Modeling and Stability Issues of Voltage-source Converter-dominated Power Systems: A Review

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***Abstract*—With the substantive increase in the proportion of voltage-source converter (VSC)-based equipment, traditional power systems that primarily constituted of synchronous generators (SGs) gradually evolved into VSC-dominated ones. At the same time, there is an urgent need for modeling and stability assessment of such systems, since low inertia and weak damping features impair the ability of the systems to resist random disturbances. Existing works model the system dynamic processes from various domains (i.e., time, frequency and energy), and analyze/determine the system stability under small or large disturbances. Among them, small-signal stability assessments mainly adopt the time-domain analysis based on the state-space model while frequency-domain methods include the impedance model, phase-amplitude dynamics model, and static synchronous generator model. Large-signal stability assessments mainly exploit the time-domain simulation with detailed models (i.e., continuous/discrete-time mixed model with differential-difference-algebraic equations), and the energy-domain analysis is based on energy function models. This paper presents a comprehensive review of existing modeling and stability analysis methods for VSC-dominated power systems, including their basic principles, key features, application scenarios and development tendencies. Key technical issues related to modeling and stability analysis are also summarized.**

***Index Terms*—Dynamic modeling, power system, stability analysis, voltage-source converter (VSC).**

I. Introduction

WITH the development of emerging technologies such as frequency converters, flexible high-voltage direct-current (HVDC) system, renewable energy generation, electrified transportation, and energy storage system (ESS), the proportion of voltage-source converters (VSCs) in the power grid has increased rapidly [1], [2], causing the pertinent grid to gradually evolve into a VSC-dominated power system (an example of which is shown in Fig. 1), or, equivalently, into a non-synchronous system [3], electronic energy network [4], or power-electronic system [5]. Though the bulk application of VSCs evidently improves grid performance and enriches grid functions, it also introduces additional dynamic stability issues.

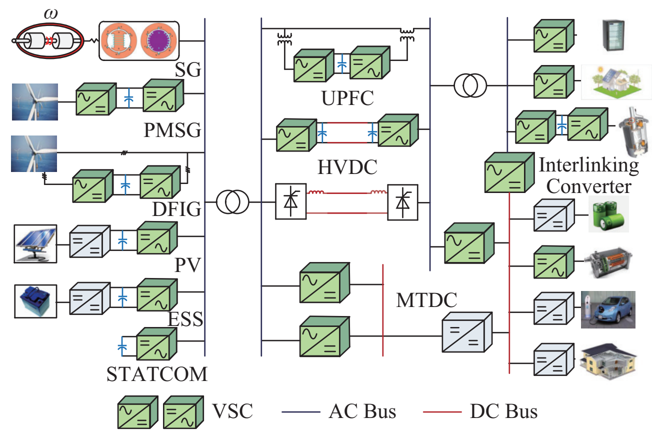

Fig. 1. An example of VSC dominated power system.

Traditional power systems are dominated by synchronous generators (SGs) that are characterized by large inertia and strong damping ability [6], hence the major state variables in traditional grids are insusceptible to common disturbances, or the oscillation processes caused by them, are damped effectively and in a timely manner. These traditional power systems possess strong robustness as well as stability. However, in power systems dominated by VSCs, with their associated low inertia and weak damping ability [6], the relatively reduced number of SGs weakens the ability of the system to resist random disturbances. During a transient event, it is difficult to dampen an oscillation component quickly and sufficiently, thus the probability of a long-term, drastic oscillation substantially endangering the safety and stable operation of the system, increases [3].

At the same time, VSC-dominated power systems exhibit a wider range of dynamic processes compared to traditional grids. On the one hand, the dynamic model of a converter has a significantly higher order than that of an SG, viz., there exist system dynamics in multiple timescales, encompassing the AC side inductance/capacitance-related electromagnetic timescale dynamics, energy conversion process-related electromechanical timescale dynamics (e.g., SG rotor angle dynamics), as

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well as mechanical timescale dynamics [e.g., wind turbine (WT) pitch angle adjustment process], and the DC side capacitor-related dynamics (along with its control-related issues) [7]. On the other hand, to effectively regulate the various VSC dynamics and ensure the inner, middle, and outer loops of the control system are well decoupled, the control loop design usually follows the principle of timescale partitioning (viz., the bandwidth ranges of different control loops are clearly separated). As a result of the diverse physical processes and their controls, as well as of the separation of the response and control time constants for dynamic processes, VSC-dominated power systems exhibit multi-timescale features (see Fig. 2) with oscillation modes ranging from slightly above DC to hundreds of Hertz and distributed in multiple frequency bands [8]–[10]. This leads to increased system susceptibility to wide-band interferences [8]; some examples of oscillation issues are the series-compensation related oscillation (about 30 Hz) [11] and the voltage oscillation in the Texas Power Grid [12], the offshore wind power system oscillation in Hamburg, Germany (about 80 Hz) [13], the sub synchronous resonance (SSR, 15–30 Hz) in Xinjiang power plants of China [14], as well as the high frequency resonance problems (100–800 Hz) encountered in several countries [8].

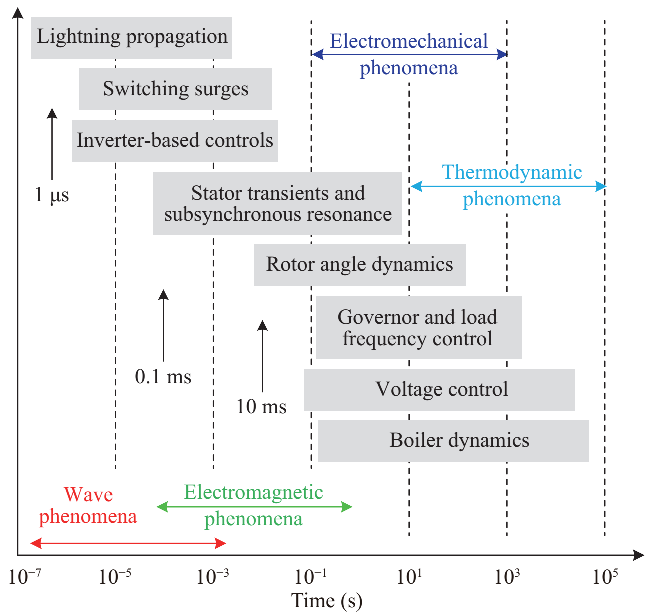

Fig. 2. Multi-timescale features of VSC dominated power systems according to the IEEE Task Force on stability definitions and characterization of dynamic behavior in power systems with high penetration of power electronic interfaced technologies.

