New-type Power System Stabilizers (NPSS) for Damping Wideband Oscillations in Converter-dominated Power Systems

Jan Shair, *Member*, *IEEE*, Xiaorong Xie, *Fellow*, *IEEE*, Haozhi Li, *Student Member*, *IEEE*, and Vladimir Terzija, *Fellow*, *IEEE*

***Abstract*—Traditionally, synchronous generators are equipped with power system stabilizers (PSSs) to stabilize electromechanical low-frequency oscillations (LFOs). With increasing applications of converter-based devices in modern power systems, system-wide control interactions between different converter-based devices are causing more prevalent electromagnetic wideband oscillations (WBOs). Extensive research has been done on design, application, and standardization of classical PSSs for addressing LFOs associated with synchronous generators. However, little attention is given to same for converter-based devices as a countermeasure to electromagnetic WBOs. This paper proposes a concept of utilizing new-type power system stabilizers (NPSSs) specifically designed to address WBOs caused by converter-control interactions in modern converter-dominated power systems. The article puts forward various design strategies, tuning methods, and implementation techniques of the NPSSs to counteract WBOs. The NPSSs are not limited to inverter-based resources (type-3/4 wind turbines); they can also be applied to other converter-based devices such as FACTS controllers, HVDC links, battery storage inverters, etc. We present several application scenarios demonstrating the importance of supplementing NPSSs in converter-based devices. Furthermore, the paper highlights current research challenges and opportunities in designing and implementing NPSS for various converter-based devices, providing a comprehensive overview of state-of-the-art and future directions in this area.**

***Index Terms*—New-type power system stabilizers, power system stability, subsynchronous oscillation, wideband oscillation.**

I. INTRODUCTION

THE traditional power systems dominated by synchronous generators are continuously being transformed into modern power systems with a high proportion of power electronic converters on generation, transmission, distribution, and utilization sides. Oscillatory problems in traditional power systems are mainly associated with *electromechanical* dynamics of synchronous generators, leading to local/interarea low-frequency oscillations (LFOs). Due to fast-acting converter controls and multi-time dynamics of converter-based devices, new *electromagnetic* wideband oscillations (WBOs) have been reported in modern power systems around the globe [1].

Similar to traditional power system stabilizers (PSSs) for synchronous generators, there is an urgent need to design and develop standardized new-type power system stabilizers (NPSSs) for converter-interfaced generators and other power electronic converter-based devices. In this paper, we put forward the concept of NPSS, specifically designed to address emerging oscillatory stability issues arising from their converter control interaction with other components in the power system. Fast-acting multi-time scale control of converter-based devices offers excellent flexibility to add supplementary damping control loops. NPSSs can be augmented to existing converter controllers and suppress WBOs under a full range of operating conditions without affecting primary operation of the power electronic device. Adoption of NPSSs may be seen as an active damping control method for mitigating system-level oscillations caused by interactions between different power system components. This is essentially different from active damping of LCL resonance and/or other harmonics that are local to power electronic converters [2].

In this paper, we first revisit classical PSSs for damping LFOs and subsynchronous resonance (SSR) in power systems dominated by traditional synchronous generators. Then, we highlight emerging WBOs problems associated with converter-based devices and need for NPSSs. NPSSs with different design configurations can be added not only to converter-interfaced generators (such as type-3/4 wind turbines and PV inverters) but also to other grid/network-side converter-based devices such as SVC, STATCOM, BESS, and HVDC converters. This paper presents preliminary ideas, strategies, and examples for designing the NPSSs for a wide range of converter-based devices with different capabilities and requirements. Finally, we present real-world implementation scenarios of different NPSSs, demonstrating their application cases in the context of minimizing risk of WBOs. The paper also sheds light on challenges and future developments in designing and implementing NPSS for different converter-based devices. The authors believe the topic of NPSSs for

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J. Shair, X. R. Xie (corresponding author, email: xiexr@tsinghua.edu.cn), and H. Z. Li are with the State Key Laboratory of Power System, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China.

V. Terzija is with the Center for Energy Science and Technology, Skolkovo Institute of Science and Technology, Bolshoy Boulevard 30, Bld. 1, Moscow 121205, Russia.

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converter-based devices deserves the research community's attention.

The rest of the article is organized as follows: Section II discusses classical and emerging oscillatory stability problems and their solutions. Section III presents the concept of a class of NPSSs for converter-based devices to mitigate WBOs. Section IV presents practical application cases to mitigate WBOs using different NPSS design structures. Section V demonstrates various possible application scenarios, followed by conclusions in Section VII.

II. Problem Statement

A. Power System Oscillations and System Stability

The power system is characterized by self-sustaining oscillations at power/fundamental frequency, typically 50/60 Hz. However, specific dynamics within the system, such as mechanical, electromagnetic, or coupled multi-time scale dynamics, can cause oscillations outside this frequency, named as power system oscillations. Oscillations can negatively affect system's normal operation, cause system stability or power quality issues, and endanger equipment safety. With this definition, power system oscillations can be divided into 1) power/fundamental frequency oscillation and 2) non-power/non-fundamental frequency oscillation, as shown in Fig. 1. The former is fundamental to operation of ac power system, while the latter is necessary to be avoided for maintaining stable operation of power system, and is also commonly referred to as a *stability problem*. In terms of dynamic interaction mechanism, non-power frequency oscillation can be categorized into 1) electromechanical oscillation, which is usually associated with dynamic interactions involving synchronous machines, and 2) electromagnetic oscillation, which is usually caused by dynamic interactions involving converter-based devices such as type-3 or type-4 wind turbines. Study of power system oscillations, their causes, and ways to mitigate them is a crucial area of research in ensuring power systems' safe, reliable, and stable operation.

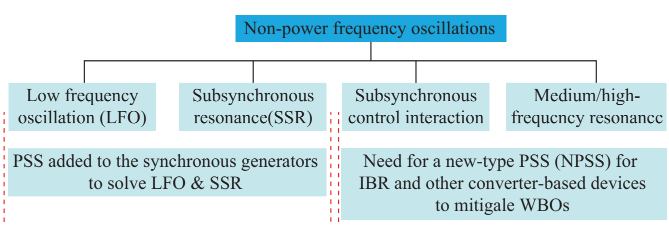

Fig. 1. Classification of power system oscillations.

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

1) Low-Frequency Oscillation (LFO)

LFO was first identified in 1964 during the early stages of the Western Power Grid networking project in the United States [3]. During interconnection of Northwest and Southwest Power Grids, it was found torque, speed, and output power of many units fluctuated continuously at around 0.1 Hz, significantly impacting system's safe operation. Frequency of the LFO is determined by the inertia time constant and equivalent elastic coefficient. With large inertia of steam turbine units, oscillation frequency is low, typically in the 0.01 to 2.5 Hz range.

A cost-effective solution to the LFO problem is to improve their excitation systems by adding PSSs as supplementary controllers [4]–[6]. The PSS, first proposed in the 1970s, has gradually become one of the standard control functions of synchronous generators, and standardized modules such as PSS1 A, PSS2B, PSS3B, and PSS4B have been formed [7].

2) Subsynchronous Resonance/Oscillation (SSR)

SSR is caused by the so-called torsional interaction (TI), induction generator effect (IGE) and torque amplification (TA). It first emerged as a risk in the 1970s, with several SSR incidents reported at Navajo and San Juan power plants in the United States. With increase in series compensation and high-voltage direct current (HVDC) projects in countries such as China, India, and Brazil in the early 21st century, SSR/SSO problems re-emerged and prompted a renewed focus on theoretical research and engineering practice to address these issues. Frequency of SSR/SSO depends on system structure, synchronous generators's shaft dynamics, level of series compensation, and so on. Frequency typically ranges from 10 Hz to 45 Hz.

