g \left(\frac{1 + sT_1}{1 + sT_2} \right)^n \tag{3}$$

The **order of cascading lead-lag blocks** determines the total phase lead or lag provided at the target frequency. The **time constants** set the amount of phase compensation, while the **order** specifies how many lead-lag elements are connected in series to cover a wider phase range. The **output is scaled by a gain**, which defines the damping coefficient of the virtual resistance.

Figure 6 presents the **frequency response of NPSS-3** with different time constants and unity gain. Here, the lead-lag transfer function is set to order 2, covering a full phase range from 0° to 360°. By selecting an appropriate time constant $T = T_1 = T_2$, the desired phase lead or lag can be achieved at the target oscillation frequency.

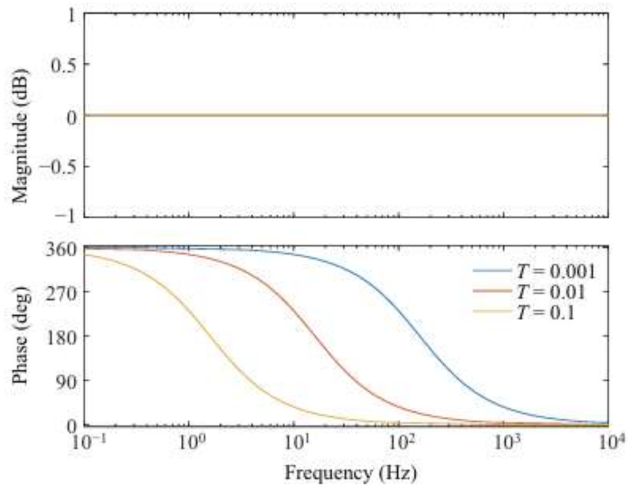

Fig. 6. Bode plots of NPSS-3 at different time constants.

IV.DISCUSSIONSONTHETUNING,PLACEMENT, FREQUENCYRANGE,ANDECONOMICANALYSIS

A. Tuning and parameter selection.

Unlike **low-frequency oscillations (LFOs)** and **subsynchronous resonance (SSR)**, which are linked to synchronous generators, **wideband oscillations (WBOs)** caused by power electronic converter interactions exhibit **time-varying behavior**. Therefore, NPSS design must account for these changing characteristics. Linear NPSS designs can either be made **robust for a specific set of operating conditions** or include **frequency-adaptive features** to handle the time-varying nature of WBOs.

1) Offline-tuned NPSS for specific operating conditions:

NPSS designs can be optimized using **offline information** about the target WBO modes, typically derived from post-event analysis or detailed electromagnetic transient (EMT) studies. Because WBO magnitude and frequency vary with system operating conditions, the NPSS parameters are tuned for a specific range of conditions. **Metaheuristic algorithms** such as particle swarm optimization or genetic algorithms can be used to find optimal NPSS settings. Robustness, a key aspect of classical PSS design, is especially critical for converter-based devices due to their flexible control designs and intermittent power generation.

2) Online-tuned NPSS for all operating conditions: Online-tuned NPSSs, often called **adaptive NPSS (ANPSS)**, adjust their parameters dynamically based on the real-time magnitude and frequency of oscillations. This allows them to stabilize WBOs across a wide range of operating conditions. For example, **adaptive notch filters**, an adaptive variant of NPSS-2, have been used successfully to suppress high-frequency resonances (HFR) in HVDC systems. Online adaptation ensures that the NPSS remains effective even as operating conditions and oscillation characteristics change.

$$T_{2k} = -T_{1k} = T_k = -\frac{1}{8\pi} \tan\left(\frac{\phi_{\text{filter}-k} + \phi_{\text{req}}}{50 - f_{\text{osc}-k}} \right) \tag{5}$$

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TABLE I
OSCILLATION CHARACTERISTICS AND CHOICE OF NPSS DESIGN

Oscillation Characteristic	NPSS-1	NPSS-2	NPSS-3	NPSS-4
Sub-/super-synchronous	✓	✓	✓	✓
High-frequency resonance	×	✓	×	×
Single mode (including its coupled oscillation mode)	✓	✓	✓	✓
Multiple oscillation modes	×	✓	×	✓