Due to the essentially distinct dynamic features of VSC-dominated systems as compared to traditional power grids, it is critical that pertinent modeling and stability assessment are performed to provide a theoretical basis for control strategy research. In existing research studies, the dynamic processes of VSC-dominated systems are modeled mainly in time, frequency, and energy domains, and the result is used as the basis for stability assessment under small or large disturbances. Among them, the small-signal stability assessment mainly adopts the time-domain analysis based on the state-space model, and the frequency-domain methods based on the impedance model, phase-amplitude dynamics (PAD) model, and static synchronous generator (SSG) model. The large-signal stability assessment mainly exploits the time-domain simulation analysis based on the detailed model, and energy-domain analysis based on energy function models. A summary of major methods in different scenarios is given in Fig. 3.

This paper aims at providing a comprehensive overview of the state-of-the-art methods in dynamic modeling and stability analysis of VSC-dominated power systems, including their basic principles, key features, application scenarios, and development tendencies. Finally, some critical technical issues that still need to be resolved are summarized.

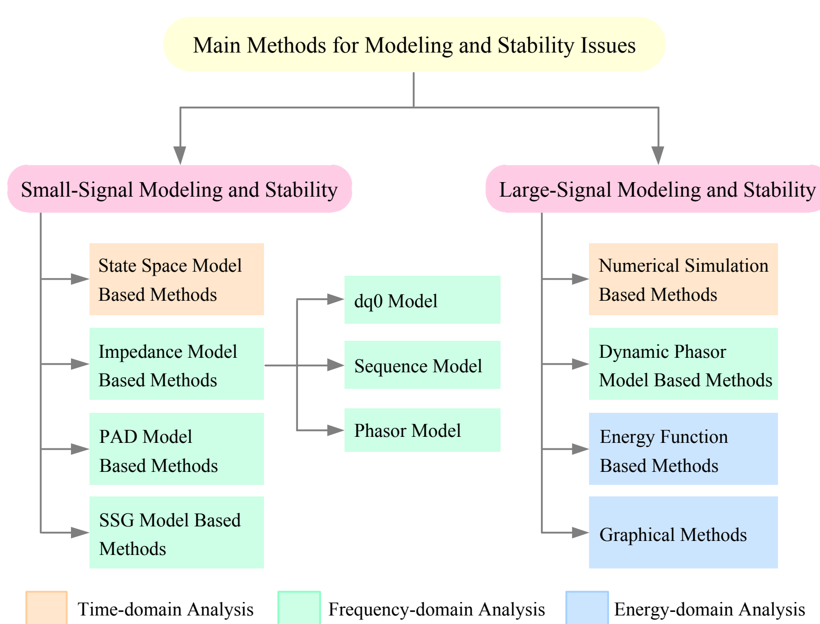

Fig. 3. Main methods for dynamic modeling and stability analysis.

II. Small-Signal Modeling and Stability

A. State-Space Model in Time Domain

1) Basic Principle

The state-space model in time domain, also known as the eigenvalue analysis, is a classic method for the small-signal stability analysis of a power system. Its mathematical model [15] is given by

$$\begin{cases} \dfrac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t} = \boldsymbol{f}\left(\boldsymbol{x}, \boldsymbol{y}\right) \\ \boldsymbol{0} = \boldsymbol{g}\left(\boldsymbol{x}, \boldsymbol{y}\right) \end{cases} \tag{1}$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are column vectors of grid state and algebraic variables, respectively.

The general steps of the eigenvalue analysis are as follows:

a) The steady-state operating point of the power grid is obtained via power flow calculation;

b) (1) is linearized at the steady-state point to yield:

$$\begin{cases} \frac{\mathrm{d}\Delta\boldsymbol{x}}{\mathrm{d}t} = \tilde{\boldsymbol{A}}\Delta\boldsymbol{x} + \tilde{\boldsymbol{B}}\Delta\boldsymbol{y} \\ \boldsymbol{0} = \tilde{\boldsymbol{C}}\Delta\boldsymbol{x} + \tilde{\boldsymbol{D}}\Delta\boldsymbol{y} \end{cases} \tag{2}$$

where $\Delta\boldsymbol{x}$ and $\Delta\boldsymbol{y}$ are incremental vectors of state and algebraic variables, respectively, and

$$\begin{aligned} \tilde{\boldsymbol{A}} &= \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}, \ \tilde{\boldsymbol{B}} = \begin{bmatrix} \frac{\partial f_1}{\partial y_1} & \cdots & \frac{\partial f_1}{\partial y_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial y_1} & \cdots & \frac{\partial f_n}{\partial y_n} \end{bmatrix} \\ \tilde{\boldsymbol{C}} &= \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_n}{\partial x_1} & \cdots & \frac{\partial g_n}{\partial x_n} \end{bmatrix}, \ \tilde{\boldsymbol{D}} = \begin{bmatrix} \frac{\partial g_1}{\partial y_1} & \cdots & \frac{\partial g_1}{\partial y_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_n}{\partial y_1} & \cdots & \frac{\partial g_n}{\partial y_n} \end{bmatrix} \end{aligned} \tag{3}$$

The system small-signal state-space model at the steady state operating point can be obtained by simplifying (2) as:

$$\frac{\mathrm{d}\Delta\boldsymbol{x}}{\mathrm{d}t} = \boldsymbol{A}\Delta\boldsymbol{x} \tag{4}$$

where $\boldsymbol{A}$ is the state matrix of the system model given by

$$\boldsymbol{A} = \tilde{\boldsymbol{A}} - \tilde{\boldsymbol{B}}\tilde{\boldsymbol{D}}^{-1}\tilde{\boldsymbol{C}} \tag{5}$$

c) The system stability is assessed by analyzing the eigenvalue distribution on the complex plane pertaining to the system state matrix $\boldsymbol{A}$. The system is stable if and only if the real parts of all eigenvalues are negative. The system is marginally stable and exhibits constant amplitude oscillations in the presence of eigenvalue(s) with null real part. If there are a pair of negative, conjugated eigenvalues near the imaginary axis (i.e., with low damping ratio), the long-term oscillation process associated with weakly damped oscillation modes is prohibited in practical applications, despite the system stability.

In addition to system stability, the dynamic process features under small disturbances, the encompassing oscillation frequency, attenuation factor, oscillation amplitude and phase, etc., can be analyzed. The correspondence between the eigenvalue distribution and typical system dynamics is shown in Fig. 4. The system is unstable if any system eigenvalue is located on the right half plane (RHP).

