

Small-signal Stability Analysis of VSCs with Neative-sequence Current Control Based on LTP and HSS Theory

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Abstract—In many countries, the negative sequence current control (NSCC) has been the national standard for connecting renewable energy to power systems. At the same time, the original relationship of voltage source converters (VSCs), commonly used in renewable power generation, shows inherent periodic time-varying characteristics. Considering the pros and cons of the different small-signal models for nonlinear time-varying systems, the comprehensive analysis based on linear time periodic (LTP) and harmonic state-space (HSS) models are introduced to studying the small-signal stability of power systems dominated by VSCs with NSCC. Considering the advantages of the LTP model in stability determination, the stable domains of control parameters are described. Additionally, the structural effect of the decoupled double synchronous reference frame (DDSRF), widely used for separating positive and negative sequences, is compared. Then, considering that the HSS model is a linear time-invariant (LTI) model, and its stability mechanism analysis method is mature, we characterize the interaction among controls based on the participation factor analysis. These comprehensive analysis results are beneficial for understanding the impact of NSCC on system dynamics and provide theoretical support for the optimization of NSCC and DDSRF. Finally, case studies validate the effectiveness of the analysis results.

Index Terms—Decoupled double synchronous reference frame (DDSRF), harmonic state-space (HSS), linear time periodic (LTP), negative sequence current control (NSCC), voltage source converter (VSC).

I. INTRODUCTION

RENEWABLE energy, represented by wind power and photovoltaic, has dramatically developed [1]–[5], and

their total installed capacity has exceeded 1.2 billion kilowatts in August 2024 in China, achieving the national energy targets 6 years ahead of schedule. This has led to a power system increasingly dominated by voltage source converters (VSCs), which are extensively used in renewable power generation (RPG). Since RPG is mainly located at the end of the power grid [6], the strength of the power grid is weak, and the unbalanced grid conditions due to AC grid faults are rather general [7]–[10]. Therefore, the grid connection conditions of VSC further deteriorate. To improve the ability of VSC grid connection under complex grid conditions, one of the requirements for grid code is that the converters should have the negative sequence current control (NSCC) [11]–[13]. However, the dynamic stability of power systems dominated by VSCs with NSCC may deteriorate and require urgent study.

The structure of NSCC mainly adopts linear proportional-integral (PI) control in a negative sequence rotating coordinate system. Therefore, a process for separating positive and negative sequences is necessary [14] is needed. After considering the NSCC and positive and negative sequence separation process, the original relationship of VSCs shows inherent periodic time-varying characteristics [15]. Then, several methods were introduced to study the electromagnetic stability. The early method is based on electromagnetic transient simulation [16]. However, this method can only summarize the criteria of system instability via simulated results without the quantitative mechanism analysis. Therefore, many attempts have been made to establish a small-signal model for electromagnetic stability analysis.

For the small-signal modeling method of VSCs with only positive sequence current control (PSCC), their periodic time-varying feature can be transformed into a time-invariant one through Park transformation [17], dynamic phasors [18], and harmonic linearization or impedance [19]–[21]. Then, a linear time-invariant (LTI) model is obtained by linearizing the system at a constant operating point, which serves as the basis for dynamic stability analysis using typical LTI system analysis methods. Therefore, the modeling idea of time-invariant processing for original nonlinear time-varying relationships is considered for small-signal modeling of the VSC with NSCC. [22] built the modeling of the asymmetrical-faulted grid by decomposing coupled sequences via complex

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vectors, which is the basis for studying the dynamic stability of VSCs under unbalanced grid conditions. Then, the small-signal stability of grid-connected doubly fed induction generator (DFIG) based wind turbines and the VSC during weak-grid asymmetric faults are studied in [23], [24]. However, some ideal assumptions are necessary, such as positive and negative sequence components are perfectly separated and some time-varying components are ignored, which fail to truly reflect the complex coupling characteristics between NSCC and other controls.

Another important small-signal modeling method is the linear time-periodic (LTP) model [25], [26], which is based on the trajectory linearization for nonlinear time-periodic equations. Compared with the traditional model based on LTI theory, the LTP model avoids complex transformations, thus retaining the original time-varying coupling characteristics. Meanwhile, it has been widely used in grid-connected inverters with PI control [27] and proportional-resonant (PR) control [28], as well as in modular multilevel converter (MMC) grid-connected systems under unbalanced grid conditions [29]. Therefore, these applications highlight the LTP model's superior accuracy and adaptability across diverse scenarios [30], [31], especially for power systems dominated by VSCs. Based on the Floquet-Lyapunov theory [32], the analysis method of the LTP model still has limitations. In addition to being able to make accurate stability determinations, other information, such as stability dominant factors, cannot be obtained [29]. Therefore, the LTP model is commonly used to describe the stable range of system parameters. Facing the limitations of the LTP model, [33] transformed the LTP model into the harmonic state-space (HSS) model. The HSS model is a doubly infinite constant matrix in theory (i.e., LTI model). Thus, the mature analysis methods of the LTI system can apply to the HSS model, although it faces truncation problems in the actual calculation process. By constructing the relationship between the analysis results of the truncated HSS model and the LTP model, [34] proposed a practical and physically meaningful method for truncating the HSS model. Then, the key factors leading to system stability can be analyzed using the participation factor analysis of the LTI system. However, affected by spurious eigenvalues of truncated HSS mode, the description of stable parameter domains is not convenient.

To face the pros and cons of the LTP and HSS models, we propose to study the effect of NSCC through a comprehensive analysis of both models, which is the core contribution of this paper. Given the advantage of the LTP model in accurately determining system stability, the stable domains of different control parameters are described by the LTP model. The control structures for the positive and negative sequence separation process are varied, and we adopt the most commonly used one, namely, the decoupled double synchronous reference frame (DDSRF) [35]. However, the influence of the DDSRF structure on the small-signal dynamic stability is rarely discussed. Thus, the stable parameter domains are compared under different DDSRF structures, and a DDSRF structure is recommended based on system stability. Considering the limitation that the LTP model can only determine whether the system is stable, we further introduce the HSS model for in-depth analysis of

the mechanism. Therefore, the stability mechanism and the key factors that dominate the system stability are given by the HSS model. These comprehensive analyses are beneficial for understanding the impact of NSCC on system dynamics and provide theoretical support for optimizing NSCC and DDSRF. The contributions of this article can be concluded as:

- 1) We propose to study the effect of NSCC through a comprehensive analysis of both LTP and HSS models.
- 2) Based on the accurate description of the stable parameter range by the LTP model, NSCC and DDSRF structure have a great effect on small-signal stability.
- 3) Type I DDSRF is beneficial for improving small-signal stability, and this conclusion is also applicable to other multi-machine systems.
- 4) The structure of DDSRF affects the interactions among controls of VSCs, with Type I DDSRF reducing the interaction between NSCC and other controls.