TABLE II
TYPE OF CONVERTER-BASED DEVICE AND NPSS DESIGN

Converter-based Device		NPSS-1	NPSS-2	NPSS-3	NPSS-4
Device	Type-3 wind turbine	✓	✓	✓	×
	Type-4 wind turbine/PV	✓	✓	✓	×
System	BESS inverter	✓	✓	✓	×
	HVDC converters	×	✓	×	×
	SVC/STATCOM/ Custom-shunt converter	×	✓	✓	✓

When addressing WBO mitigation, it is important to consider the **trade-offs between different types of converter-based devices** to minimize overall costs, depending on which devices are involved in the interaction. For instance, Tian et al. [35] studied the **coordination of two supplementary damping controllers**: one added to the **rotor-side converter control** of a type-3 wind turbine, and the other integrated into the **AC voltage control loop** of a **static var generator (SVG)**.

Application cases:

This application example focuses on subsynchronous oscillation (SSO) events in the Guyuan wind power system in Northern China. In this system, SSOs occurred due to interactions between DFIG-based wind farms and a series-compensated network. Detailed analysis of this SSO phenomenon is available in [36]. Research has shown that modifying individual wind farms can help reduce the overall severity of these oscillations. Specifically, the rotor-side converter (RSC) control significantly influences the impedance characteristics of the DFIG, whereas the grid-side converter (GSC) control has limited voltage control capability, especially under high series compensation and low wind speed conditions—the circumstances under which SSO typically occurs. Consequently, NPSS-1 is integrated into the RSC control.

To implement this, the DFIG controllers of four wind turbines in the Lianhuatan wind farms of Guyuan have been upgraded by **NPSS-1** [14] was incorporated into the DFIG controllers by adding it to both **d- and q-axes of the current controllers**, as illustrated in Fig. 8. This modification enhanced the **overall stability** of the DFIG's converter control system. Conceptually, NPSS-1 can be viewed as a **virtual impedance** placed in parallel with the inner current controllers, introducing **positive resistance** specifically in the **SSO frequency range**. The **d-axis impedance** of the RSC control, as observed from the stator terminals and ignoring the dynamics of slower outer control loops, is expressed as:

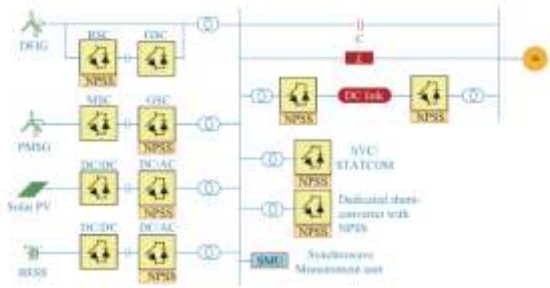

Fig. 7. A typical converter-dominated modern power system.

The **parameters of NPSS-1** are detailed in [14]. Its implementation also includes an **extraction filtering module**, which ensures that the control adjustments **do not interfere with the normal operation** of the wind turbine, but only modify the dynamics around the **target oscillation frequency of approximately 6 Hz**.

Figure 9(a) presents **field-recorded stator currents** of the DFIG before and after deploying NPSS-1 as a mitigation measure for SSO. The results clearly demonstrate the **excellent damping capability** of the DFIG controller once NPSS-1 is activated. Additionally, the **frequency spectrum** shown in Figure 9(b) confirms **substantial suppression** of the oscillations near 6 Hz.

The second application case focuses on actual **SSO events** observed in **DFIG-PV farms** connected to a **multi-terminal high-voltage DC (MTDC) network** in Zhangjiakou, Northern China. This SSO event is notable as it is the **first reported instance** caused by interactions between DFIG-based wind farms and an MTDC network. From the perspective of the wind farm-side converter station, the **MTDC network behaved like a virtual capacitor** at the SSO frequency [37].