Since classical SSR/SSO is also associated with synchronous generator, the SSR/SSO problem can also be solved by modifying the excitation system of synchronous generators [8]–[10]. There have been several efforts toward developing standardized schemes to mitigate SSR/SSO in synchronous generators.

C. Converter Associated Oscillations and Need for NPSS

1) Emerging Converter Control Interactions

Modern power systems are witnessing an increasing share of converter-based devices in the form of inverter-based resources such as wind and solar, flexible ac transmission systems (FACTS), HVDC, battery energy storage systems (BESS), etc. Due to multi-time scale dynamics, converter-based devices and their controls are prone to interact with each other and other power system components. This has led to emergence of electromagnetic oscillatory problems, which have attracted widespread attention and have been known to cause damage to power grids and equipment. Oscillations can grow quickly and destabilize the system or cause equipment damage. Oscillation magnitude and frequency are determined by system-wide parameters such as generation dispatch, control settings, grid strength, and so on. Unlike the SSR/SSO associated with synchronous generators, frequency of resulting oscillations can range from a fraction of hertz to several kilohertz. In the past decade, many such oscillation events have been reported around the world, for instance, ERCOT system in Texas, US, First Solar's solar farms in California US, Southeast and West-Murray zones in Australia, Hornsea offshore wind farms in the UK, and Guyuan/Hami wind bases and NanAo, LuXi, and ZhangBei HVDC systems in China, to name a few [1]. With increasing penetration of converter-based devices, risk of oscillatory instability caused by control interactions among different power system components is also increasing. Some of the key interaction mechanisms include 1) interaction between type-3 wind turbine and series compensated grid, 2) interaction between type-4 wind turbine and weak ac grid, whereas oscillations can propagate into the grid and can trigger torsional oscillation in nearby synchronous generators, 3) interaction between PV farm and weak ac grid, 4) interaction between type-3 wind farms and multi-terminal HVDC network, 5) interaction between type-3/4 wind turbines with HVDC converters due to control delay.

WBO associated with power electronic converter control essentially differs from classical LFO or SSR in synchronous generators. This has also led to reclassifying the power system stability problem mentioned in [11] as *converter-driven stability* and *non-fundamental component stability* in [12]. Emerging oscillatory stability is one of the key obstacles to achieving stable operation of power systems with a higher proportion of renewables and power electronics.

2) Existing Mitigation Methods

WBOs pose a great risk to system instability; there is an urgent need to develop generic countermeasures to suppress the WBOs in converter-dominated power systems. Well-known existing mitigation techniques include retuning of control parameters, modification of device's control structures by adding supplementary loops, adding auxiliary control loops to FACTS devices, and a special-purpose shunt current generator [13]. In literature, quite a few methods on generator and grid sides have been proposed to mitigate the WBO problems [13], [14]. A novel BESS/STATCOM is proposed to enhance grid stiffness to dampen SSO caused by interaction between type-4 wind farms and weak ac grids [15]. Reference [16] investigates influence of a feedforward voltage filter and a feedback current filter on damping of the HFR of an MMC connected to ac grid. In [17], an additional voltage controller in the VSC-HVDC's outer control loop is proposed to dampen HFR in VSC-HVDC and wind farms. Although significant efforts have been made toward understanding the mechanism and mitigating the WBOs, rigorous research is needed to devise generic mitigation solutions to these problems.

III. New-type Power System Stabilizers

A. Fundamental Principles

Similar to basic design principles of PSS for mitigation of LFO in synchronous generators, the WBO associated with converter-based devices can be mitigated by supplementing NPSS in device's excitation or control system. By doing so, damping in oscillation frequency band of each unit, respectively, can be increased and dynamic stability of the entire power grid can be improved. The goal is to achieve active damping of WBOs using a properly designed NPSS while maintaining reasonable control bandwidth and robustness margins.

B. Linear and Nonlinear NPSSs

Similar to PSS for synchronous generators, the NPSS for converter-based devices may as well be based on simplistic linear or advanced nonlinear control theory. Linear NPSS design assumes the power system operates in a linear region around an operating point and small perturbations around operating point can be linearized. In literature, many linear designs (e.g., lead-lag control [18], proportional-derivative control [14], linear quadratic regulator [19], H-infinity control [20], etc.) have been used to suppress wideband oscillations.

On the other hand, nonlinear NPSS design is based on nonlinear control theory, which takes into account power system's nonlinear behavior. Several nonlinear control methods have also been proposed to mitigate the WBOs, for example, partial/full feedback linearization control [21], [22], sliding mode control [23], etc. Nonlinear NPSS designs can be more complex and computationally intensive.

For power electronic converter control applications, power system industry prefers practical and simplistic control designs (e.g., P, I, PD, PID, etc.) based on linear control theory. The time-varying nature of wideband oscillations can be addressed by adding adaptive capabilities to linear control designs. Therefore, this paper will limit our discussions, control designs, and real-world implementation cases to linear NPSS only. The term NPSS, from now on, will refer to linear NPSS.

C. General Structure and Design of Linear NPSSs

Design of a linear NPSS involves several factors, including primary objectives, capacities, control philosophies, control structures of converter-based devices, and mechanism and characteristics of the WBOs.

Figure 2 shows general structure of a typical NPSS. It consists of four modules. 1) A prefiltering module cleans input control signal by removing unwanted components such as high-frequency noise and/or fundamental component from incoming signal. 2) A cascaded filtering module is added to extract specific oscillation mode. It generally consists of several band-stop filters to reject unwanted modes and a band-pass filter to pass target oscillation mode. 3) Control or filtering block is a digital filter or controller that further drives input control signal. It can be a proportional derivative controller or a second-order low-pass/band-pass/band-stop filter. 4) Finally, a gain & phase shifting block is added to compensate for gain and phase lag or lead filters may have introduced in earlier modules.

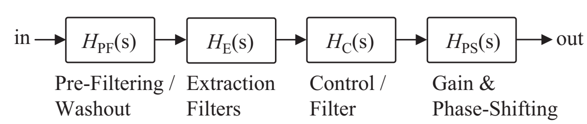

Fig. 2. General structure of a linear NPSS.

An adequately designed NPSS may not comprise all four modules. For instance, sometimes, there is no need for a prefilter module; other times, gain and phase compensation are unnecessary. Here, four variations of the NPSS are presented that may be used for damping WBO, for example, SSO and HFR. Fig. 3 shows design structures of the four linear NPSSs.

1) NPSS-1: Proportional Derivative Controller

NPSS-1 configuration consists of a washout filter and a proportional derivative controller. Washout filter is added to prevent misoperation during steady-state and avoid interfering

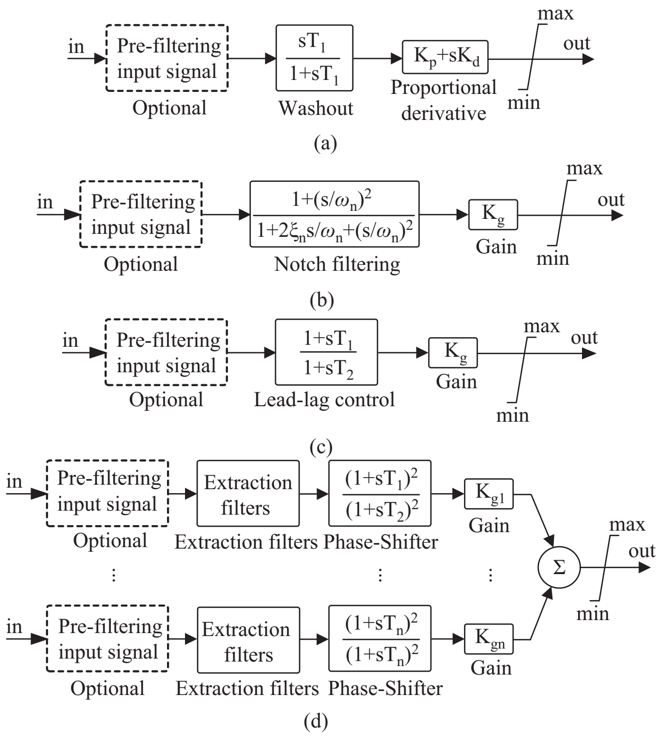

Fig. 3. Design structures of new-type power system stabilizer for converter-based devices. (a) NPSS-1. (b) NPSS-2. (c) NPSS-3-. (d) NPSS-4.