This paper is organized as follows. Section II illustrates the essential structure of a single-VSC grid-connected system and builds its LTP and HSS model. Then, the stable parameter domains for different controls are described by the LTP model in Section III. Section IV studies the interaction among NSCC and other controls using the truncated HSS model. Then, the analysis results are verified in Section V by the single-machine VSC grid-connected system and a multi-machine VSC grid-connected system in RT-LAB, respectively. Finally, Section VI draws some conclusions.

II. THE SINGLE-VSC GRID-CONNECTED SYSTEM AND ITS LTP/HSS MODEL

A. A Single-VSC Grid-connected System

Due to the variety of RPGs, we choose to consider the inverter as a typical representative for the study. As shown

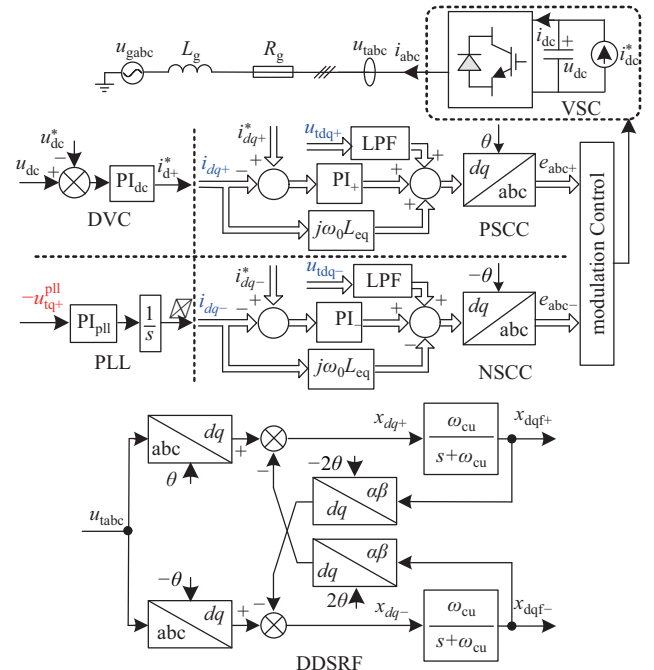


Fig. 1. A single-VSC grid-connected system.

in Fig. 1, a single-VSC grid-connected system is given. The DC side is simplified as a constant current source, and the dynamic of DC capacitance is reserved. u_{dc} and i_{dc} are the DC voltage and current. The inductive L_g and resistance R_g form the power grid, which contains the transformer's leakage reactance. The diagrams of the control system are commonly used in projects. To highlight the focus of this paper, we only consider the PSCC, NSCC, DC voltage control (DVC), DDSRF control, and phase-locked loop (PLL) control.

B. LTP Modeling of the Single-vsc Grid-connected System

The LTP modeling process is mature [26], [29], [36]. Therefore, only the LTP modeling of coordinate transformation is given to illustrate. For a general three-phase variable $\mathbf{x}$ (bold variables are matrix or vectors), the transformation between ABC and DQ can be repressed as

$$\mathbf{x}_{dq} = [x_d \ x_q]^T = \mathbf{P}_{k\theta} \mathbf{T} [x_a \ x_b \ x_c]^T = \mathbf{P}_{k\theta} \mathbf{T} \mathbf{x}_{abc} \quad (1)$$

$$\mathbf{P}_{k\theta} = [\cos(k\theta) \ -\sin(k\theta); \sin(k\theta) \ \cos(k\theta)] \quad (2)$$

where $\mathbf{T}$ is the constant amplitude Clark transformation matrix, $\mathbf{P}_{k\theta}$ is the Park transformation matrix, and θ comes from PLL control, the integer k represents the multiples and direction of rotation transformation.

Then, the results of the trajectory linearization for this coordinate transformation are

$$\Delta \mathbf{x}_{dq} = \mathbf{P}_{k\theta_0} \mathbf{T} \Delta \mathbf{x}_{abc} + [-x_{q0} \ x_{d0}]^T k \Delta \theta \quad (3)$$

where the prefix ' Δ ' represents a small perturbation of variables, and the subscript '0' means the trajectories of variables in steady-state conditions.

Similarly, the LTP model of the single-VSC grid-connected system can be obtained, and its state-space equation is

$$\Delta \dot{\mathbf{x}}(t) = \mathbf{A}(t) \Delta \mathbf{x}(t) + \mathbf{B}(t) \Delta \mathbf{u}(t) \quad (4)$$

$$\Delta \mathbf{u}(t) = [\Delta i_{dc}^*; \Delta u_{dc}^*; \Delta i_{q+}^*; \Delta i_{dq-}^*; \Delta \mathbf{u}_{gabc}] \quad (5)$$

where $\mathbf{A}(t)$, $\mathbf{B}(t)$ are system matrix, $\mathbf{x}(t)$ and $\mathbf{u}(t)$ are state vector and input vector, respectively. The detail expressions of $\mathbf{A}(t)$, $\mathbf{B}(t)$, and $\mathbf{x}(t)$ are not given due to the limited space.

C. HSS Modeling of the Single-vsc Grid-connected System

The HSS model can be obtained from the LTP model. A brief modeling process is presented here. First, define an exponentially modulated periodic (EMP) signal as the input signal of the LTP system,

$$\Delta \mathbf{u}(t) = e^{st} \sum_{n=-\infty}^{\infty} \mathbf{U}_n e^{jn\omega_0 t} = \sum_{n=-\infty}^{\infty} \mathbf{U}_n e^{s_n t} \quad (6)$$

where $s_n = s + jn\omega_0$.

The state variables and output signals also have the form of EMP signals, whose frequency components are the same as the input EMP signals, ensuring that the input and output signals have the same signal space. The state variables are expressed in complex exponential form as

$$\Delta \mathbf{x}(t) = \sum_{m=-\infty}^{\infty} \mathbf{X}_m e^{s_m t} \quad \Delta \dot{\mathbf{x}}(t) = \sum_{m=-\infty}^{\infty} \mathbf{X}_m s_m e^{s_m t} \quad (7)$$

Besides, the periodic time-varying coefficient matrix $\mathbf{A}(t)$ and $\mathbf{B}(t)$ is decomposed into the Fourier series form.

$$\mathbf{A}(t) = \sum_{m=-\infty}^{\infty} \mathbf{A}_m e^{jm\omega_0 t} \quad \mathbf{B}(t) = \sum_{m=-\infty}^{\infty} \mathbf{B}_m e^{jm\omega_0 t} \quad (8)$$

Substitute (6)–(8) into (4), and the coefficients of the same frequency on both sides of the equation are equal due to the principle of harmonic balance. Then, we can obtain the HSS mode as a Toeplitz matrix.