Based on the underlying principles of SSO in DFIG wind turbines, such oscillations can be mitigated by **enhancing DFIG converter controls with NPSS**. For this case, **NPSS-2** is selected to upgrade the DFIGs' converter control system [38]. NPSS-2 is implemented in **series within the inner current control loop of the d-axis only**, as illustrated in Figure 10. When the slower outer control loops are neglected, the **impedance of the RSC control at the oscillation frequency** is expressed as:

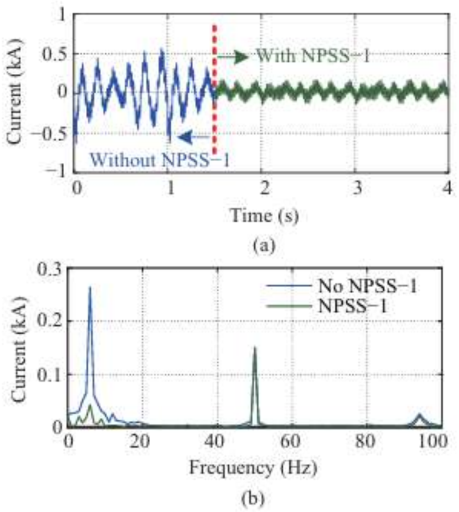

Fig. 9. DFIG output current and its FFT with and without NPSS-1. (a) Output current without and with NPSS-1. (b) Frequency spectrum of the output current without and with NPSS-1.

$$Z_{\mathrm{dRSC}}(s) = \frac{s}{s - j\omega_r}\left(\frac{K_{ir}}{s - j\omega_0} + Z_{\mathrm{NPSS\text{-}2}}(s) - jK_{\mathrm{dr}}\right) \quad (7)$$

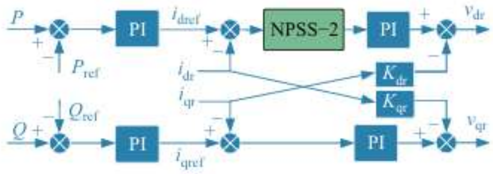

Fig. 10. NPSS-2 embedded into DFIG's RSC control.

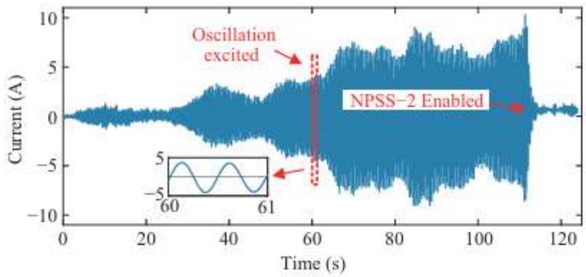

Fig. 11. Subsynchronous current filtered from field recorded line current of the wind farm before and after enabling NPSS-2.

Case 3 examines a **hypothetical test system** composed of a **200 MW Type-4 wind farm** connected to a **weak AC grid**. Additionally, a **10 MW battery energy storage system (BESS)**—representing 5% of the wind farm's total capacity—is installed at the **point of interconnection (POI)**. Its primary role is to **store surplus energy and supply it when required**. The system's single-line diagram is presented in **Figure 12**.

In this setup, the **Type-4 wind turbines operate in grid-following mode**, while the **BESS functions in grid-forming mode**. Under weak grid conditions, the system experiences **coupled SSO at 45 Hz and 55 Hz**, which occurs when the **short-circuit ratio abruptly drops from 4 to 1.91 at t = 4 s**.

The **BESS operates using virtual synchronous generator (VSG) control**, which incorporates **dq-axis inner current controllers** to maintain control stability. To suppress the **subsynchronous oscillations (SSO)**, **NPSS-3** can be integrated into the **inner current controllers** of both the **Type-4 wind turbines' grid-following control** and the **BESS's grid-forming control**. In this case, NPSS-3 is applied specifically to the **BESS's inner current controllers**. This approach is advantageous because the **BESS is a single unit or relatively large in capacity**, while the wind farm consists of **tens or hundreds of smaller turbines**. Therefore, in certain scenarios, **adding the damping function via NPSS-3 to the BESS is simpler and more cost-effective** than equipping every individual wind turbine with a separate NPSS.