system's normal operation. Proportional derivative provides control action and drives input control signal. This type of design structure improves overall stability of converter control without affecting system's steady-state response. Output-to-input transfer function of the NPSS-1 is given as:

$$H_{\text{NPSS-1}}(s) = \left(\frac{sT_{\text{w}}}{1+sT_{\text{w}}}\right)(K_{\text{p}} + sK_{\text{d}}) \qquad (1)$$

where T_{w} is washout time constant, K_{p} and K_{d} are proportional and derivative constants.

NPSS-1 structure can be designed to exhibit virtual inductive behavior as it can add a leading phase shift, especially for lower range of subsynchronous frequency band. The proportional term provides a direct relationship between error signal and control action, while derivative term contributes to rate of change of error signal. Derivative term introduces a phase lead in frequency response, which can help increase stability margins and improve system's transient response. Therefore, a PD controller can provide damping and reduce overshoot and oscillations in system response. Fig. 4 shows bode plots of NPSS-1 for different K_{p} and K_{d} values, which demonstrates varying damping ability of PD controller.

NPSS-1 is implemented parallel to PI regulators of dq-axes of fast-acting inner loop current controllers. A similar control for SSO in DFIG wind turbines was first reported in [24]. Its improved version was further verified through controller hardware in the loop and implemented in four actual type-3 wind turbines to suppress SSO [14].

2) NPSS-2: Band Reject/Notch Filter

NPSS-2 is a second-order band-reject or notch filter which is used to stop target oscillation frequency component from

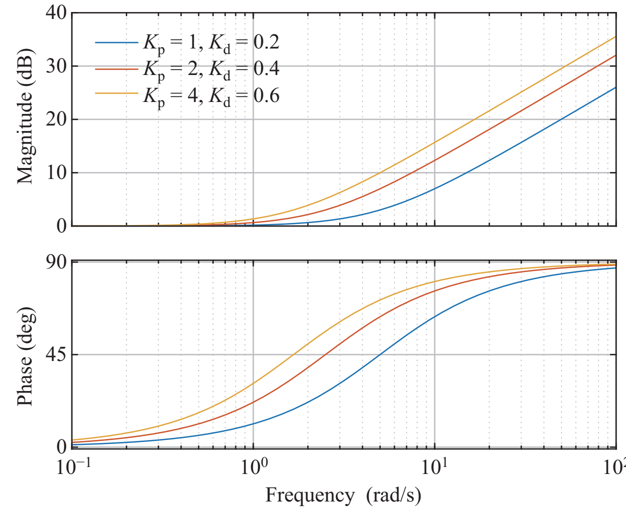

Fig. 4. Bode plots of NPSS-1 for different Kp and Kd values.

incoming signal. The idea is to remove oscillation of a certain frequency by a notch filter tuned at an antiresonance peak. For this design type, a first or second-order low or high-pass filter may be added as a prefilter depending on type of converter-based device and characteristics of target WBO. Output-to-input transfer function is given as:

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

where ζ is damping factor; ω_n is natural frequency of notch filter, which is set according to oscillation frequency; depth and width of notch filter are determined by its damping factor and bandwidth. Fig. 5 gives bode plots of NPSS-2 with 40, 600, and 1200 Hz oscillation frequencies.

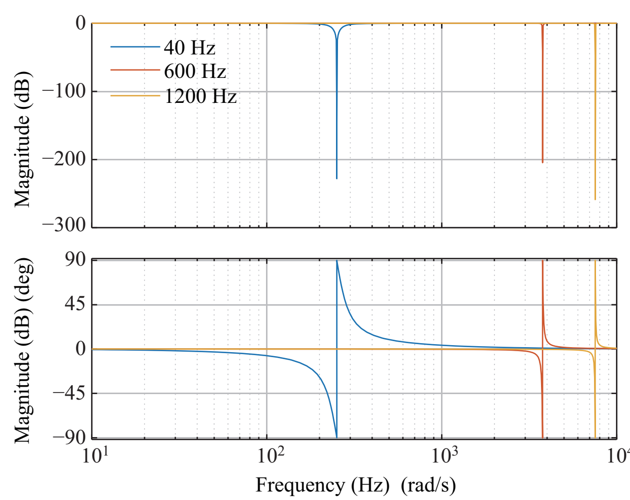

Fig. 5. Bode plots of NPSS-2 for different oscillation frequencies.

NPSS-2 structure is generally adopted when oscillation frequency is high, as it is rather tricky to handle high-frequency oscillations by adding a phase shift. It may be added in parallel or in series with PI regulators of dq-axes of fast inner loop current controllers. Extraction and compensation modules are generally not needed for this design type. Compared to other NPSS design types, NPSS-2 notch filter design is suitable for HFR damping independent of ratio of resonance frequency and control frequency.

3) NPSS-3: Lead Lag Control

NPSS-3 consists of a gain and lead-lag control. Because of lead or lag phase shift added by lead-lag control, NPSS can be seen as a virtual impedance. Output-to-input transfer function is given as:

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

where K_g is controller gain; T_1 and T_2 are time constants; n is order of cascading lead-lag blocks.

Amount of phase lead or lag for target frequency is determined by values of time constants. Order n determines number of series connected lead-lag elements to cover a relatively large phase lead or lag range. Output is multiplied by gain, which determines damping coefficient of virtual resistance. Fig. 6 shows frequency response of NPSS-3 for different time constants and unity gain. Order of lead-lag transfer function is set to 2 to cover entire frequency range from 0 to 360 degrees. Frequency response shows a desired phase lead (lag) can be achieved at target oscillation frequency by setting an appropriate value for time constant $T = T_2 = T_1$.

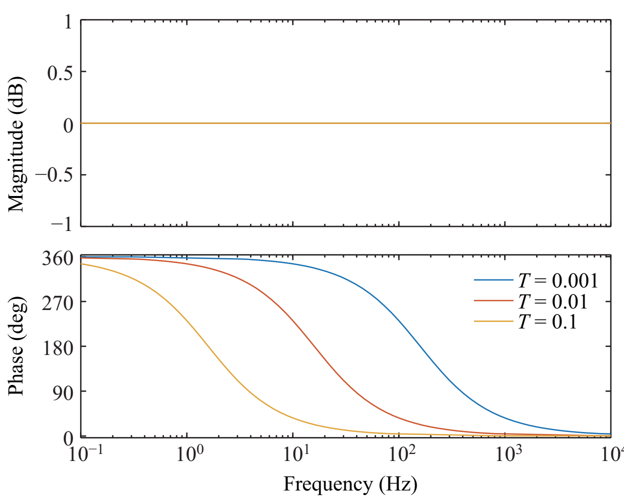

Fig. 6. Bode plots of NPSS-3 at different time constants.

This NPSS structure is practical for damping oscillations with relatively low frequencies. This is because it may amplify high-frequency noise and thus make control unstable. NPSS-3 is generally supplemented in parallel with PI regulators of dq-axes current controllers. Prefiltering and oscillation extraction blocks are optional.