$$\mathbf{s} \mathbf{X}_{hss} = (\mathbf{A}_{hss} - \mathbf{N}_{hss}) \mathbf{X}_{hss} + \mathbf{B}_{hss} \mathbf{U}_{hss} \quad (9)$$

$$\mathbf{X}_{hss} = [\cdots, \mathbf{X}_{-2}, \mathbf{X}_{-1}, \mathbf{X}_0, \mathbf{X}_1, \mathbf{X}_2, \cdots]^T \quad (10)$$

$$\mathbf{U}_{hss} = [\cdots, \mathbf{U}_{-2}, \mathbf{U}_{-1}, \mathbf{U}_0, \mathbf{U}_1, \mathbf{U}_2, \cdots]^T \quad (11)$$

$$\mathbf{A}_{hss} = \begin{bmatrix} \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ \cdots & \mathbf{A}_0 & \mathbf{A}_{-1} & \mathbf{A}_{-2} & \mathbf{A}_{-3} & \mathbf{A}_{-4} & \cdots \\ \cdots & \mathbf{A}_1 & \mathbf{A}_0 & \mathbf{A}_{-1} & \mathbf{A}_{-2} & \mathbf{A}_{-3} & \cdots \\ \cdots & \mathbf{A}_2 & \mathbf{A}_1 & \mathbf{A}_0 & \mathbf{A}_{-1} & \mathbf{A}_{-2} & \cdots \\ \cdots & \mathbf{A}_3 & \mathbf{A}_2 & \mathbf{A}_1 & \mathbf{A}_0 & \mathbf{A}_{-1} & \cdots \\ \cdots & \mathbf{A}_4 & \mathbf{A}_3 & \mathbf{A}_2 & \mathbf{A}_1 & \mathbf{A}_0 & \cdots \\ \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad (12)$$

D. The Validation of the LTP Model

Before carrying out the small-signal stability analysis, it is necessary to conduct a preliminary verification of the small-signal model. The parameters are shown in Appendix A. Initially, an unbalanced grid condition is simulated by setting u_{ga} to zero. The reference of DVC u_{dc}^* is set as 1.0 p.u. The references of currents control i_{q+}^* and i_{dq-}^* are set as 0 p.u. As shown in Fig. 2, since the positive and negative sequence separation process cannot achieve ideal sequence separation, the positive and negative currents in the DQ rotating coordinate are all not constant values, which also reflects the time-varying coupling characteristics of the studied system. Then, a tiny perturbation of +0.01 p.u. is added to u_{dc}^* at 1.5 s, and the time domain results of i_{dq+} , and i_{dq-} are given in Fig. 2. The time-domain response of the LTP model (solid blue line) coincides with the electromagnetic transient (EMT) model (red dotted line). Therefore, the LTP model is validated.

III. STABILITY ANALYSIS THROUGH THE LTP MODEL

A. The Stability Analysis Method for an LTP System

Compared with the typical LTI system, the analysis method of an LTP system is still immature. Based on the Floquet-Lyapunov theory [32], any LTP system can be equivalently transformed into an LTI system. The state variables of the obtained LTI system is $\mathbf{v}(t)$, and the relationship between the state variables of the LTP system $\mathbf{x}(t)$ and $\mathbf{v}(t)$ is

$$\mathbf{v}(t) = \mathbf{P}(t) \mathbf{x}(t) \quad (13)$$

where the periodic matrix $\mathbf{P}(t)$ is the transformation matrix.

Then, the general state-space LTP equation (4) is transformed as,

$$\dot{\mathbf{v}}(t) = (\mathbf{P}(t) \mathbf{A}(t) + \dot{\mathbf{P}}(t)) \mathbf{P}^{-1}(t) \mathbf{v}(t) = \mathbf{Q} \mathbf{v}(t) \quad (14)$$

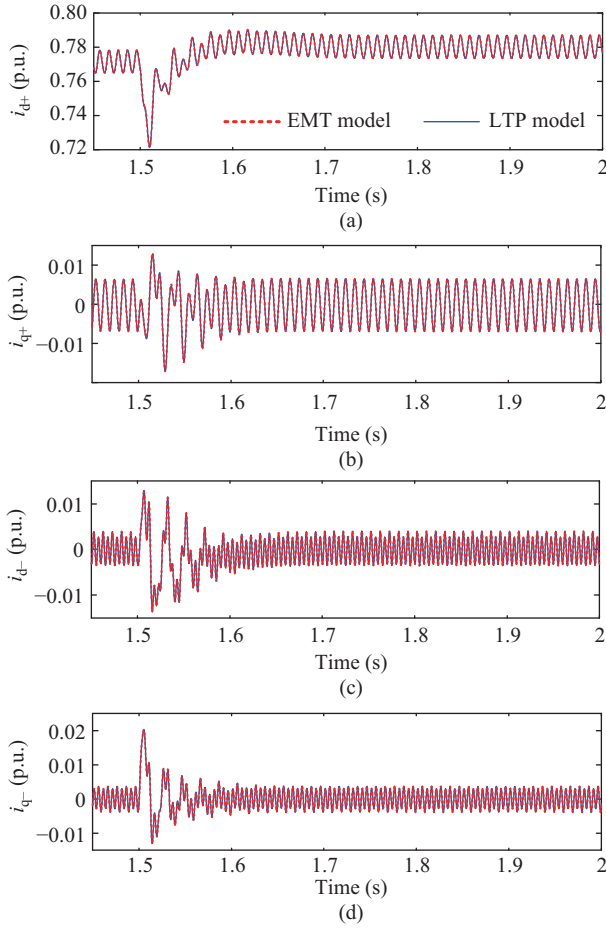


Fig. 2. The time-domain response of EMT model and LTP model, (a) i_{d+} , (b) i_{q+} , (c) i_{d-} , (d) i_{q-} .

where matrix Q is the system matrix of the obtained LTI model.

However, the existing theory does not provide a method for constructing an analytical expression of $P(t)$. Because the LTP model of VSC grid-tied systems is complicated, we cannot obtain an analytical expression of $P(t)$. Therefore, to perform a stability analysis of the LTP system, the state transition matrix (STM) $\Phi(T, 0)$ should be calculated first, where $T = (2\pi)/\omega_0$. Then, based on the connection between $\Phi(T, 0)$ and matrix Q of the LTI system, the numerical result of matrix Q is obtained, whose eigenvalues are the Floquet characteristic exponents (FCE). The real part of FCE represents the system damping, which is a measure of stability. Due to the matrix exponential function operation, the imaginary part of FCE lies between $[-\omega_0/2, \omega_0/2]$. The frequency obtained from FCE differs from the integer multiple of ω_0 , where the multiple is unknown. The analysis method for the LTP model is summarized in Fig. 3. Therefore, the stability domains of different system parameters are described by FCE.

B. Impact of Structure and Parameters of DDSRF

As DDSRF control was proposed in [35], it has been widely adopted in various power electronics applications. Although the core idea of DDSRF is the same, its structure has specific differences based on the output. According to whether the

output signal is before or after the low pass filter (LPF), [37] call DDSRF as feedback structure and feedforward structure, and the structure effect of DDSRF are compared when only considering the dynamic of DDSRF and PLL control. Based on the output for current controls and PLL, there are four different structures of DDSRF control, as shown in Fig. 4. The feedback and feedforward DDSRF in [37] are Type I and Type IV DDSRF. Therefore, the effect of four DDSRF structures is compared thoroughly.