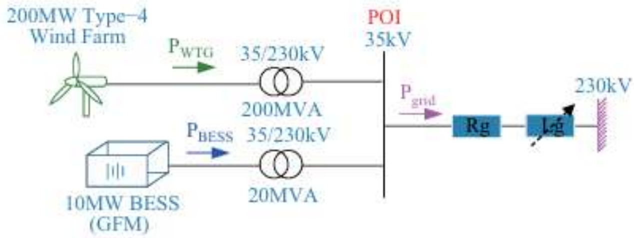

Fig. 12. Type-4 wind farm and BESS connected to a weak grid.

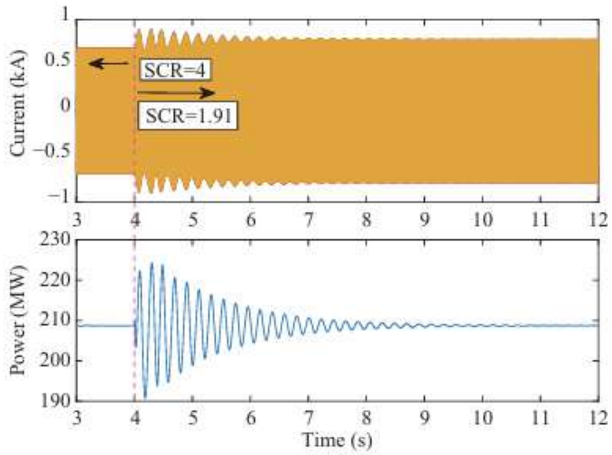

Fig. 14. Total line current and active power flow after adding the NPSS-3.

Case 4 illustrates the use of **NPSS-4** in combination with a **shunt-connected converter at the point of interconnection (POI)** to mitigate **SSO** in the **Guyuan wind power system**, with a simplified schematic shown in **Fig. 15**. The system experienced **SSO events in the 6–9 Hz range** under specific operating conditions.

The **design concept of this NPSS configuration** is based on the **grid-side subsynchronous damping controller (GSDC)**. Essentially, it involves a **custom shunt converter that injects phase-shifted oscillation**

currents into the network, reshaping the system's overall impedance response at the target oscillation frequency. NPSS-4 is responsible for **generating the appropriate reference control signals** for this shunt converter. The resulting **impedance of the wind farm**, after integrating the shunt converter with NPSS-4, is expressed as follows:

$$Z'_{WF}(s) = \frac{u_B}{i_L} = \frac{u_B}{i_W - i_{NPSS\text{-}4}} \quad (8)$$

In this formulation, **uB** represents the bus voltage, **iL** and **iW** denote the line currents flowing into and out of the bus, respectively, while **iNPSS-4** corresponds to the current injected by the shunt converter. The effect of **control delays is neglected** in this representation.

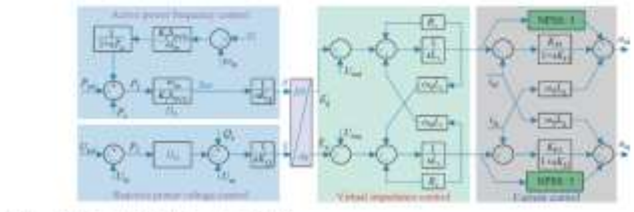

Fig. 15. NPSS-5 embedded into grid forming control of BESS

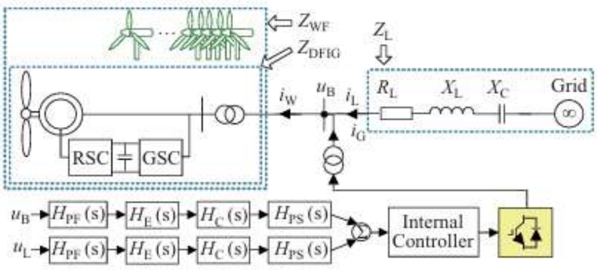

Fig. 15. A series-compensated wind power system with NPSS-4.