4) NPSS-4: Multi Mode NPSS

Converter control participated interactions can lead to multiple unstable oscillation modes of distinct oscillation frequencies. This type of NPSS is adopted when there are multiple oscillation modes, completely independent or coupled. Each oscillation mode is extracted and controlled independently from other oscillation modes. NPSS-4 structure is aimed at damping out such multiple oscillation modes simultaneously. Transfer function of kth channel NPSS-4 for m oscillation modes would be

$$H_{\text{NPSS-4}}(s) = \sum_{k=1}^{m} K_{gk}.H_{Ek}(s). \left(\frac{1 + sT_{1k}}{1 + sT_{2k}} \right)^2 \tag{4}$$

where K_{gk} is controller gain; $H_{Ek}(s)$ is transfer function of extraction filters; T_{1k} and T_{2k} are time constants – all for kth oscillation mode.

An example of NPSS-4 is its application with a static compensator (STATCOM) or customized shunt converter [13] to damp SSO. Bus voltage and/or line currents are input to NPSS-4. It injects magnitude-rescaled and phase-shifted controlled current into grid at desired oscillation frequencies. Reference [25] utilized NPSS-4 to damp multiple oscillation modes.

IV. Discussions on the Tuning, Placement, Frequency Range, and Economic Analysis

A. Tuning and Parameter Selection

Unlike LFOs and SSR associated with synchronous generators, WBOs resulting from power electronic converter control interactions exhibit time-varying characteristics. Therefore, design of NPSS must consider time-varying nature of the WBOs. Linear control design of NPSS can be made robust for a given set of operating conditions or frequency adaptive capability can be added to tackle time-varying properties of the WBOs.

1) Offline-tuned NPSSs for Specific Operating Conditions

NPSS designs presented in Section III-C rely on accurate information about target WBO modes. Characteristics of WBOs are generally known either after carrying out post-event analysis on field-recorded data or detailed EMT analysis. Since magnitude and frequency of WBOs depend on system-level operating conditions, NPSS design must consider time-varying characteristics of WBOs to be able to stabilize WBOs for a specific range of operating conditions. NPSS parameters can be optimized for a given set of operating conditions using metaheuristic algorithms, e.g., particle swarm optimization, genetic algorithm, etc [13]. Similar to robust designs of classical PSSs, robustness is imperative to design of NPSS. It is even more important for applications in converter-based devices due to flexible control designs and highly intermittent power generation.

2) Online-tuned NPSSs for All Operating Conditions

NPSSs presented in Section III-C are based on linear control theory and are generally designed using frequency response techniques. Control design can be made adaptive to oscillation characteristics by adjusting parameters of NPSS based on magnitude and frequency of oscillation, depending on operating condition. Resulting NPSS is named as adaptive new-type power system stabilizer (ANPSS). Digital filter/control-based NPSSs can be designed in a way that their parameters can be adjusted online as per characteristics of target oscillations. In [26], authors used adaptive notch filters (an adaptive variant of NPSS-2) to mitigate HFR in a practical HVDC system. In

[25], [27], authors proposed an adaptive NPSS-4, which relies on an inter-harmonic phasor estimation algorithm to update phase shifters' time constants online. Values of time constants are calculated such that required phase shift is maintained. Expression to calculate NPSS-4's time constants is

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

where $\phi_{\text{filter}-k}$ is phase delay introduced by filters, ϕ_{req} is overall required phase shift, $f_{\text{osc}-k}$ being oscillation frequency.

B. Placement of the NPSS

1) Placement in System (node, System Infrastructure)

WBO is usually triggered due to interaction of converter-based devices with other system components. Excited oscillation modes propagate throughout the system via different system nodes and transmission networks of different voltage levels [28]. Nodal/loop participation factors, branch observability and component sensitivity can be identified to form a global view of oscillation path [29]. Such impedance-based methods [28]–[31] help identify placement of converter-based device to be supplemented by an appropriate NPSS.

2) Placement in the Converter-control System

A converter-based device equipped with an NPSS can provide a controlled impedance response at desired frequency. Placement of NPSS in the converter control system should be carefully considered to ensure it provides effective damping to WBOs without adversely impacting stability and performance of converter-based device and power system. In modern power systems, converter-based devices come in a wide variety of types, sizes, capacities, primary objectives, control structures, and so on. For the most part, any converter-based device in generation, transmission, distribution, and utilization sides can be equipped with a properly designed NPSS. However, placement in control system depends on type of converter-based device and its primary function.

a) Rotor/machine-side Converter Control or Grid-side Converter Control: For WBOs in type-3 wind turbines connected to a series compensated network, rotor-side converter control plays a critical role in defining resistance at oscillation frequency. Whereas grid-side converter control has less impact as its ability to control output voltage is restricted by its relatively low capacity. Therefore, in this case, NPSS should be added to rotor-side converter control of type-3 wind turbine.

In the case of WBOs in type-4 turbines or PV generators, dynamics of machine-side converter do not have much impact on controller-grid interactions. But grid-side converter control and its PLL play a critical role in stability under weak ac grid conditions. Therefore, in this case, NPSS should be added to grid-side dc-ac inverter.

b) Inner Current Control Loop or Outer Control Loop: Typically, current system of a converter consists of slower outer control loops (to regulate active power, reactive power, or dc voltage) and fast-acting inner current control loops (to regulate currents in the dq-domain) and generate reference control signals for pulsed width modulation. Location of NPSS in converter control is determined by mechanism of WBOs and control blocks participating in oscillation mechanism.

In general, in case of type-3/4 wind turbines, PV inverters, and BESS inverters, the NPSS may be added to fast-acting inner current controllers. As per authors' knowledge, NPSS added in parallel to PI regulators of inner current controllers is a preferred location. Some reasons include:

- Outer current control loops aim at fulfilling the primary objective of regulating quantities such as active or reactive power control. Addition of NPSS to outer control loop may affect normal operation and dynamics of control system.
- Fast-acting inner current controllers can effectively impact higher frequency dynamics as control action is faster than outer control loops. In addition, since inner current control loops only regulate current, an appropriately designed NPSS would only affect control dynamics within concerned oscillation frequency range i.e. without impacting converter control's normal operation and dynamic performance.
- With NPSS supplemented in parallel to PI regulators of inner current controllers, an isolated d- and q-axis current can be used as an input control signal for the NPSS. This means dynamics of output outer control loops would not impact NPSS performance.

However, in case of FACTS devices such as SVC, STATCOM, SSSC, etc., NPSS may be added to outer control loops such as reactive power control loop [32]. However, in some cases, this may cause unwanted DC voltage fluctuations. The effect of NPSS added to active or reactive power control and coordination between NPSSs in different devices is an exciting research area that needs further investigation.

In literature, some papers have added supplementary controllers for phase compensation in PLL to improve oscillatory stability caused by PLL [33].

c) Series or Parallel Connected NPSS in the Control System: NPSS may be added in series or parallel to PI regulators of converter's inner current controllers. Parallel connection is usually done with inner current controllers. Series-connected NPSS is more like a feedforward filter, which is primarily a notch filter to remove resonance peaks in dq-axes currents [34].

C. Effect on Converter-based Device's Dynamic Performance

A properly selected and designed NPSS can dampen unstable oscillation of any frequency range, including super-/sub-synchronous oscillation, intermediate and high-frequency resonance, etc. Normally, power electronic converter-based device is designed to operate at fundamental frequency. An appropriately designed NPSS affects dynamics only at concerned oscillation frequency – without adversely impacting normal operation of converter-based device. Reference [14] demonstrates NPSS-1 added in type-3 wind turbine units does not affect dynamic and LVRT performance of wind turbine unit. In [32], it is shown dynamic performance of STATCOM is unaffected after adding an NPSS-like damping controller.