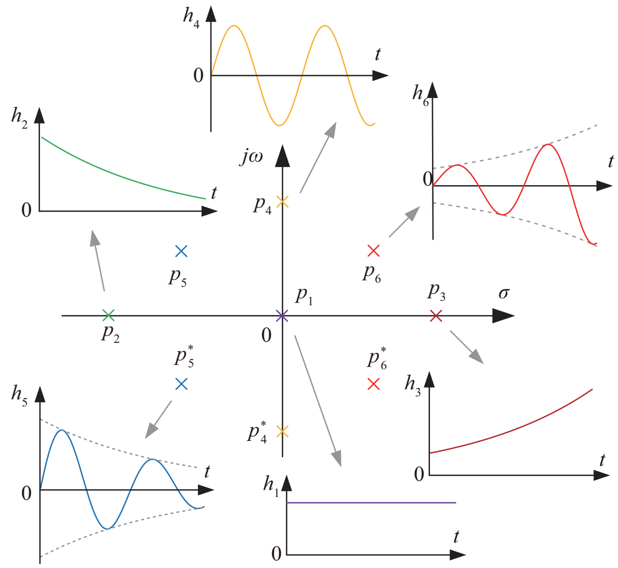

Fig. 4. Eigenvalue distribution versus typical system dynamics. A raised asterisk is used to denote the complex conjugate.

2) Key Features and Main Applications

With a mature theoretical foundation for eigenvalue analysis, root locus analysis, participation analysis, and sensitivity analysis [16], the eigenvalue analysis method has been widely adopted for small-signal modeling and stability analysis in single-, multi-, and system level-VSC dominated systems.

a) Dynamics Modeling: Focusing on the 3–4 Hz low-frequency oscillations of Type-4 wind plant under weak grid condition, the simplified small-signal model in [17] only uses a first-order delay to replace the VSC current control loop and neglects the transmission line dynamics and phase-locked loop (PLL). In [18], the small-signal stability of two droop-controlled VSCs is analyzed by neglecting the dynamic behavior of voltage control loop, parallel inductance, and load. In [19], a microgrid with multiple VSCs is investigated and a 13-th order VSC model is established by considering the model of each VSC in its pertinent dq frame, and by also considering the detailed dynamic behavior of each element in the system. However, this method does not consider the dq frame difference among VSC models. In [15], a unified dq frame is established to accurately reflect the electrical connection among subsystems, and a general state-space based modeling method, which is standard for VSC-dominated systems, is proposed. This method is also widely used for wind/photovoltaic power generation [20], modular multi-level converter [21], HVDC system [22], hybrid ESS and renewable power generation system [23], and interconnected microgrids [24].

b) Stability Analysis: By using a small-signal VSC model, [22] finds that the impact of PLL parameters on the behavior of an HVDC system is determined as a function of the system strength. In [25], the maximum delayed time method based on a small-signal model is proposed to address the instability issues caused by time delays during signal transfer processes. Focusing on low-frequency modes of droop-controlled microgrids, the reduced-order model for inter-VSC oscillations analysis is proposed in [26] and successfully benchmarked against the detailed model and other germane models over the full range of operational damping ratios. Based on the timescale classification, the voltage dynamics and stability issues in each timescale are well elaborated respectively in [16], and typical sensitivity analysis is introduced for investigating the influence of critical parameters on voltage stability. The small-signal VSC model is also introduced to deal with the stability problems during deep voltage sags [27] and symmetrical faults in a weak grid [28], [29]. Small-signal analysis reveals that if there is an equilibrium, the WT could also be linearly unstable due to the low-voltage ride through (LVRT) control [30].

3) Technical Challenges and Development Tendency

Despite being mature and widely used, the application of state-space model-based time-domain analysis to VSC systems is still limited by several technical challenges that require further research:

a) The method only applies to *white-box* systems with linear time-invariant (LTI) feature and fixed structure. The obvious nonlinear features of VSC equipment, which may result in prominent stability issues, are neglected by the linearization. Several emerging modeling methods, encompassing harmonic linearization [31], dynamic phasor (DP) modeling [32], [33] and harmonic state-space (HSS) model [21], can partially alleviate this limitation and are worthy of in-depth development.

b) Traditional large-capacity generator sets are being replaced by distributed, small-capacity power supplies, leading to an increase in the number of VSCs in the power system, due to which, deriving the state-space model is difficult and there is a high computational demand. As a result, it is desirable to develop efficient modeling and eigenvalue calculation methods for large-scale complex power systems. The component connection method [15], characterized by modularity and scalability, presents a computationally efficient procedure for deriving the complete LTI state-space model of multi-VSC systems. At the same time, investigation on the efficient eigenvalue solution for an ultra-high dimensional state matrix is also required, especially for the online computation of the rightmost and critical (with least damping ratio) eigenvalues [34]. This directly affects the performance of online optimization-based power system control [35].

c) Though it is technically feasible to directly obtain the detailed model and eigenvalues of a large-scale multi-VSC power system, the ultra-high-dimensional model can be difficult to interpret intuitively in terms of physical meaning [10]. The inevitably complicated mathematical and mechanism analysis is not conducive to understanding the evolution of system dynamics or the physical mechanism of instability phenomena [26], thereby restricting its utility in stability controller design. This imposes an essential need for investigations on complex system simplification and model-order reduction via the timescale features [7], the stability classification [16] and the aggregation of VSCs with similar characteristics [36].

B. Impedance Model in Frequency Domain

1) Basic Principle

This technique considers the system as a cascaded system consisting of a source subsystem and a load subsystem, both represented by their frequency-domain port characteristics (i.e., output/input impedances or admittances). A principle diagram is shown in Fig. 5, where $V_{\mathrm{S}}(s)$ is the output voltage of the source subsystem when operated alone; $V_{\mathrm{L}}(s)$ is the input voltage of the load subsystem, and $Z_{\mathrm{S}}(s)$ and $Z_{\mathrm{L}}(s)$ are the output impedance of the source subsystem and the input impedance of the load subsystem, respectively.

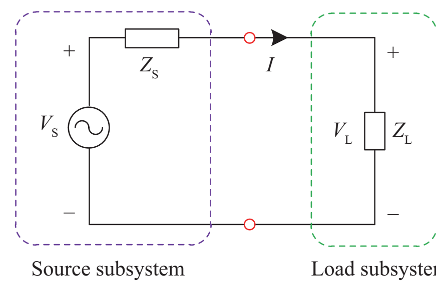

Fig. 5. Cascaded system from the perspective of impedance model.

The impedance model in the frequency domain analyzes the cascaded system stability by exploiting the Nyquist criterion based on $Z_{\mathrm{S}}(s)$ and $Z_{\mathrm{L}}(s)$ [37], and the result is used to further assess the power system stability [38]. As a prerequisite, this method requires the stability of source and load subsystems when operated separately, which is usually guaranteed by suitable module design.

The system transfer function is expressed as the ratio of $V_{\mathrm{L}}(s)$ to $V_{\mathrm{S}}(s)$ as

$$\frac{V_{\mathrm{L}}(s)}{V_{\mathrm{S}}(s)} = \frac{1}{1 + Z_{\mathrm{S}}(s)/Z_{\mathrm{L}}(s)} = \frac{1}{1 + T_{\mathrm{m}}(s)} \tag{6}$$

where T_{m} is defined as the system minimum loop gain [39].