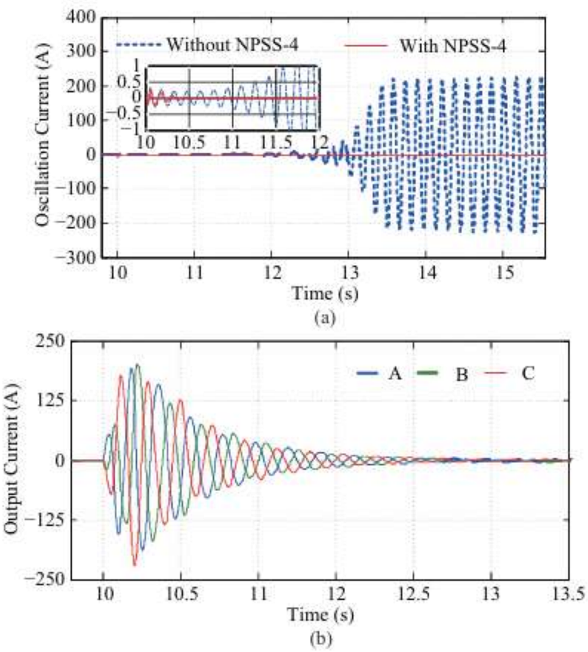

Fig. 16. Dedicated shunt converter with NPSS-4. (a) Subsynchronous current (b) Three-phase injected currents.

To eliminate unwanted components such as the 50 Hz fundamental and other coupled frequencies, the signal is passed through dedicated filters. The gain and phase shifters then compensate for any magnitude or phase shifts introduced by these filters, ensuring the desired phase relationship is maintained. In [13], the controller hardware was thoroughly validated through controller-hardware-in-the-loop (CHIL) simulations and later implemented in the Guyuan wind power system in Northern China, which had experienced subsynchronous oscillations (SSOs).

Figure 16(a) illustrates the measured subsynchronous components of line current before and after integrating the shunt-converter-based NPSS-4, while Figure 16(b) displays the three-phase oscillation currents injected by the shunt converter.

1) Single-Mode Adaptive NPSS-4 with Shunt Converter:
The shunt converter equipped with NPSS-4, described in the previous subsection, is tuned to operate at a fixed oscillation frequency, which is typically identified after the oscillation event occurs. To enable real-time monitoring, phasor measurement units (PMUs) with enhanced inter-harmonic tracking capabilities or synchronous waveform measurement units (SWMUs) can be installed at the point of interconnection (POI) to track oscillation phasors [39]. Once the magnitude and frequency of the oscillation are detected, the NPSS-4 can be designed to adapt dynamically to these parameters [27].

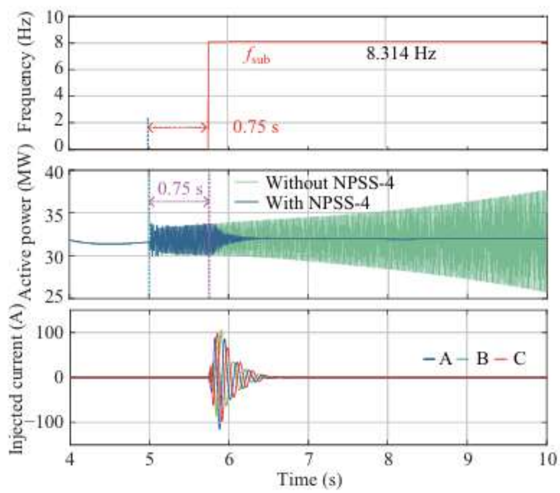

Fig. 17. Dedicated shunt converter with NPSS-4: estimated oscillation frequency, active power flow, and injected subsynchronous current.