D. Frequency Range and Economic Analysis

Choice is NPSS to dampen WBOs is based on mechanism and characteristics of oscillation, primary design objective and design of converter-based device, and so on. Table I shows choice of candidate NPSS for damping oscillations in different frequency ranges. Table II demonstrates compatibility of different NPSSs with different device- and system-level converter-based devices. Generally, capacity of individual units/devices such as wind turbine units ($\sim$ 1 MW to $\sim$ 5 MW) is smaller than system-level equipment such as STATCOM or BESS. Thus, damping ability of NPSS added to a device-level unit and system-level equipment is significantly different. For instance, for a 200 MW wind farm, one has to add NPSSs to 100 wind turbine units (2 MW each). However, if a BESS or STATCOM is available at the PCC of wind farm, only 5% capacity (with reference to total capacity of wind farm) of BESS would be sufficient to achieve an acceptable level of oscillation damping. This demonstrates how NPSS added to a different type of converter-based device would impact cost of migration solution. In practical scenarios, a trade-off between different types of converter-based devices is needed to minimize cost of WBO mitigation depending on devices participating in interaction phenomenon. In [35], Tian *et al* investigated coordination of two supplementary damping controllers added to rotor-side converter control of a type-3 wind turbine and ac voltage control loop of a static var generator (SVG).

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	×	✓	✓	✓

V. APPLICATION CASES

A. A Typical Converter-Dominated Power System with NPSSs

Figure 7 shows a typical converter-dominated power system comprising type-3/4 wind farms, photovoltaic generators, BESS, SATCOM, series compensated transmission line, HVDC link, and main grid. Converter-based devices in such a system can adversely interact with each other or other passive components including capacitors (series or compensated line) or inductor (weak grid connection). Such interactions can lead to WBOs spreading throughout power grid. Several WBOs have been reported around the world [1]. In the rest of this section, we provide practical application cases of NPSS supplemented with different converter-based devices as a countermeasure to different types of WBOs.

B. Case 1: DFIG with NPSS-1 Connected to Series-Compensated Transmission Line

This application case is based on SSO events in Northern China's Guyuan wind power system. SSO in target system occurred due to interaction between DFIG-based wind farms and a series-compensated network. Further details on SSO phenomenon can be found in [36]. Several theoretical studies have established modifying individual wind farms may reduce overall severity of the SSOs. Compared to GSC, RSC control has noticeable impact on defining impedance of the whole DFIG. In addition, voltage control capability of GSC is restricted, especially at high series compensation levels and low wind speeds – and that's when SSO usually occurs. Therefore, NPSS-1 is added to RSC control.

To this end, DFIG controllers of four wind turbines in Guyuan's Lianhuatan wind farms have been upgraded by

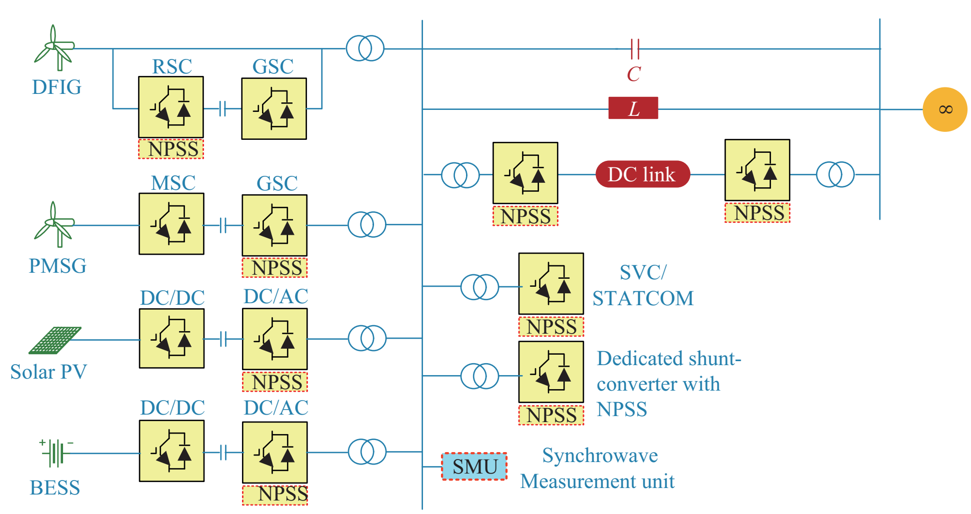

Fig. 7. A typical converter-dominated modern power system.

adding NPSS-1 [14]. NPSS-1 was added in both dq-axes of current controllers, as shown in Fig. 8. It improved overall stable performance of DFIG's converter control. It can be understood as a virtual impedance added in parallel to inner current controllers, adding positive resistance in SSO frequency range. d-axis impedance of RSC control as seen from stator terminals and ignoring dynamics of slower outer control loops, is given as:

$$Z_{\mathrm{dRSC}}(s) = sL_r + \frac{s}{s - j\omega_r}\left(R_r + K_{\mathrm{pr}} + \frac{K_{ir}}{s - j\omega_0} + Z_{\text{NPSS-1}}(s) - jK_{\mathrm{dr}}\right) \quad (6)$$

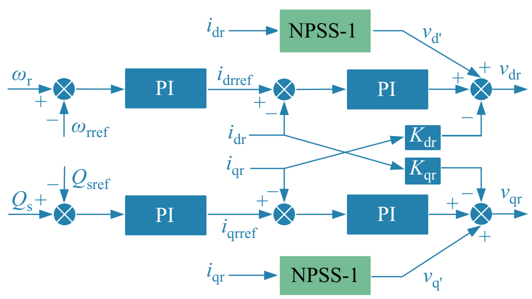

Fig. 8. NPSS-1 embedded into DFIG's RSC control.

Parameters of NPSS-1 are given in [14]. NPSS-1 implementation in [14] also uses an extraction filtering module to ensure control modification does not affect normal operation of wind turbine but only changes dynamics at concerned oscillation frequency of around 6 Hz.

Figure 9(a) shows field-recorded DFIG's stator current before and after inserting NPSS-1 as a countermeasure to SSO. Field results demonstrate excellent damping ability of DFIG controller when NPSS-1 is put into service. Frequency spectrum of current in Fig. 9(b) also demonstrates significant suppression of around 6 Hz oscillation.

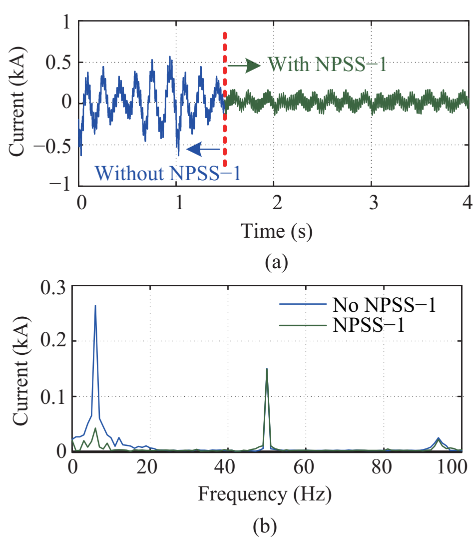

Fig. 9. DFIG output current and its FFT with and without NPSS-1. (a) Output current without and with NPSS-1. (b) Frequency spectrum of the output current without and with NPSS-1.