As shown in Fig. 5, the maximum real part of FCEs with different parameter combinations of current controls are given with type III DDSRF, a commonly used DDSRF structure. The parameters of PSSC and NSCC are the same, and their design principle is given in Appendix B. Within the given parameter combinations, the studied system is unstable in most parameter domains. Besides, according to the empirical current control parameters selection principle, i.e., damping is 0.707, and the bandwidth frequency is several hundred Hz, the studied system cannot be stable. For type I DDSRF, as shown in Fig. 6, the stable parameter domains are increased for all studied DDSRF-LPF bandwidths when compared with Fig. 5. Theoretically, variable $x_{dq\pm}$ contains high-frequency components, and variable $x_{dqf\pm}$ does not contain high-frequency components due to the effect of the LPF. However, from the

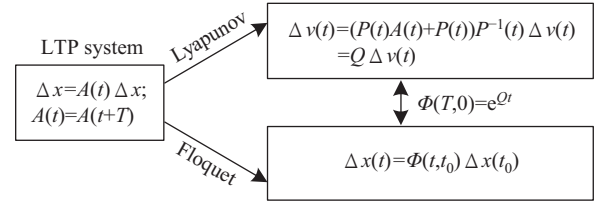


Fig. 3. The analysis methods for the LTP model.

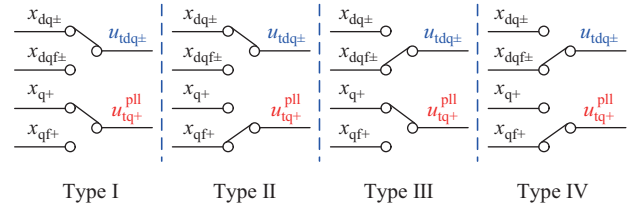


Fig. 4. Four different structures of DDSRF control.

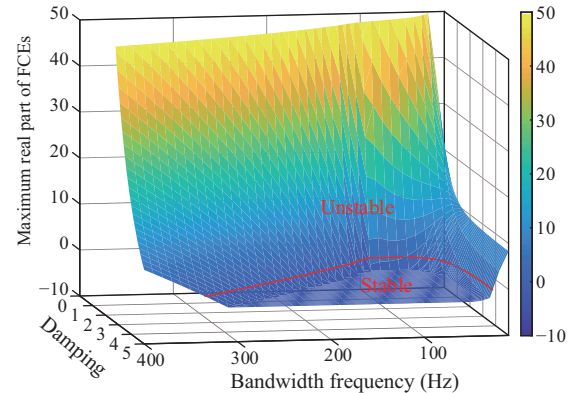


Fig. 5. The maximum real part of FCEs with different parameters combine of current controls with type III DDSRF.

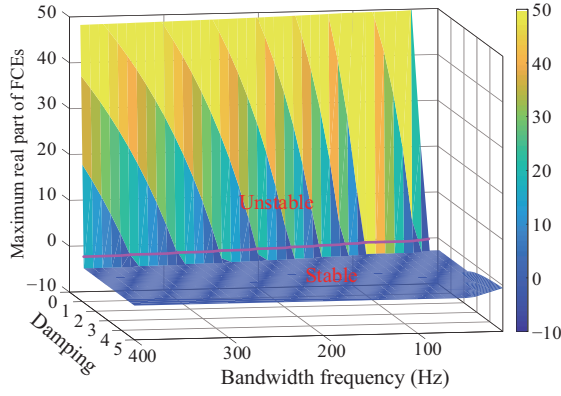


Fig. 6. The maximum real part of FCEs with different parameters combine of current controls with type I DDSRF.

perspective of small-signal stability, taking variable $x_{dq\pm}$ for PSSC and NSCC benefits the system stability. Then, the stable parameter domains of four different DDSRF structures are summarized in Fig. 7. When compared with type III and type I DDSRF, change the u_{tq+}^{pl} from x_{q+} to x_{qf+} (i.e., change type III/I to type IV/II), the small-signal stability does not change significantly. Considering that LPF may affect the dynamic response speed of PLL control, selecting the signal before the LPF (i.e., x_{q+}) as the input signal of PLL control (i.e., u_{tq+}^{pl}) is recommended.

The bandwidth of the LPF for DDSRF also has a significant effect on system stability. Considering the dynamic response speed, it is usually taken as $0.7\omega_0$ [35]. As shown in Fig. 8, the stable parameter domains of current controls with different bandwidths of LPF of type III DDSRF are given. As the DDSRF-LPF bandwidth decreases, the system stability parameter domain is decreased. Additionally, a larger DDSRF-LPF bandwidth primarily expands the stable parameter range in the lower bandwidth range of the current controls, which is not conducive to selecting current control parameters with a fast dynamic response. Then, the stable parameter domains of current controls with different DDSRF-LPF bandwidths of type I DDSRF are shown in Fig. 9, where the adjustment of DDSRF-LPF bandwidth has little effect on system stability and only affects current control parameters with damping less than 1.5. Moreover, unlike type III DDSRF, the decrease of

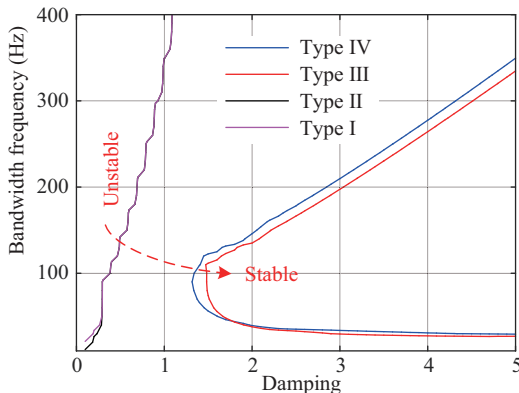


Fig. 7. The stable parameter domains of current controls with four different DDSRF structure.

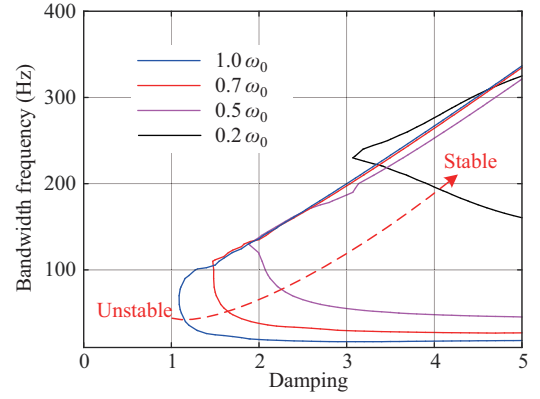


Fig. 8. The stable parameter domains of current controls with different DDSRF-LPF bandwidth of type III DDSRF.

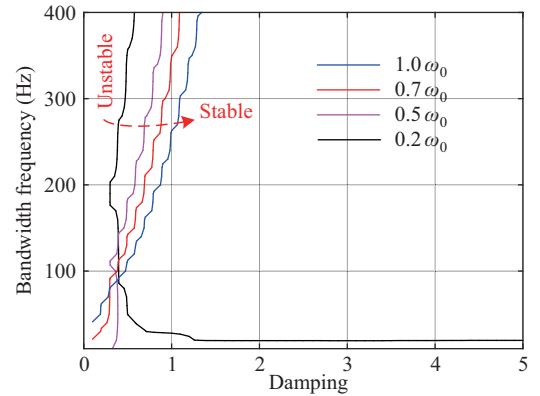


Fig. 9. The stable parameter domains of current controls with different DDSRF-LPF bandwidth of type I DDSRF.