2)Multi-ModeAdaptiveNPSS-4withShunt-Converter

In real-world power systems, it is common for multiple oscillation modes to be triggered simultaneously due to complex control interactions among various devices. To address this, the study in [25] extended the ANPSS-4 design to effectively dampen two oscillation modes at once. The interharmonic estimation algorithm used in [25] enables accurate tracking of the frequencies of both oscillation modes in a type-4 wind farm connected to a weak AC grid. The corresponding tracked oscillation frequencies, active power flow, and three-phase injected currents are illustrated in Figure 18, demonstrating the ANPSS-4's ability to maintain system stability under multiple interacting oscillatory conditions.

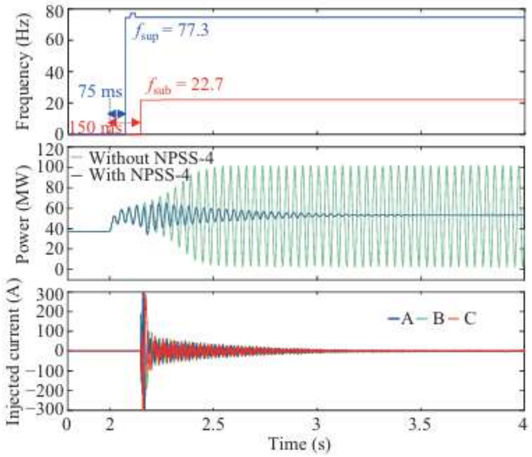

Fig. 18. Dedicated shunt converter with NPSS-4: estimate oscillation frequency, active power flow, and injected subsynchronous current.

This case study focuses on the application of an adaptive new power system stabilizer (ANPSS-2) to mitigate high-frequency resonance (HFR) in a modular multilevel converter-based HVDC (MMC-HVDC) system. The effectiveness of the proposed control strategy is validated through a detailed electromagnetic transient (EMT) model developed using the Luxi MMC-HVDC project located in Southwestern China. A detailed resonance analysis reveals that the resonance frequency of the system depends heavily on system-wide operating conditions, which can vary dynamically during operation. The study identifies both positive and negative sequence components near 1272 Hz.

To counteract the resonance, [26] employs a notch filter-based NPSS-2 configuration, which is particularly effective for high-frequency oscillations. These adaptive notch filters are incorporated in parallel with the PI regulators of the dq-axis current controllers for both positive and negative sequence components. The filters automatically adjust to oscillation frequency variations, addressing the time-varying nature of wideband oscillations (WBOs). The magnitude and frequency of the HFR are continuously estimated using a Hanning-windowed Discrete Fourier Transform (DFT) with interpolation. Once an HFR is detected, the NPSS-2 is automatically activated to suppress the oscillation. As shown in Figure 19, the estimated frequency and MMC output current confirm that the HFR is effectively mitigated, even when the resonance frequency suddenly shifts from 1273 Hz to 1420 Hz.

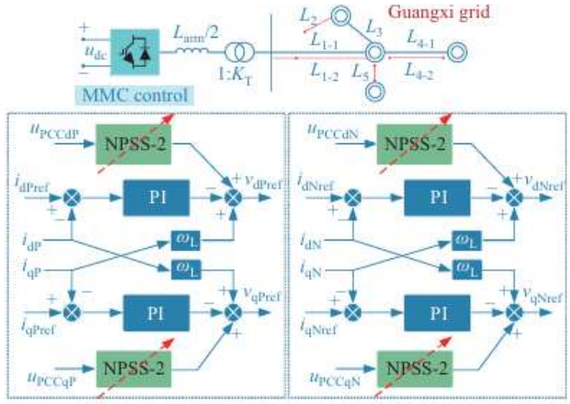

Fig. 19. ANPSS-2 embedded into MMC-HVDC control in Guangxi, China.

VI. CHALLENGES AND FUTURE WORKS

Despite the promising potential of New Power System Stabilizers (NPSSs) in enhancing system stability and damping wideband oscillations (WBOs), several challenges remain that must be addressed before their large-scale deployment. These challenges span across aspects such as design methodologies, practical implementation, equipment constraints, and standardization requirements. The key issues are summarized below:

1. Adaptive and Robust Control Design: From a theoretical perspective, it is essential to develop NPSSs capable of providing effective damping across a wide range of system operating conditions and time-varying oscillation frequencies. However, in practice, there is a lack of efficient and responsive control hardware capable of suppressing WBOs under rapidly changing grid dynamics.