C. Case 2: DFIG with NPSS-2 Connected to MTDC Network

The second application case is based on actual SSO events in DIFG-PV farms connected to a multi-terminal high-voltage DC (MTDC) network in Zhangjiakou, Northern China. The SSO event is the first of its kind as it is caused by interaction between DFIG-based wind farms and MTDC network where MTDC network, as seen from wind farm side converter station, behaved as a virtual capacitor at SSO frequency [37]. Taking into account basic principle of SSO associated DFIG wind turbines, SSO can be suppressed by supplementing DFIG converter controls with NPSS. In this case, NPSS-2 is chosen to upgrade DFIGs' converter controls [38]. NPSS-2 is added in series in inner current control in d-axis only, as shown in Fig. 10. Ignoring dynamics of rather slower outer control loops, impedance of RSC control at oscillation frequency is given as:

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

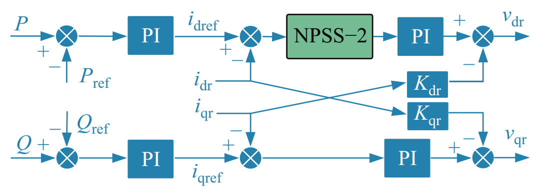

Fig. 10. NPSS-2 embedded into DFIG's RSC control.

Parameters of NPSS-2 are chosen such that it offers robust damping performance under a wide range of operating conditions. This ensures reliable damping performance of NPSS-2 under varying operating conditions such as wind speed and number of in-service wind turbines. Center frequency of notch filter in NPSS-2 is set to 4 Hz, which in dq-domain would become 46 Hz for a 50 Hz system. NPSS-2 is implemented in three out of six DFIG wind turbines in Mijiagou wind farm in Zhangjiakou [38]. Fig. 11 shows oscillation component extracted from field recorded current through wind farm's collecting cables. Results show 2.1 Hz SSO is suppressed with NPSS-2 being in service. Successful application of NPSS-2 in a practical wind power system ensured stable operation of target system.

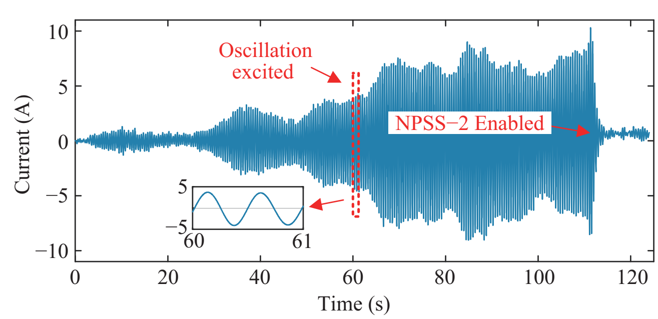

Fig. 11. Subsynchronous current filtered from field recorded line current of the wind farm before and after enabling NPSS-2.

D. Case 3: BESS with NPSS-3 Connected to PCC of a Type-4 Wind Farm Connected to Weak AC Grid

Case 3 is based on a hypothetical test system consisting of a 200 MW type-4 wind farm connected to a weak ac grid. In addition, a 10 MW BESS (which is 5% of total capacity of wind farm) is connected at point of interconnection (POI) with its primary purpose being storing excess energy and supplying when needed. System one-line diagram is shown in Fig. 12. Type-4 wind turbines adopt grid following control mode while BESS is controlled in grid-forming mode. System experiences 45/55 Hz coupled SSO under weak grid conditions, i.e. when short circuit ratio is suddenly changed from 4 to 1.91 at $t = 4$ s.

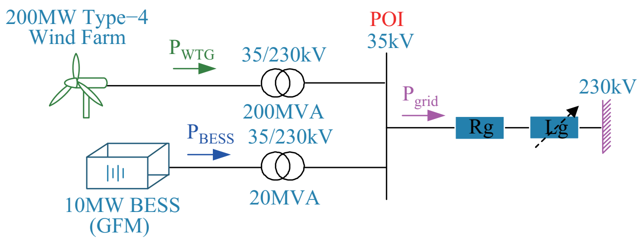

Fig. 12. Type-4 wind farm and BESS connected to a weak grid.

BESS's virtual synchronous generator control includes dq-axes inner current controllers to ensure control stability. To dampen SSO, NPSS-3 can be added to inner current controllers of both type-4 wind turbine's grid following control and BESS's grid forming control. Here, NPSS-3 is added to inner current controllers of grid forming control. This is favorable because BESS is a single unit or a relatively larger capacity, whereas wind turbines are of tens of hundreds in number or smaller in capacity. Thus, in some cases, it would be easier and more economical to add a damping function or NPSS-3 in one BESS unit instead of hundreds of wind turbine units.

Figure 13 shows BESS's grid forming control structure with NPSS-3 implemented in parallel to PI regulators in fast-acting inner current controllers. Grid current and total active power after adding NPSS-3 are shown in Fig. 14. Results demonstrate SSO is damped when BESS is equipped with NPSS-3.

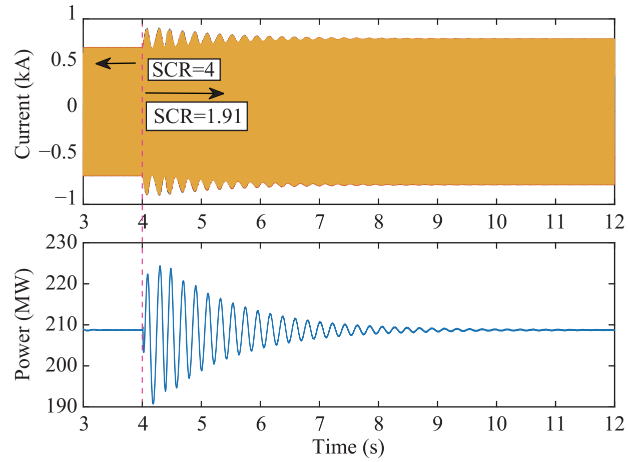

Fig. 14. Total line current and active power flow after adding the NPSS-3.

E. Case 4: Dedicated Shunt-Converter with NPSS-4 Connected to PCC of a Series Compensated Type-3 Wind Farm

Case 4 demonstrates implementation of NPSS-4 with a shunt-converter connected at the POI to damp SSO in Guyuan wind power system, with its simplified representation shown in Fig. 15. System experienced several 6–9 Hz SSO events under certain system operating conditions. The basic idea of this NPSS configuration is taken from so-called grid-side sub-synchronous damping controller (GSDC), which is a custom shunt-converter for injection of phase-shifted oscillation currents into system [13]. This way, system's overall impedance response at specific oscillation frequency is reshaped. NPSS-4 design structure is responsible to generate appropriate reference control signals for custom shunt converter. Impedance of wind farm after adding shunt-converter with NPSS-4 is given as:

$$Z'_{WF}(s) = \frac{u_{\mathrm{B}}}{i_{\mathrm{L}}} = \frac{u_{\mathrm{B}}}{i_W - i_{\text{NPSS-4}}} \tag{8}$$

where u_{B} is bus voltage; i_{L} and i_{w} are line currents entering and leaving bus, and $i_{\text{NPSS-4}}$ is current generated by shunt converter (neglecting the control delay).

NPSS-4 structure uses a series of carefully tuned band-pass and band-stop filters to extract 7 Hz SSO component and

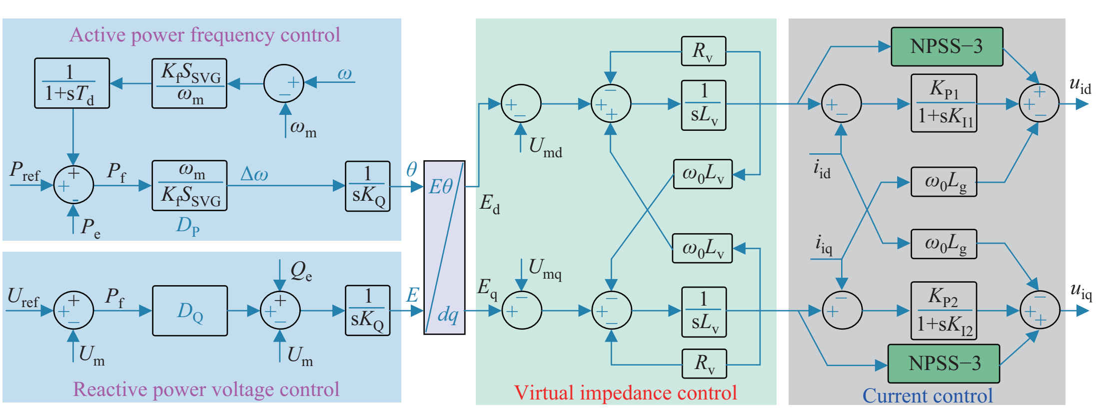

Fig. 13. NPSS-3 embedded into grid forming control of BESS.