Middlebrook points out that the system stability is determined by whether T_{m} satisfies the Nyquist criterion, i.e., the system is stable if and only if the number of turns that T_{m} is counterclockwise around the $(-1, \mathrm{j}0)$ point is zero on the complex plane. Furthermore, the separation between the T_{m} trajectory and the $(-1, \mathrm{j}0)$ point characterizes the relative system stability, which can be represented by the gain margin (GM) and phase margin (PM) [see Fig. 6(a)].

To overcome the complexity issue of the Nyquist criterion, the forbidden region notation is adopted, i.e., the system stability is assured when T_{m} is limited within the unit-circle on the complex plane, whereas the zone outside is the forbidden region of T_{m} [see Fig. 6(b)]. This approach, known as the Middlebrook criterion [40], is formulated to determine the cascaded system stability by

$$|T_{\mathrm{m}}(s)| = \left|\frac{Z_{\mathrm{S}}(s)}{Z_{\mathrm{L}}(s)}\right| < 1 \tag{7}$$

Owing to the simplification made available by this criterion, stability assessment via the impedance model becomes simple and practical. Nevertheless, the unit-circle forbidden region-based stability criterion is highly conservative [41]. To this

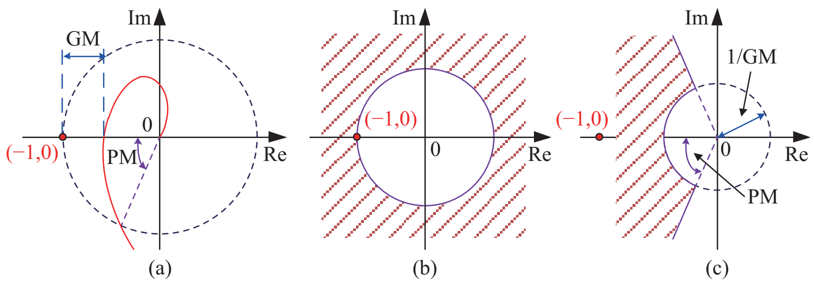

Fig. 6. (a) Definition of gain margin and phase margin; (b) Middlebrook criterion and (c) GMPM criterion.

end, some criteria that are less conservative are proposed [39], [42]. Among them, the most representative one is Wildrick's GMPM criterion [see Fig. 6(c)], which foresees system instability if the cascaded system yields [42]

$$\begin{cases} \left|T_{\mathrm{m}}(s)\right| = \left|\frac{Z_{\mathrm{S}}(s)}{Z_{\mathrm{L}}(s)}\right| \geqslant \left|\frac{1}{\mathrm{GM}}\right| \\ 180^\circ - \mathrm{PM} \leqslant \angle T_{\mathrm{m}}(s) \leqslant 180^\circ + \mathrm{PM} \end{cases} \tag{8}$$

2) Key Features and Main Applications

In the 1970s, Middlebrook first adopted the impedance model to study the stability issues in DC systems [37]. Compared with the state space model-based approach, the impedance-based approach simplifies the computation process, and is more practical. As a matter of fact, this approach represents the terminal dynamics by resorting to the terminal impedance that can be directly obtained by external measurement [43]. Furthermore, impedance-based approaches do not rely on the inner information (topology and control parameters) or analytical model of VSCs [44]. This method predicts system stability only through the port impedance information, thereby ensuring the intellectual property protection of converter products and an unrestricted interconnection between different converters. Therefore, impedance model-based small-signal stability analysis has become the mainstream in converter systems.

a) Impedance Modeling:

The impedance model analysis for AC systems is considerably complicated with respect to DC systems, since unlike a DC system that can be modeled as a single-input-single-output model, the AC system is in essence a multi-input-multi-output (MIMO) system with wide timescale and frequency-coupling dynamics [10]. Despite these differences, the AC system stability can be analyzed following the common principle, i.e., based on a criterion that exploits source subsystem output impedance $\boldsymbol{Z}$ and the load subsystem input admittance $\boldsymbol{Y}$ [45]. Currently, three main definitions of AC system impedance are used:

- *The dq-domain impedance* $\boldsymbol{Z}_{\mathrm{dq}}(s)$ that relates the dq-domain voltage and current components [46] as

$$\begin{bmatrix} \Delta U_{\mathrm{d}}(s) \\ \Delta U_{\mathrm{q}}(s) \end{bmatrix} = \boldsymbol{Z}_{\mathrm{dq}}(s) \begin{bmatrix} \Delta I_{\mathrm{d}}(s) \\ \Delta I_{\mathrm{q}}(s) \end{bmatrix} \tag{9}$$

where

$$\boldsymbol{Z}_{\mathrm{dq}}(s) = \begin{bmatrix} Z_{\mathrm{dd}}(s) & Z_{\mathrm{dq}}(s) \\ Z_{\mathrm{qd}}(s) & Z_{\mathrm{qq}}(s) \end{bmatrix} \tag{10}$$

The d-/q-axis voltages and currents are frequency-domain quantities (Δ represents a small disturbance from the equilibrium), and are calculated via Park transformation using the pertinent time domain quantities. The transformation angle $\theta = \omega t$ and the frequency ω is usually obtained by the PLL.

- *The sequence-domain impedance* $\boldsymbol{Z}_{\mathrm{pn}}(s)$ that relates the positive and negative sequence voltage and current components [47] as

$$\begin{bmatrix} \Delta U_{\mathrm{p}}(s+\mathrm{j}\omega) \\ \Delta U_{\mathrm{n}}(s-\mathrm{j}\omega) \end{bmatrix} = \boldsymbol{Z}_{\mathrm{pn}}(s) \begin{bmatrix} \Delta I_{\mathrm{p}}(s+\mathrm{j}\omega) \\ \Delta I_{\mathrm{n}}(s-\mathrm{j}\omega) \end{bmatrix} \tag{11}$$

where

$$\boldsymbol{Z}_{\mathrm{pn}}(s) = \begin{bmatrix} Z_{\mathrm{pp}}(s) & Z_{\mathrm{pn}}(s) \\ Z_{\mathrm{np}}(s) & Z_{\mathrm{nn}}(s) \end{bmatrix} \tag{12}$$

Here, the positive and negative sequence components are denoted as $x(s+\mathrm{j}\omega)$ and $x(s-\mathrm{j}\omega)$ (with x a voltage or current quantity) to relate to the dq-axis components. The component with frequency ω_{dq} in dq frame is mapped to components with frequency $\omega_{\mathrm{dq}}+\omega$ and $\omega_{\mathrm{dq}}-\omega$ in the sequence frame, respectively. For example, an AC component with a 65 Hz oscillation mode in dq frame has a pertinent oscillation component of 115 (15) Hz in the positive (negative) sequence.