2. Design Considerations and Control Interaction: An effective NPSS design must account for multiple factors such as the type of device, connection topology, rated capacity, intended control objective, and converter control architecture. Moreover, integrating NPSSs with existing converter-based devices can impact their control bandwidth and dynamic performance, which necessitates detailed investigation. For instance, while a STATCOM typically operates at the fundamental grid frequency, supplementing it

with an NPSS for power oscillation damping could inadvertently introduce DC-link voltage fluctuations, potentially causing equipment stress or damage.

3. Converter Capacity Constraints: The capacity of a converter-based device integrated with an NPSS significantly influences its ability to contribute positive damping to system-wide oscillations. Hence, power and energy limitations—such as those inherent in Battery Energy Storage Systems (BESSs)—must be carefully evaluated to ensure adequate damping capability.
4. Coordination Among Multiple NPSSs: In systems where multiple converter-based devices are equipped with NPSSs, coordinated control is crucial to avoid multi-modal instability and ensure effective damping of WBOs. Proper coordination not only minimizes the risk of adverse interactions but also helps reduce the overall capacity requirements for oscillation damping. Establishing optimal coordination strategies between NPSS-equipped converters to achieve desired damping performance remains an open and active area of research.
5. Integration with Synchronous Condensers: With the growing deployment of synchronous condensers to strengthen weak AC grids, integrating PSSs or NPSSs into these devices presents a promising approach to further enhance system damping and improve overall grid resilience.

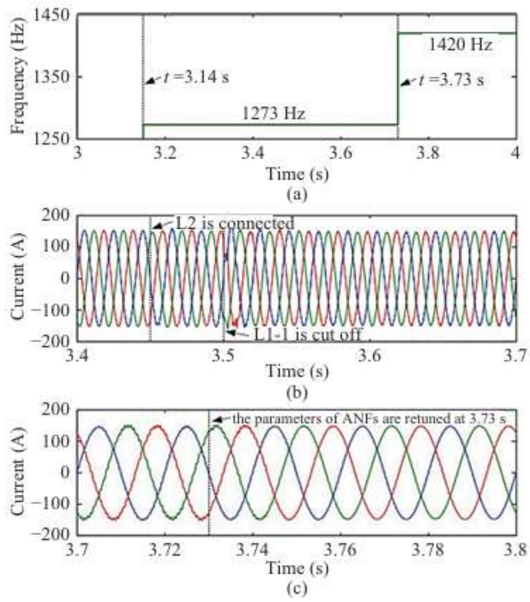

Fig. 20. Case 5: Adaptive-NPSS-2 embedded into MMC-HVDC converter. (a) Estimated frequency. (b) MMC output current first set of operating conditions. (c) MMC output current second set of operating conditions.

VII. CONCLUSION

In modern converter-dominated power systems, the coexistence of diverse equipment and the complex multi-timescale coupling dynamics often result in unstable wideband oscillations (WBOs) exhibiting time-varying characteristics. These phenomena pose significant challenges to achieving adaptability and robustness in both system configuration and control parameter design. To overcome these challenges, the deployment of converter-based devices integrated with New Power System Stabilizers (NPSSs) has emerged as a promising strategy for effectively suppressing WBOs and enhancing overall system stability.

This paper has discussed the design principles, implementation approaches, and performance characteristics of several NPSS configurations, highlighting their potential to mitigate WBOs under varying system conditions. It is important to note that the design philosophy and performance requirements of NPSSs for WBO damping differ fundamentally from those of traditional Power System Stabilizers (PSSs) designed for low-frequency oscillations (LFOs). The authors conclude that addressing the WBO challenge in converter-dominated systems represents a critical and evolving research frontier, offering substantial opportunities for innovative control strategies and advanced damping solutions in next-generation power grids.

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BIOGRAPHIES

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