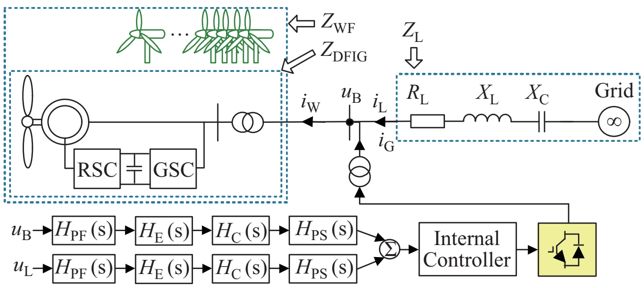

Fig. 15. A series-compensated wind power system with NPSS-4.

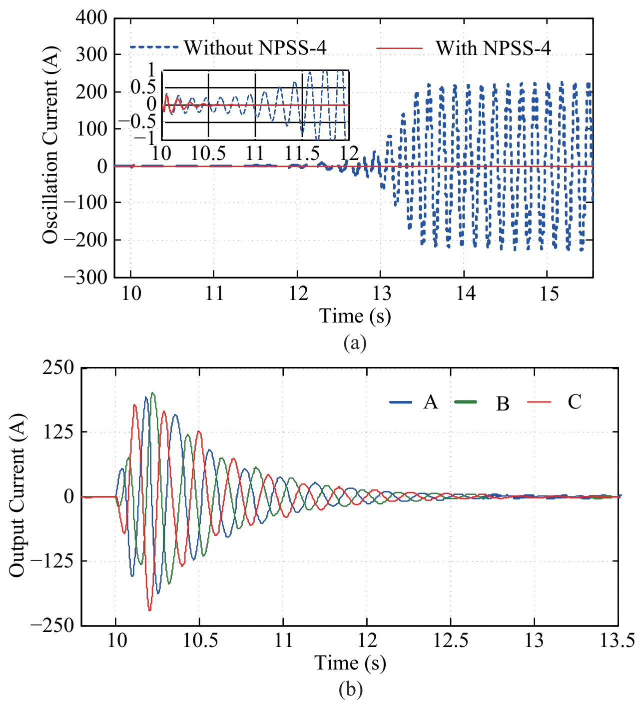

Fig. 16. Dedicated shunt converter with NPSS-4. (a) Subsynchronous current (b) Three-phase injected currents.

remove 50 Hz fundamental and other coupled frequency components. Gain and phase shifters then compensate for gain and phase lead/lag incurred by filters and maintain required phase shift. In [13], actual controller hardware has been extensively validated through CHIL simulations and later implemented in Guyuan wind power system facing SSO in Northern China. Subsynchronous components of measured line current with and without adding shunt-converter-based NPSS-4 are shown in Fig. 16(a). Three-phase oscillation currents injected by shunt converter are shown in Fig. 16(b).

1) Single Mode Adaptive NPSS-4 with Shunt-Converter

Shunt-converter with NPSS-4 discussed in previous subsection is tuned and designed to operate at a fixed oscillation frequency which is known only after oscillation event has occurred. Traditional phasor measurement units (PMUs) with added functionality to track inter harmonics or synchronous waveform measurement units (SWMUs) may be installed at POI to track oscillation phasors [39]. With magnitude and frequency of oscillation available, NPSS-4 design can be made adaptive to oscillation frequency and magnitude. In [27], a single-mode adaptive NPSS-4 (ANPSS-4) is designed to dampen SSO without knowing oscillation frequency beforehand. Fig. 17 shows tracked oscillation frequency, active power without and with NPSS-4, and injected oscillation currents. Results are promising as oscillation is quickly detected and damped out.

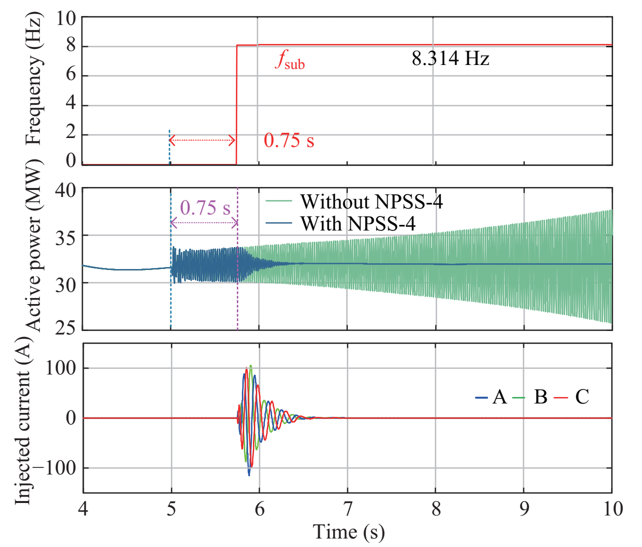

Fig. 17. Dedicated shunt converter with NPSS-4: estimated oscillation frequency, active power flow, and injected subsynchronous current.

2) Multi-Mode Adaptive NPSS-4 with Shunt-Converter

In practical scenarios, multiple oscillation modes may be excited due to adverse control participated interactions. In [25], ANPSS-4 design is extended to damp two oscillation modes simultaneously. Interharmonic estimation algorithm used in [25] is able to track frequencies of two oscillation modes in a type-4 wind farm connected to a weak ac grid. Tracked oscillation frequencies, active power flow, and three-phase injected currents are shown in Fig. 18.

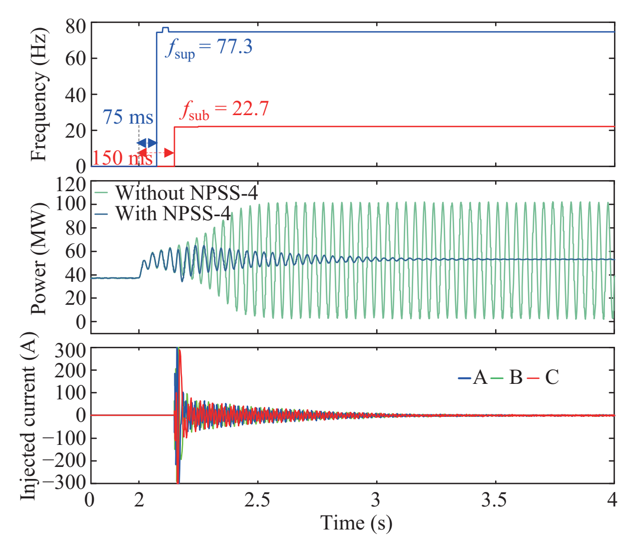

Fig. 18. Dedicated shunt converter with NPSS-4: estimate oscillation frequency, active power flow, and injected subsynchronous current.