- *The phasor-domain impedance* $\boldsymbol{Z}_{\mathrm{M}\theta}(s)$ that relates the voltage and current amplitudes and phases [48] as

$$\begin{bmatrix} \Delta U(s) \\ U\Delta\theta_{\mathrm{U}}(s) \end{bmatrix} = \boldsymbol{Z}_{\mathrm{M}\theta}(s) \begin{bmatrix} \Delta I(s) \\ I\Delta\theta_{\mathrm{I}}(s) \end{bmatrix} \tag{13}$$

where

$$\boldsymbol{Z}_{\mathrm{M}\theta}(s) = \begin{bmatrix} Z_{\mathrm{MM}}(s) & Z_{\mathrm{M}\theta}(s) \\ Z_{\theta\mathrm{M}}(s) & Z_{\theta\theta}(s) \end{bmatrix} \tag{14}$$

U and I are the voltage and current amplitudes, and θ_{U}, θ_{I} are the angles between the voltage and current vectors and the d-axis, respectively.

Different impedance models can be obtained if voltages and currents are acquired in different frames. With various impedance models, the analysis results should be consistent if strict and accurate modeling is performed. Additionally, choosing specific coordinate frames facilitates highlighting particular physical characteristics of the VSC, as well as simplification of the model (e.g., $\boldsymbol{Z}$ and $\boldsymbol{Y}$ can have special properties such as symmetry or diagonality) to aid the stability analysis and physical mechanism interpretation.

Impedance models of the same VSC system can be equally converted [47], e.g., by expressing the sequence components in terms of three-phase AC components

$$\begin{bmatrix} x_{\mathrm{p}}(t) \\ x_{\mathrm{n}}(t) \end{bmatrix} = \begin{bmatrix} 1 & e^{\mathrm{j}2\pi/3} & e^{-\mathrm{j}2\pi/3} \\ 1 & e^{-\mathrm{j}2\pi/3} & e^{\mathrm{j}2\pi/3} \end{bmatrix} \begin{bmatrix} x_{\mathrm{a}}(t) \\ x_{\mathrm{b}}(t) \\ x_{\mathrm{c}}(t) \end{bmatrix} \tag{15}$$

the sequence and the dq components can be related as

$$\begin{bmatrix} x_{\mathrm{d}}(s) \\ x_{\mathrm{q}}(s) \end{bmatrix} = \frac{\sqrt{6}}{2} \begin{bmatrix} 1 & 1 \\ -\mathrm{j} & \mathrm{j} \end{bmatrix} \begin{bmatrix} x_{\mathrm{p}}(s+\mathrm{j}\omega) \\ x_{\mathrm{n}}(s-\mathrm{j}\omega) \end{bmatrix} \tag{16}$$

Therefore, the dq- and sequence-domain impedances yield

$$\boldsymbol{Z}_{\mathrm{pn}} = \boldsymbol{T}_{\mathrm{pn/dq}}^{-1} \boldsymbol{Z}_{\mathrm{dq}} \boldsymbol{T}_{\mathrm{pn/dq}} \tag{17}$$

where

$$\boldsymbol{T}_{\mathrm{pn/dq}} = \frac{\sqrt{6}}{2} \begin{bmatrix} 1 & 1 \\ -\mathrm{j} & \mathrm{j} \end{bmatrix} \tag{18}$$

Similarly, by transformation of the dq-axis components to the voltage/current signal x in polar coordinates as

$$\begin{bmatrix} \Delta x_{\mathrm{d}}(s) \\ \Delta x_{\mathrm{q}}(s) \end{bmatrix} = \begin{bmatrix} \cos\theta_{\mathrm{x0}} & -\sin\theta_{\mathrm{x0}} \\ \sin\theta_{\mathrm{x0}} & \cos\theta_{\mathrm{x0}} \end{bmatrix} \begin{bmatrix} \Delta x(s) \\ x\Delta\theta_{\mathrm{x}}(s) \end{bmatrix} \tag{19}$$

the phasor domain- and dq-impedances can be related by:

$$\boldsymbol{Z}_{\mathrm{M}\theta} = \boldsymbol{T}_{\mathrm{M}\theta/\mathrm{dq}}^{-1} \boldsymbol{Z}_{\mathrm{dq}} \boldsymbol{T}_{\mathrm{M}\theta/\mathrm{dq}} \tag{20}$$

b) Stability Analysis:

In [49], it is proved that: in order for a general system to be stable, both the VSC impedances should not have any RHP zeros or poles, i.e., they satisfy the generic impedance-sum criterion as given by

$$\sum_{i=1}^{\infty} N_{\mathrm{RHP}i}(\boldsymbol{Z}_{\mathrm{dq}i}) = 0 \tag{21}$$

To simplify the stability criterion, [37] proposes that a VSC system can remain stable if the ratio between the source block impedance and the load block impedance satisfies the Nyquist stability criterion. Since the VSC control strategies are usually implemented in dq frame [50], [51], the existing works usually define the pertinent VSC system source block impedance matrix $\boldsymbol{Z}_{\mathrm{Sdq}}$ (22) and load block admittance matrix $\boldsymbol{Y}_{\mathrm{Ldq}}$ (23) in dq frame, and obtain the necessary and sufficient condition for the VSC system stability according to the linear system theory, i.e., the roots of (24) are all located on the left half complex plane [52].

$$\boldsymbol{Z}_{\mathrm{Sdq}}(s) = \begin{bmatrix} Z_{\mathrm{Sdd}}(s) & Z_{\mathrm{Sdq}}(s) \\ Z_{\mathrm{Sqd}}(s) & Z_{\mathrm{Sqq}}(s) \end{bmatrix} \tag{22}$$

$$\boldsymbol{Y}_{\mathrm{Ldq}}(s) = \begin{bmatrix} Y_{\mathrm{Ldd}}(s) & Y_{\mathrm{Ldq}}(s) \\ Y_{\mathrm{Lqd}}(s) & Y_{\mathrm{Lqq}}(s) \end{bmatrix} \tag{23}$$

$$\det(\boldsymbol{I} + \boldsymbol{Z}_{\mathrm{Sdq}}(s)\, \boldsymbol{Y}_{\mathrm{Ldq}}(s)) = 0 \tag{24}$$

It is proposed in [31] that the stability of a VSC system in dq frame requires that the matrix $\boldsymbol{Z}_{\mathrm{Sdq}}\boldsymbol{Y}_{\mathrm{Ldq}}$ satisfies the generalized Nyquist criterion (GNC). GNC effectively promotes the in-depth research and application for stability analysis of the VSC system, which is essentially identified as a MIMO impedance model [53], [54]. Considering the complexity of GNC [55], the existing literature usually exploits the coupling relationship between the dq components to obtain simplified criteria, encompassing the singular value criterion, the D channel criterion and the norm criteria.