DDSRF-LPF bandwidth of type I DDSRF benefits small-signal stability.

According to the comprehensive analysis of the influence of the structure and parameters of DDSRF, type I DDSRF is more conducive, and its parameters are less sensitive to system stability.

C. Impact of Bandwidth Frequency of NSCC

Although the previous analysis assumes that PSSC and NSCC parameters are the same, they can differ. Here, we describe the stability parameter domain of PSSC with different NSCC parameters and summarize the law governing NSCC's effect on system stability.

Initially, we set the damping of NSCC and PSSC to 2, and the bandwidth frequency of NSCC varies from 100 to 400 Hz with type I DDSRF. Then, the influence of the bandwidth frequency of PSSC from 10 Hz to 400 Hz on the FCE is given in Fig. 10. With the increase of bandwidth frequency of PSSC, as shown in Fig. 10(a), no parameter range of bandwidth frequency of PSSC makes the system unstable, and from the movement of FCE, it can be seen that a more significant bandwidth frequency of PSSC is conducive to system stability. Then, as shown in Figs. 10(b)–10(d), three other similar operations are performed, except the bandwidth frequency of NSCC is set to 200 Hz, 300 Hz, and 400 Hz, respectively. Similarly, only one pair of FCE across the imaginary axis

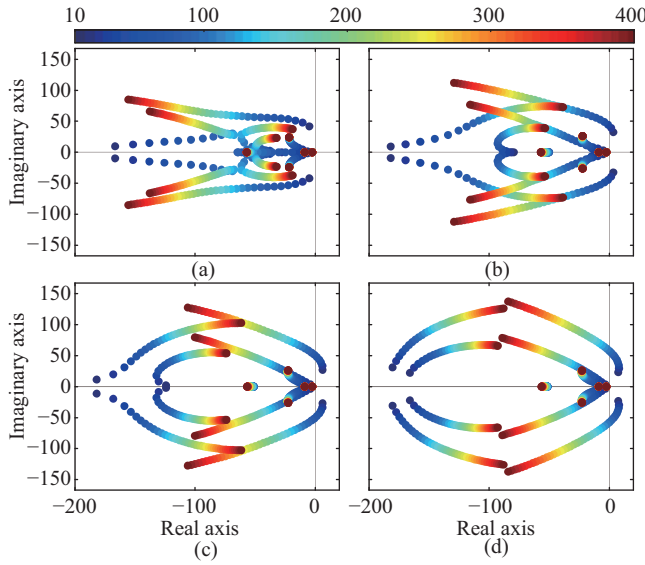


Fig. 10. The FCE for bandwidth frequency of PSCC changing from 10 Hz to 400 Hz with bandwidth frequency of NSCC (a) 100 Hz, (b) 200 Hz, (c) 300 Hz, (d) 400 Hz.

causes the system to become unstable, and the parameter range of bandwidth frequency of PSCC for a stable system for them are 30 Hz–400 Hz, 60 Hz–400 Hz, and 110 Hz–400 Hz. Therefore, the increase in bandwidth frequency of NSCC is detrimental to system stability.

Then, the influence of damping of PSCC from 0.1 to 5 on the FCE is shown in Fig. 11, where the bandwidth frequency of PSCC is 200 Hz. When the bandwidth frequency of NSCC is set to 100 Hz, as shown in Fig. 11(a), only one pair of FCE across the imaginary axis causes the system to become unstable, and the parameter range of damping of PSCC for a stable system is 0.2–5. When the bandwidth frequency of NSCC is set to 200 Hz and 300 Hz, as shown in Fig. 11(b) and (c), no parameter range of damping of PSCC makes the

system unstable. When the bandwidth frequency of NSCC is set to 400 Hz, as shown in Fig. 11(d), only one pair of FCE across the imaginary axis when the damping of PSCC is lower than 0.2.

The influences of the bandwidth frequency of NSCC on the stable parameter bounds of PSCC are summarized in Fig. 12. When the bandwidth frequency of PSCC is lower than 200 Hz, the increase in bandwidth frequency of NSCC reduces the stable parameter bounds of PSCC. When the bandwidth frequency of PSCC is larger than 200 Hz, the rise in bandwidth frequency of NSCC is beneficial to system stability, but the effect is not so noticeable.

D. Impact of Damping of NSCC

A similar method is used to study the impact of damping of NSCC. The bandwidth frequency and damping of NSCC are set to 200 Hz and 1. The damping of PSCC is set to 2. The influence of the bandwidth frequency of PSCC from 10 Hz to 400 Hz on the FCE is given in Fig. 13(a). With the increased bandwidth frequency of PSCC, one pair of FCE turns to the imaginary axis but does not cross it. Then, as

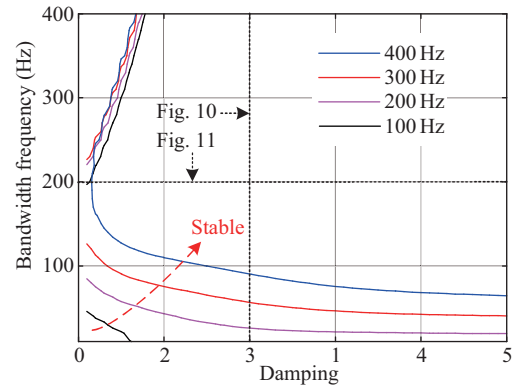


Fig. 12. The stable parameter domains of PSCC with different bandwidth of NSCC.

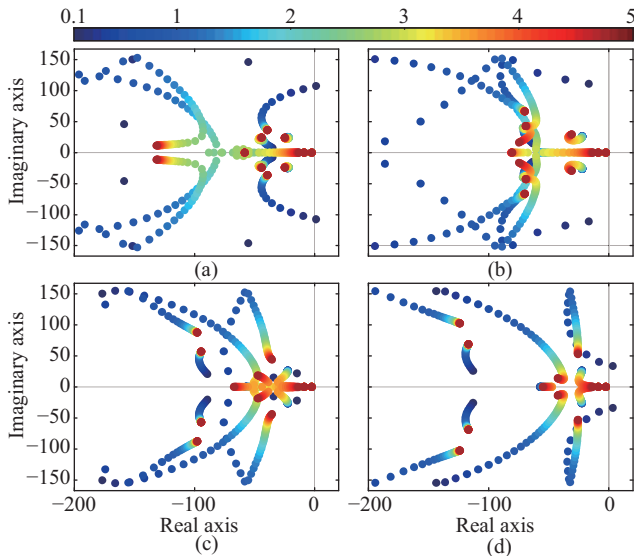


Fig. 11. The FCE for damping of PSCC changing from 0.1 to 5 with bandwidth frequency of NSCC (a) 100 Hz, (b) 200 Hz, (c) 300 Hz, (d) 400 Hz.