F. Case 5: MMC-HVDC Converter with NPSS-2

This case presents a scenario where adaptive new power system stabilizer (ANPSS-2) is used to mitigate HFR, validated through a detailed EMT model of a real-world MMC-HVDC system [40]. Target system model is based on Luxi MMC-HVDC system in South-Western China. Characteristic analysis of resonance event shows system-wide operating conditions determine resonance frequency and is subject to varying operating conditions. There exists a positive and a negative sequence component around 1272 Hz. For mitigating HFR, [26] uses a notch filter or NPSS-2 configuration since it can effectively notch out resonance and this configuration is suitable for high frequencies. Filters are added in parallel to current controller PI regulators in dq-axes of positive and negative sequence controls. Notch filters are made adaptive to oscillation frequency variations to solve the problem of WBO's time-varying characteristics. Magnitude and frequency of HFR are estimated using Hanning windowed DFT with interpolation. When the HFR occurs, NPSS-2 is automatically enabled to suppress it. Fig. 19 shows estimated frequency and MMC output currents. Results show HFR is mitigated even when frequency is suddenly changed from 1273 Hz to 1420 Hz.

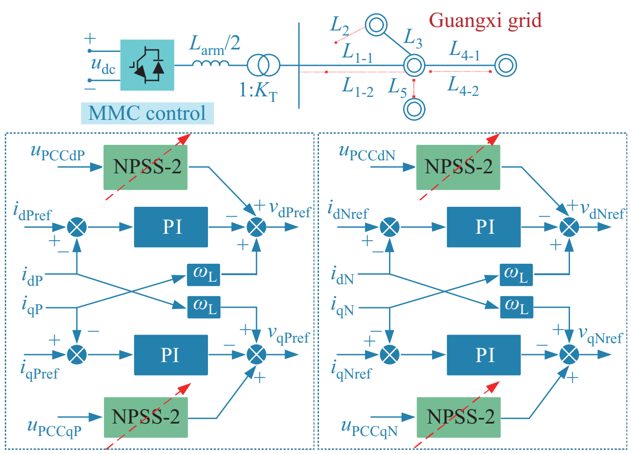

Fig. 19. ANPSS-2 embedded into MMC-HVDC control in Guangxi, China.

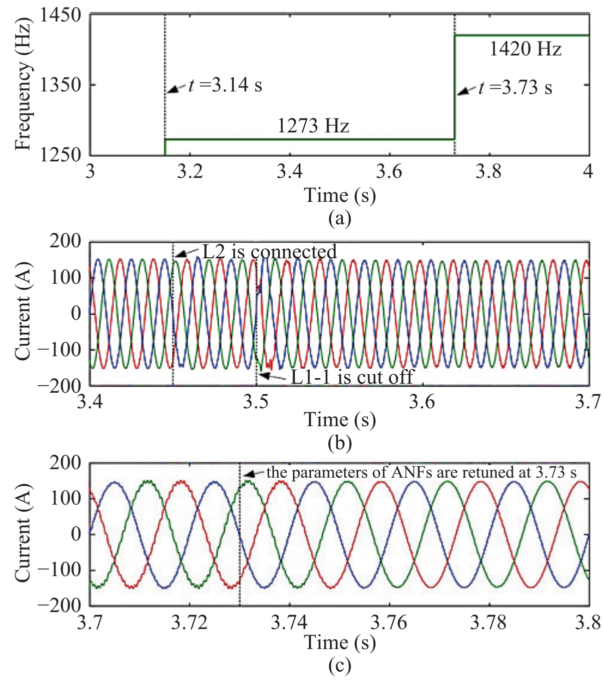

Fig. 20. Case 5: Adaptive-NPSS-2 embedded into MMC-HVDC converter. (a) Estimated frequency. (b) MMC output current first set of operating conditions. (c) MMC output current second set of operating conditions.

VI. Challenges and Future Works

Some challenges related to the concept of NPSS include design principles, practical implementation, equipment limitations, and standardizations. Below, we list some of the dire challenges that must be addressed.

1) In theory, solving adaptive and/or robustness problems is necessary so NPSSs dampen the WBOs under a wide range of system working conditions and time-varying oscillation frequencies. In practice, efficient control equipment is lacking to suppress the WBOs.

2) A properly designed NPSS must consider factors such as type, connection scheme, capacity, primary objective, and control structures of converter-based devices. Effect of implementing NPSSs with a converter-based device on controller bandwidth and device's dynamic performance needs rigorous research. For example, a STATCOM operates at system frequency; however, if it is supplemented with an NPSS to add power oscillation damping functions, it may lead to DC fluctuations leading to equipment damage.

4) Capacity of a converter-based device equipped with an NPSS plays an important role in providing overall positive damping to system-wide WBOs. Thus, capacity limitations, such as BESS's active power limitations, should be considered.

5) If multiple converter-based devices in a system are equipped with NPSS, there needs to be coordination between different NPPs so risk of system-wide unstable multi-modal WOBs can be effectively reduced. This results in reduced capacity requirements for damping WBOs. Establishing optimal coordination between different converter-based devices with NPSSs to achieve the desired performance objective (e.g., damping rate) is an open research area to look into.

6) Applications of synchronous condensers are increasing to enhance grid strength in a weak ac power grid. PSSs/NPSSs can also be added to these to add damping to power system oscillations.

VII. Conclusion

In an actual converter-dominated power system, complexity of diverse equipment and coupling dynamics of different time scales lead to unstable WBOs with time-varying characteristics. This poses significant adaptability and robustness challenges to control system's overall configuration and parameter design. To address these challenges, use of converter-based devices equipped with NPSSs is a promising approach for effectively mitigating WBOs in converter-dominated power systems. This paper presented design and implementation of a few possible NPSS structures. Design considerations and performance requirements of NPSS to mitigate WBO are essentially different from the same for PSS to damp LFO. The authors believe this is an important area of research, which is open for novel developments to address the WBO problem in converter-dominated power systems.

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Jan Shair received Ph.D. degree in Electrical Engineering from Tsinghua University, Beijing, China, in 2021. Currently, he is working as Tsinghua-Shuimu Fellow at Tsinghua University. His research interests include modeling, analysis, and control of subsynchronous oscillation/resonance in converter-dominated power systems. He is a member of the IEEE Task Force on IBR-SSO and a contributor to several IEC and CIGRE working groups related to subsynchronous oscillation in new power system. Dr. Shair also serves as Guest Associate Editor of a Special Issue on "Control Interactions in Power Electronic Converter Dominated Power Systems" in *International Journal of Electrical Power and Energy Systems*.

Xiaorong Xie is a Professor and Director of the Flexible Transmission & Distribution Systems Research Institute at the Department of Electrical Engineering, Tsinghua University, China. His research interests include dynamics analysis and control of power systems, especially those with high penetration of renewable energy sources and power electronics. Dr. Xie is an Editor of *IEEE Transaction on Power Delivery* and Associate Editor for *IET Renewable Power Generation and International Journal of Electrical Power and Energy Systems*.

Haozhi Li received a B.S. degree in 2019 in Electrical Engineering from Tsinghua University, Beijing, China, where he is currently working toward a P.hD. degree. His research focuses on the mitigation of subsynchronous oscillation in power systems.

Vladimir Terzija received the Dipl-Ing., M.Sc., and Ph.D. degrees in Electrical Engineering from the University of Belgrade, Beograd, Serbia, in 1988, 1993, and 1997, respectively. He is the EPSRC Chair Professor in Power System Engineering with the School of Electrical and Electronic Engineering, The University of Manchester, Manchester, UK. His current research interests include smart grid applications; wide-area monitoring, protection, and control; switchgear and transient processes; and ICT, data analytics and digital signal processing applications in power systems. Dr. Terzija is an Editor-in-Chief of *International Journal of Electrical Power and Energy Systems*, Alexander von Humboldt Fellow, as well as a DAAD and Taishan Scholar. He is the National Thousand Talents Distinguished Professor at Shandong University, China.