The singular value criterion foresees the system stability if the product of the maximum singular values of $\boldsymbol{Z}_{\mathrm{Sdq}}$ and $\boldsymbol{Y}_{\mathrm{Ldq}}$ is less than 1 at any frequency point [56], i.e.,

$$\overline{\sigma}(\boldsymbol{Z}_{\mathrm{Sdq}}(s)) \cdot \overline{\sigma}(\boldsymbol{Y}_{\mathrm{Ldq}}(s)) < 1 \tag{25}$$

where the singular values of the complex matrix $\boldsymbol{A}$ are defined as (with $\boldsymbol{A^H}$ the conjugate transpose matrix of $\boldsymbol{A}$):

$$\sigma(\boldsymbol{A}) = \sqrt{\lambda(\boldsymbol{A^H} \times \boldsymbol{A})} \tag{26}$$

Due to the computational complexity and difficulty of obtaining analytical expressions of matrix singular values and system parameters, this method is only suitable for stability judgement, yet it is hardly used to guide parameter design.

The D-channel criterion assumes the system q-axis components are small enough to be neglected, besides, the coupling between the d- and q-axis components are also negligible. Accordingly, only the d-axis impedance of $\boldsymbol{Z}_{\mathrm{Sdq}}$ and admittance of $\boldsymbol{Y}_{\mathrm{Ldq}}$ need to be analyzed to determine the system stability [57], i.e., the system is stable if:

$$|Z_{\mathrm{Sdd}}(s)| \cdot |Y_{\mathrm{Ldd}}(s)| < 1 \tag{27}$$

The D-channel criterion is not a sufficient condition for system stability, and is only applicable to specific systems with a high-power factor. Analogously, Q-channel impedance can be used to determine the system stability [53].

Among all types of criteria, the norm criteria, though highly conservative, are characterized by the simplest calculation and thus facilitate system stability analysis and parameter design. The norm criteria mainly comprise the G-norm criterion [58], ∞-norm criterion [59], 1-norm criterion [59], and sum-norm criterion [60]. The expressions are:

$$\|\boldsymbol{Z}_{\mathrm{Sdq}}(s)\|_G \|\boldsymbol{Y}_{\mathrm{Ldq}}(s)\|_G < \frac{1}{4} \tag{28}$$

$$\|\boldsymbol{Z}_{\mathrm{Sdq}}(s)\|_\infty \|\boldsymbol{Y}_{\mathrm{Ldq}}(s)\|_\infty < 1 \tag{29}$$

$$\|\boldsymbol{Z}_{\mathrm{Sdq}}(s)\|_\infty \|\boldsymbol{Y}_{\mathrm{Ldq}}(s)\|_1 < \frac{1}{2} \tag{30}$$

$$\begin{aligned} &\left(\|\boldsymbol{Z}_{\mathrm{Sdq}}(s)\|_G \|\boldsymbol{Y}_{\mathrm{Ldq}}(s)\|_{\mathrm{sum}} < 1\right) \cup \\ &\left(\|\boldsymbol{Y}_{\mathrm{Ldq}}(s)\|_G \|\boldsymbol{Z}_{\mathrm{Sdq}}(s)\|_{\mathrm{sum}} < 1\right) \end{aligned} \tag{31}$$

where the norms of complex matrix $\boldsymbol{A}$ are calculated as:

$$\|\boldsymbol{A}_{m\times n}\|_G = \max_{\substack{1\leqslant i\leqslant m \\ 1\leqslant j\leqslant n}} (|a_{ij}|) \tag{32}$$

$$\|\boldsymbol{A}_{m\times n}\|_\infty = \max_{1\leqslant i\leqslant m} \left(\sum_{j=1}^{n} |a_{ij}|\right) \tag{33}$$

$$\|\boldsymbol{A}_{m\times n}\|_1 = \max_{1\leqslant j\leqslant n} \left(\sum_{i=1}^{m} |a_{ij}|\right) \tag{34}$$

$$\|\boldsymbol{A}_{m\times n}\|_{\mathrm{sum}} = \sum_{j=1}^{n}\sum_{i=1}^{m} |a_{ij}| \tag{35}$$

3) Technical Challenges and Development Tendency

Notwithstanding the incomparable advantages in processing *black-box* systems whose topology, control, and parameters are unclear, the impedance-based approaches face several challenges that require further investigation and effective solutions.

a) Impedance Modeling: Currently, the impedance models are only capable of analyzing simple systems containing a few VSCs [52]. It is crucial to establish modeling theories and methods for multi-VSC complex systems [61], e.g., the divided small-signal model in [62] provides a new perspective for the stability analysis of a multi-VSC system, by separating the whole system into several subsystems. For a complex multi-VSC system with wide frequency range coupling, one major difficulty is the separation of the source subsystem from the load subsystem and the establishment of an accurate macro-model that reflects the port impedance. For example, for unbalanced VSC systems, more frequency coupling terms corresponding to the positive- and negative-sequence components need to be considered. Instead of the dual-frequency model in (11), the multi-frequency modeling approaches, including the HSS model [21], the generalized averaging method [63] and the DP model [64], are required to capture the mutual-coupling dynamics between those components.

Besides, since the dynamic process of each coupling loop is included in the impedance matrix, and the expressions of the matrix entries are often complicated, the physical mechanism of the model is usually unclear and analytical analysis cannot be performed. The model outcomes are mainly numerical values with poor universality, prohibiting the intuitive understanding of physical processes and principles of how each dynamic process (especially the control process) affects the overall system stability. Therefore, when analyzing the system instability mechanism, it is necessary to investigate the impedance model with reasonable order and clear physical meaning [65]. In addition to the dq frame, the system modeling and stability criteria development can also be based on the polar frame [48], sequence frame [47] and stationary frame (phasor domain) [66]. For example, the impedance matrix (14) built in polar frame features a symmetric structure [51], simplifying the system analysis and facilitating intuitive understanding of the system stability. If the coupling terms of impedance matrix are small, the influence of off-diagonal elements can also be neglected [67]. Besides, aggregation methods are also adopted for simplifying the system model [68].

b) Stability Criteria: The stability boundary and condition given by the existing impedance-based methods are highly conservative [69] and existing stability criteria that reduce the computational complexity are all conservative, to some extent [59]. In addition, the system stability predictions given by different criteria are often opposite [60]. Even when correctly assessed, it is difficult to use the stability result directly in the system design in terms of structure, control, and parameters. These limitations impose a need to develop stability criteria characterized by simple and effective implementation, low calculation burden, weak conservatism, and ability to aid the complex system design [58]. In [59], the computational complexity and conservatism of typical stability criteria are analyzed and compared.