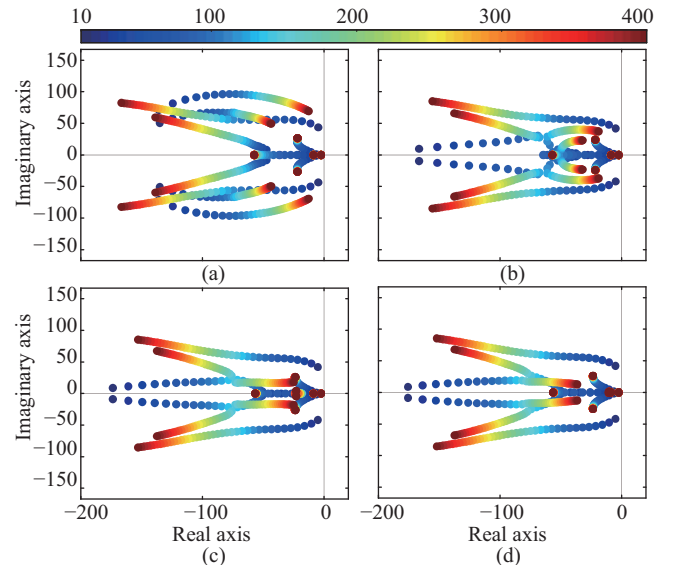


Fig. 13. The FCE for bandwidth frequency of PSCC changing from 10 Hz to 400 Hz with damping of NSCC (a) 1, (b) 2, (c) 3, (d) 4.

shown in Fig. 13(b)–13(c), three other similar operations are performed, except the damping of NSCC is set to 2, 3, and 4, respectively. Similarly, the studied system is stable for the PSCC bandwidth frequency parameter range.

Then, the influence of damping of PSCC from 0.1 to 5 on the FCE is shown in Fig. 14, where the bandwidth frequency of PSCC is 200 Hz. When the damping of NSCC is set to 1 and 2, as shown in Fig. 11(a) and (b), only one pair of FCE across the imaginary axis causes the system to become unstable, and the parameter range of damping of PSCC for a stable system is 0.5–5 and 0.2–5. When the damping of NSCC is set to 3 and 4, as shown in Fig. 14(c) and (d), no parameter range of damping of PSCC makes the system unstable.

The influences of damping of NSCC on the stable parameter bounds of PSCC are summarized in Fig. 15. When the bandwidth frequency of PSCC is larger than 150 Hz, the increase of damping of NSCC increases the stable parameter bounds of PSCC. When the bandwidth frequency of PSCC is lower than 50 Hz, the increase in bandwidth frequency of NSCC has a negligible impact on system stability.

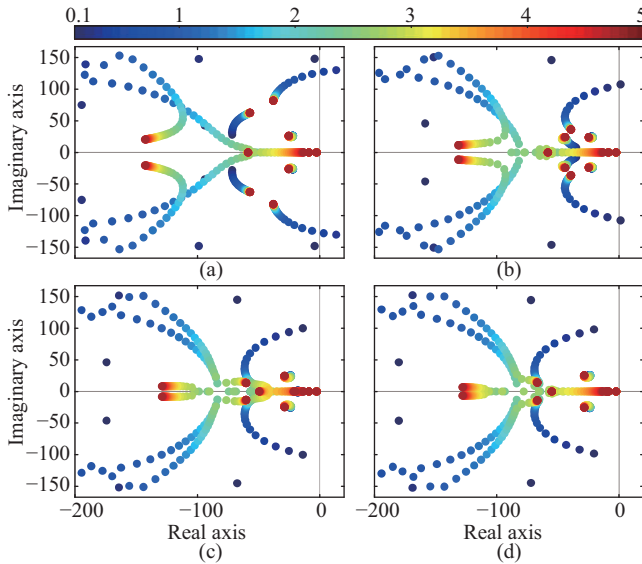


Fig. 14. The FCE for damping of PSCC changing from 0.1 to 5 with damping of NSCC (a) 1, (b) 2, (c) 3, (d) 4.

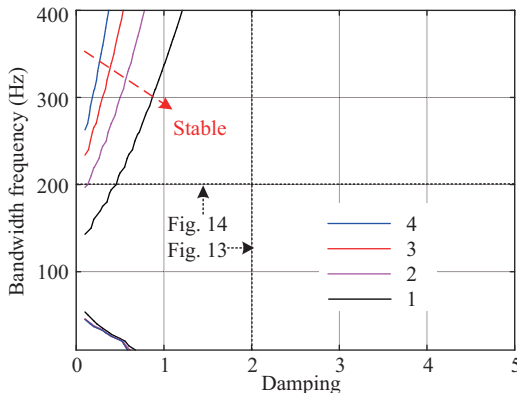


Fig. 15. The stable parameter domains of PSCC with different damping of NSCC.

IV. STABILITY ANALYSIS THROUGH THE HSS MODEL

The LTP model can only judge the stability. Thus, the stability mechanism analysis is based on the HSS model. The modeling method of the HSS model is presented in [34], and they are not shown here. An appropriate truncation number is needed for accuracy analysis for the theoretical infinite-order LTI system of the HSS model.

When the bandwidth frequency and damping are 100 Hz and 1.4 for PSCC and NSCC with type III DDSRF, the unstable FCE is $4.094 \pm 46.882i$ based on LTP mode. Based on the truncation method in [34], the proper truncation number for the studied system is 4. Then, according to the participation factor analysis of the LTI system, the main factors that dominate system instability are shown in Table I, which contains the 0th-order to 2nd-order dynamics of controls and the dynamics of the AC network and DC capacitance. There is still a strong interaction among NSCC, PSCC, PLL, and DDSRF. Besides, except for the 0th-order dynamic of DDSRF, its 2nd-order dynamic also has a significant effect on system stability.

TABLE I
PARTICIPATION FACTOR WITH TYPE III DDSRF

Mode	Participating factors ($\geq 1E-2$)	Response
$4.094 \pm 267.2i$	$\Delta x_{d+}(0) = 0.018$; $\Delta x_{d+}(0) = 0.012$;	PSCC
	$\Delta x_{q+}(0) = 0.083$; $\Delta x_{q+}(0) = 0.024$;	
	$\Delta x_{d-}(0) = 0.018$;	NSCC
	$\Delta \theta_s(0) = 0.057$;	
	$\Delta x_{id+}(0) = 0.019$; $\Delta x_{iq+}(0) = 0.230$;	PLL 0 th -order dynamic
	$\Delta x_{id-}(0) = 0.019$; $\Delta x_{iq-}(0) = 0.042$;	
	$\Delta x_{ud+}(0) = 0.042$; $\Delta x_{uq+}(0) = 0.104$;	DDSRF
	$\Delta x_{ud-}(0) = 0.035$;	
	$\Delta x_{id+}(2) = 0.017$;	DDSRF 2 nd -order dynamic
	$\Delta x_{id-}(2) = 0.025$; $\Delta x_{iq-}(2) = 0.025$;	
	$\Delta i_d(1) = 0.036$; $\Delta i_b(1) = 0.202$;	AC network and DC capacitance
	$\Delta i_c(1) = 0.106$;	
	$\Delta u_{dc}(0) = 0.044$; $\Delta u_{dc}(2) = 0.019$;	

When the bandwidth frequency and damping of PSCC are 100 Hz and 1 for PSCC, and the bandwidth frequency and damping of NSCC are 400 Hz and 2 with type I DDSRF, the unstable FCE is $2.638 \pm 85.892i$ based on LTP mode. Then, the main factors that dominate system instability are listed in Table II, which only includes the 0th-order to 1st-order dynamics of controls, the AC network, and DC capacitance. Therefore, compared to type III DDSRF, the interaction among different controls with type I DDSRF is not strong, especially for the interaction between NSCC and other controls.