To facilitate the analysis of instability mechanism and the development of stability control strategies, the connection of the pertinent impedance stability criteria with the actual system needs to be strengthened from the perspective of physical meaning. For example, [70] proposes a method that exploits system global impedance and equivalent RLC parameters. Based on the resonance point and resonance damping, the method is beneficial for revealing the resonance mechanism and assessing system stability.

c) Impedance Measurement: Since the port impedance are input information for the impedance-based stability criteria, their measurement accuracy directly affects the prediction result reliability. The port impedance can be obtained by active injection of current or voltage and pertinent measurement. Hence, the external port characteristics and system models can be obtained regardless of the internal information of the system. Due to the strong non-linearity of the VSC system, the frequency sweep method is currently used to obtain the wideband port impedance information [52], however, in general, it has a long measurement duration and a large impact on the normal operation of the device under test (DUT) [71].

Commonly used impedance measurement devices include the frequency response analyzer (FRA) [72] and harmonic current/voltage injection devices [73]. Limited by its output power, the FRA can only be applied to impedance measurement of low power systems. The harmonic injection method requires online measurement of the system port impedance pertinent to the disturbance at each frequency. With low injection power, injection signals are not obvious and impedance signals are easily overwhelmed by noise [74]. To improve the significance of measurement results, the injection power can be amplified, however, the equipment cost is increased, and notable interference is induced in the DUT operation, which would cause imprecise results of the system port characteristics. Therefore, it is critical to develop impedance measurement methods, standards, and devices aimed at large-capacity and multi-VSC system applications [71], especially for hardware-free, non-invasive parametric identification [75], to minimize the influence of the impedance measurement on the DUT.

In addition, since a boundary needs to be preliminarily chosen to separate the source subsystem from the load subsystem, the port impedance model cannot reflect the interaction between the various control loops within the subsystem. Even though the interaction processes between the interconnected systems are stable, it does not assure stability within the subsystem, especially when the working point or topology within the subsystem varies as the operating condition changes. In this sense, the system boundary, as a prerequisite for determining the measurement port, directly affects the accuracy of impedance measurement and stability assessment, and thus its reasonable selection is of paramount importance and should be investigated cautiously.

C. Small-Signal Modeling and Stability Analysis Alternatives

1) Phase-Amplitude Dynamics Model

From the perspective of the internal voltage vector of the VSC, the PAD model in [76] describes the features of the

VSCs through the relationship between the input/output power and the internal voltage phase/amplitude, i.e., motion equations of phase-amplitude dynamics:

$$\Delta E(s) = \frac{G_{\mathrm{E}}(s)}{s}\left[\Delta Q_{\mathrm{in}}(s) - \Delta Q(s)\right] \tag{36}$$

$$\Delta \omega(s) = \frac{1}{Ms + D}\left[\Delta P_{\mathrm{in}}(s) - \Delta P(s)\right] \tag{37}$$

where ΔE and $\Delta\omega$ are the changes in system voltage magnitude and phase, respectively; G_{E} is the transfer function of terminal voltage controller; M and D are the inertia and damping coefficients of the equivalent rotor (see Fig. 7), respectively; ΔP_{in} and ΔP are the changes in system active power input and output, respectively; and, ΔQ_{in} and ΔQ are the changes in system reactive power input and output, respectively.

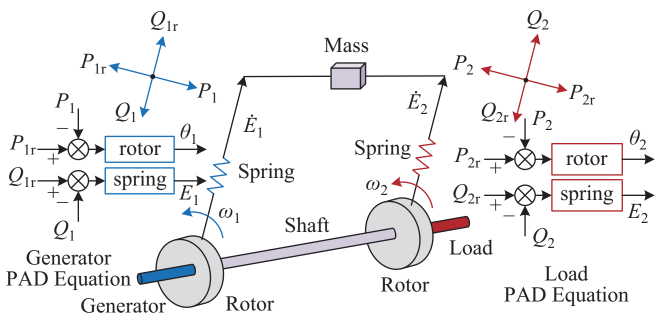

Fig. 7. A generic description of phase-amplitude dynamics model.

The PAD model is a generalized method to describe the system dynamic features, reflecting the essential physical mechanism of the AC system operation. The electromechanical motion equation established in [77] describes the inertial dynamics of doubly fed induction generator (DFIG)-based WTs. The concepts of damping and restoring components are developed in [78] to give physical insights into the DC voltage stability of the VSC system affected by AC voltage control. In [79], the equivalent inertia of the DFIG system is estimated and quantified by the phase angle motion equation that depicts the relationship between the contributed inertial response and the internal voltage. Based on the PAD model, a simplified small-signal model is constructed in [5] for clearly understanding the physical properties and frequency response of a Type 3 WT with $\mathrm{d}f/\mathrm{d}t$ control. The impact mechanism of transient control of DFIG system on the first-swing stability and electromechanical oscillation of SGs is also clearly explained in [80] and [81]. Based on motion equations, the interactions among DFIGs [5], VSCs [7], and HVDC systems [82] in DC voltage control (DVC) timescale have been physically explained. To analyze the effect of system behavior on angle and voltage stability, a small-signal DFIG model based on the internal voltage motion equation in the electromechanical timescale is proposed in [83]. Furthermore, the PAD model can also be used to reduce the order of the multi-VSC system model [84], to quantitatively analyze the interactions between AC and DC networks [76], and to effectively develop the frequency regulation scheme [85].

2) Static Synchronous Generator Model

Inertia and damping effects of the VSC system are critical from the perspective of frequency stability improvement. However, researchers have not reached an agreement upon the physical mechanism or influential factors of the VSC system inertial and damping effects; some works even deduced conflicted conclusions. For instance, the mainstream viewpoint is that droop control cannot emulate the inertia, yet in [86] it is believed that droop control and virtual synchronous generator (VSG) control are completely equivalent in terms of inertia emulation. Based on that, [6] exploits the electric torque analysis and proposes the SSG model suitable for inertia and damping analysis of VSC-dominated power systems.

According to the SSG model, the major difference between the VSC system and the rotational SG (RSG) system lies merely in the implementation of energy conversion, as shown in Fig. 8. Apart from this difference, according to the SSG model, the two systems have consistent abstract frameworks in terms of physical and control structures [6]. On this basis, dynamic analysis methods for the RSG system can be similarly adopted in the VSC system. For example, [6] introduces the electric torque analysis, and considers that various controls function as synchronous torques and/or damping torques. The dynamic characteristics of the VSC system are dependent on the overall synchronous and damping torques provided by all control functions (see Fig. 9), i.e.

$$T_{\mathrm{J}}(s)\frac{\mathrm{d}\Delta\omega(s)}{\mathrm{d}t} = -T_{\mathrm{D}}(s)\Delta\omega(s) - T_{\mathrm{S}}(s)\Delta\delta(s) \tag{38}$$

where T_{J}, T_{D}, and T_{S} are the equivalent inertia, damping, and synchronization coefficients of the VSC system, respectively.