TABLE II
PARTICIPATION FACTOR WITH TYPE I DDSRF

Mode	Participating factors ($\geq 1E-2$)	Response
$2.638 \pm 85.892i$	$\Delta x_{d+}(0) = 0.273$; $\Delta x_{q+}(0) = 0.135$;	PSCC
	$\Delta \theta_s(0) = 0.017$;	
	$\Delta x_{udc}(0) = 0.065$;	PLL 0 th -order dynamic
	$\Delta x_{id+}(0) = 0.354$; $\Delta x_{iq+}(0) = 0.106$	
	$\Delta i_a(1) = 0.010$; $\Delta i_b(1) = 0.010$;	DDSRF
	$\Delta i_c(1) = 0.010$; $\Delta u_{dc}(0) = 0.219$;	
		AC network and DC capacitance

V. VERIFICATION OF ANALYSIS RESULTS

For the single-VSC grid-connected system, when the damping and bandwidth frequency of PSCC is (1, 100) with type

III DDSRF, we change the damping and bandwidth frequency of NSCC to (2, 400) and (2, 300) at 1.5 s, respectively. The nonlinear time-domain response is given in Fig. 16(a). It shows that a lower bandwidth frequency of NSCC is beneficial. When the damping and bandwidth frequency of PSCC is (0.7, 300), we change the damping and bandwidth frequency of NSCC to (1, 200) and (2, 200) at 1.5 s, respectively. The nonlinear time-domain response is given in Fig. 16(b). It shows that a more significant damping of NSCC is beneficial. The time-domain responses are all consistent with the results of the theoretical analysis. When the parameters of PSCC and NSCC are the same, and their bandwidth frequency is all set to 100 Hz, we change the type I DDSRF to type III DDSRF at 1.5 s as their damping is 1 and 2, respectively. The nonlinear time-domain response is given in Fig. 16(c), which shows that the VSC grid-tied system with type III DDSRF cannot operate stably under some control parameters.

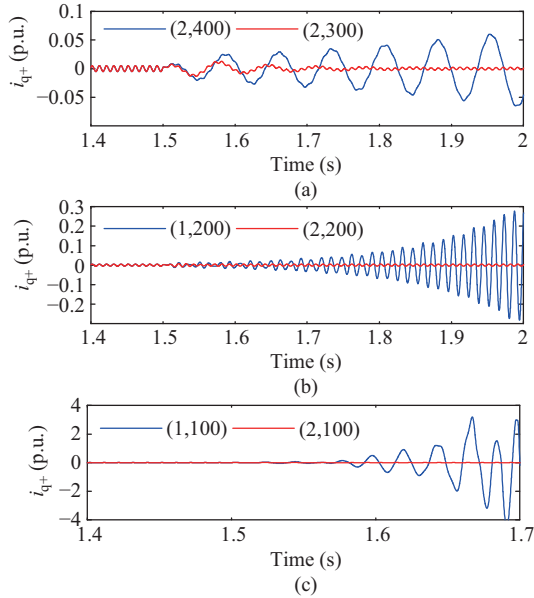


Fig. 16. Time response of i_{q+} with changing parameters of NSCC (a) to (2, 400) and (2, 300), (b) to (1, 200) and (2, 200), with changing DDSRF (c) from type III to I at 1.5 s.

The influence of DDSRF structure on the small-signal stability has been fully elucidated. Another concern about the effectiveness of different DDSRFs under fault disturbance should also be given sufficient attention. Therefore, the time responses with single phase grounding short circuit fault are given in Fig. 17, and four DDSRF structures have effectively controlled negative sequence current. For the currently commonly used Type III DDSRF, the maximum value of grid fault currents i_{abc} is 0.884 pu, which is the minimum value for four DDSRF structures. The maximum grid fault currents for Type II and Type IV DDSRF have reached 0.996 pu and 1.001 pu. The significantly increased fault current is not conducive to transient stability. For type I DDSRF, the maximum value of grid currents i_{abc} is 0.886 pu, which is 0.002pu larger than the III structure. Therefore, although changing the DDSRF structure from Type 3 to Type 1 control may result in a slight increase in fault current, the improvement in system stability

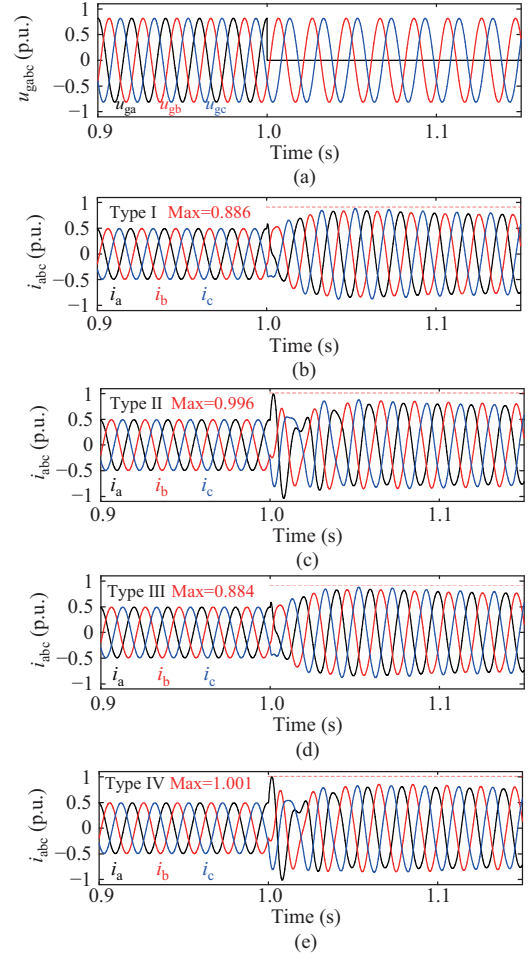


Fig. 17. Time responses with single phase grounding short circuit fault occurs at 1 s (a) grid voltages u_{gabc} , grid fault currents i_{abc} with (b) Type I DDSRF, (c) Type II DDSRF, (d) Type III DDSRF, (e) Type IV DDSRF.

is significant from the perspective of small signal stability.

The stable parameter bounds obtained here may not be accurate for other large-scale VSC grid-connected systems. However, the results regarding the impact of the DDSRF structure on system stability remain applicable in many diverse real-world scenarios. Since the conclusions from the single-machine system can be directly extended to multi-machine systems, we are still conducting in-depth research. The detailed theoretical analysis results will be provided in the future. Here, the electromagnetic transient simulation analyses of multi-machine systems are presented. As shown in Fig. 18, a power system dominated by VSCs with NSCC, originating from China, is presented. It features large-scale RPGs and a four-terminal HVDC system. Their parameters are referred to [6]. Renewable energy initially adopts type I DDSRF, and the large-scale power system can operate stably. When we switch the control of wind turbines 1 and 2 (i.e., WF1 and WF2) to type III DDSRF, respectively, the time-domain response results from RT-LAB (OP5600, 2 CPUs with Intel i7 6-Core, 3.3 GHz) are shown in Fig. 19, both showing unstable states. Therefore, consistent with theoretical analysis, VSC with type I DDSRF is conducive to system small-signal stability.

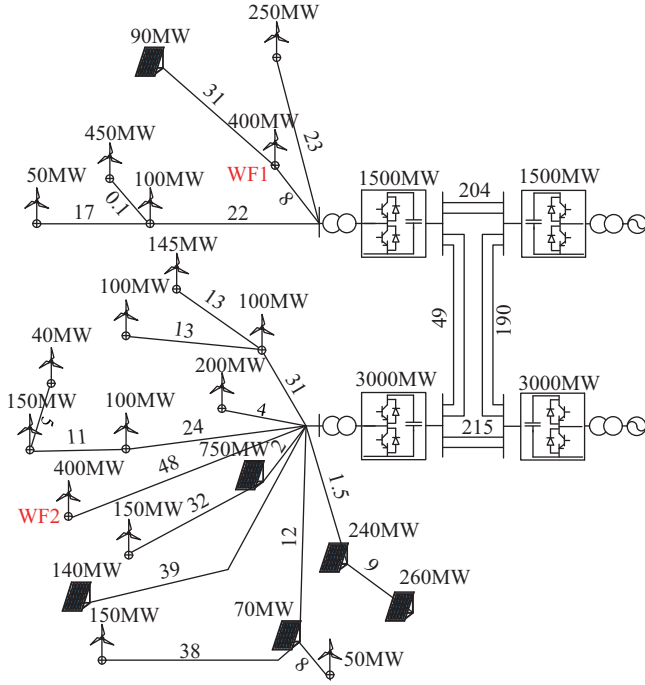


Fig. 18. Schematic of power system dominated by VSCs with NSCC in China.

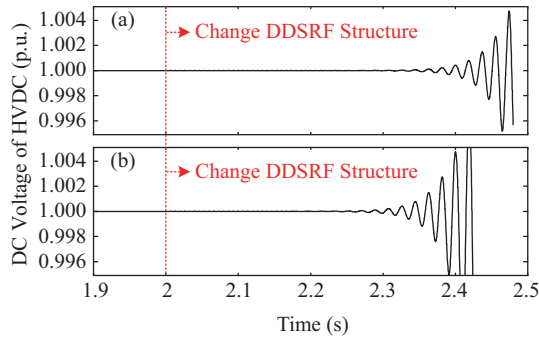


Fig. 19. Time response of with DDSRF changed from type III to type I at 2 s. (a) WF1; (b) WF2.

VI. CONCLUSION

The effect of NSCC of VSCs on electromagnetic small-signal stability is studied using the LTP and HSS models. Based on the LTP model, the NSCC has a significant impact on system stability, and the effects of bandwidth and damping on system stability differ. The increase in the bandwidth of NSCC reduces the stable parameter domain of PSCC. The increase in the damping of NSCC increases the stable parameter domain of PSCC. Besides, compared with commonly used DDSRF structures (i.e., type III DDSRF), although the type I DDSRF structure will increase the dynamic response of maximum value of grid currents by 0.2%, it will significantly enhance and expand the stable parameter range, especially for the empirical current control parameters selection principle, i.e., damping is 0.707, and the bandwidth frequency is several hundred Hz. Furthermore, based on the appropriate truncated HSS model, the interaction among different controls with type I DDSRF is not strong when compared with type III

DDSRF, especially for the interaction between NSCC and other controls. Furthermore, the relevant conclusion regarding the influence of the DDSRF structure remains applicable to other multi-machine power systems dominated by VSCs with NSCC, and the specific reasons will be studied in detail in the future.

APPENDIX

A. Parameters of the Single-VSC Grid-connected System

TABLE A

Quantity	Values
S_N	Based power 2 MVA
u_{DC}	Based DC voltage 1100 V
u_N	Based AC voltage 690 V
L_f	Inductor of filter 0.15 p.u.
R_f	Resistance of filter 0.002 p.u.
$k_{p/i+}$	Parameters of PSCC 3/100 Hz
$k_{p/i-}$	Parameters of NSCC 3/100 Hz
$k_{ppll/ipll}$	Parameters of PLL 0.707/20 Hz
i_{dc}^*	Reference of direct current 0.8 p.u.
L_g	Inductor of network 0.4741 p.u.
R_g	Resistance of network 0.001 p.u.

B. The Parameters Design of PSCC and NSCC

The parameters of PSCC and NSCC are as follows [38]. The parameters of PSCC are:

$$k_{p+} = (L_g + L_f)2\zeta_{i+}\omega_{ni+}k_{i+} = (L_g + L_f)\omega_{ni+}^2 \quad (B1)$$

where ω_{ni+} and ζ_{i+} are the undamped natural frequency and damping ratios.

Besides, refer to the design principles of control bandwidth ω_{i+} , the relationship between ω_{ni+} and ω_{i+} is

$$\omega_{i+} = \omega_{ni+} \sqrt{\sqrt{(4\zeta_{i+}^4 + 4\zeta_{i+}^2 + 2) + 2\zeta_{i+}^2} + 1} \quad (B2)$$

Then, the parameters of PSCC are

$$k_{p+} = \frac{(L_g + L_f)2\zeta_{i+}\omega_{i+}}{\sqrt{\sqrt{(4\zeta_{i+}^4 + 4\zeta_{i+}^2 + 2) + 2\zeta_{i+}^2} + 1}} \quad (B3)$$

$$k_{i+} = \frac{(L_g + L_f)\omega_{i+}^2}{\sqrt{(4\zeta_{i+}^4 + 4\zeta_{i+}^2 + 2) + 2\zeta_{i+}^2} + 1} \quad (B4)$$

Similarly, the parameters of NSCC are

$$k_{p-} = \frac{(L_g + L_f)2\zeta_{i-}\omega_{i-}}{\sqrt{\sqrt{(4\zeta_{i-}^4 + 4\zeta_{i-}^2 + 2) + 2\zeta_{i-}^2} + 1}} \quad (B5)$$

$$k_{i-} = \frac{(L_g + L_f)\omega_{i-}^2}{\sqrt{(4\zeta_{i-}^4 + 4\zeta_{i-}^2 + 2) + 2\zeta_{i-}^2} + 1} \quad (B6)$$

where ω_{i-} and ζ_{i-} are the bandwidth and damping ratio of NSCC, respectively.

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