In view of the electric torque analysis, the left-hand side term in (38) describes the system inertia effect, while the right-hand side terms describe the damping torque and synchronous torque effect on the system, respectively, revealing the damping and synchronization ability of each control process with respect to frequency dynamics. Hence, from the SSG model perspective, $T_{\mathrm{J}}(s)$ in Fig. 9 is considered as the virtual rotor of the VSC system; $T_{\mathrm{D}}(s)$ and $T_{\mathrm{S}}(s)$ are virtual damping and synchronous torques imposed on the virtual rotor, and the system stability depends on the direction of the resultant total torque.

Since $T_{\mathrm{J}}(s)$, $T_{\mathrm{D}}(s)$, and $T_{\mathrm{S}}(s)$ are transfer functions whose amplitudes and phases vary with different frequencies, e.g., the system inertia can be partially negative in a certain frequency range due to the control effect [87], the VSC system stability needs to be analyzed based on the synthetic torque at a specific frequency. If $T_{\mathrm{J}}(s)$ is positive (negative) at a given frequency, the system is stable when the total torque is in the first (third) quadrant. If the stability is assured in the full frequency range, the system is full-frequency-domain stable. Therefore, the power angle stability and frequency stability of the power system are determined by the combination effect of system inertia and damping/synchronous torques at various frequency points, and the pertinent stability criterion is written as:

$$\left[T_{\mathrm{J}}(s)\cdot T_{\mathrm{D}}(s) > 0\right] \cap \left[T_{\mathrm{J}}(s)\cdot T_{\mathrm{S}}(s) > 0\right] \tag{39}$$

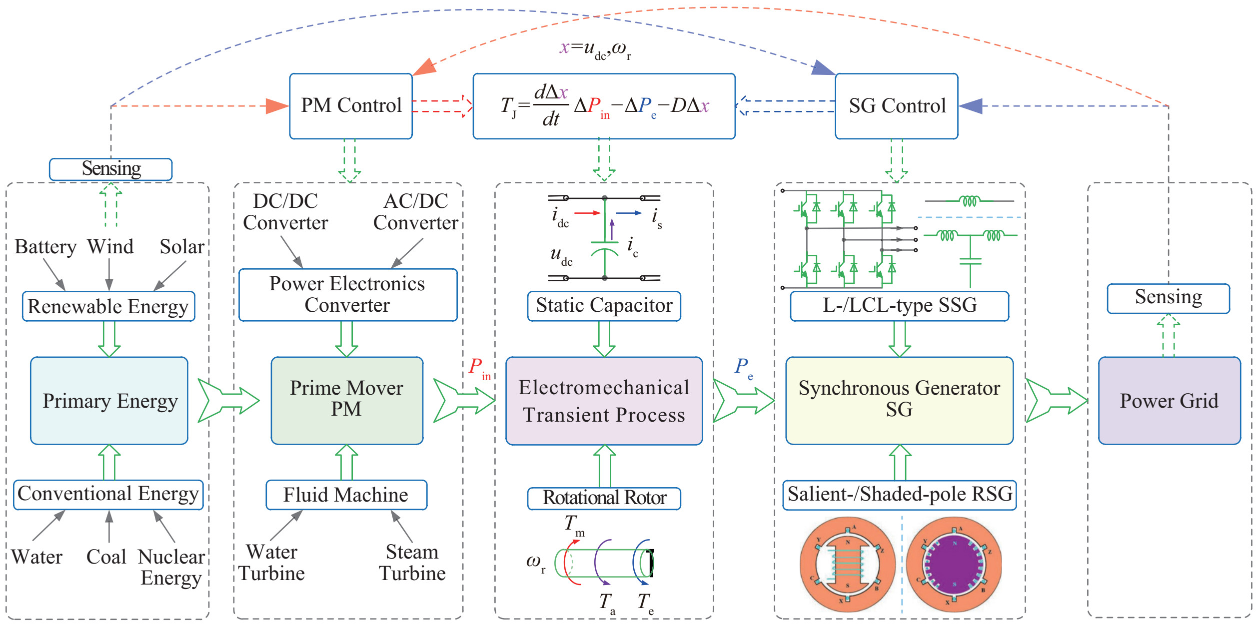

Fig. 8. General physical and control structures of a VSC system from the SSG model perspective.

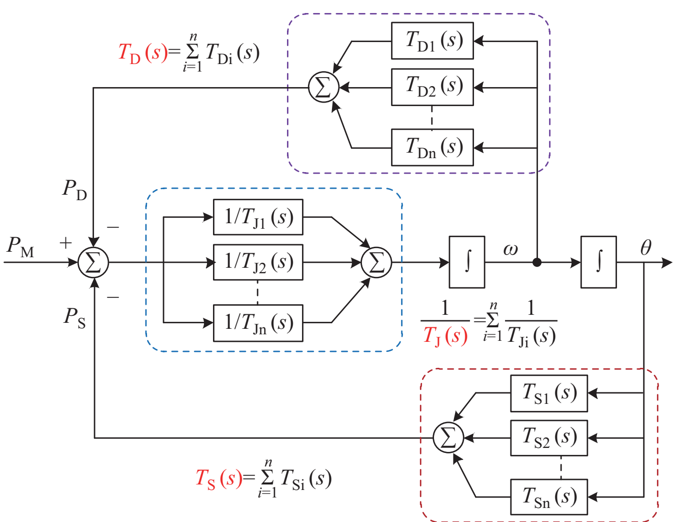

Fig. 9. Effect of VSC system control from the electric torque perspective.

With a clear physical meaning, the SSG model is beneficial for analysis and control of the VSC system dynamic features from the view of the physical mechanism. [88] further summarizes the VSC system inertia and damping features under common control schemes. By establishing the SSG model, the inertia and damping features of a grid-tied ESS with different control modes are compared in [89] and the influence of PLL is also investigated in [90]. Considering the ESS and the static var generator when suppressing the grid power oscillation, the ability of VSCs with traditional controls to provide the grid with inertia/damping support is affirmed, [91], [92].

3) Discussion for PAD and SSG Models

Both, the PAD model and the SSG model, can meet the main requirements and are essentially analogous to a real physical system, i.e., a rotor's rotation versus the voltage across a capacitor. Power engineers are quite familiar with the physical models that are similar to the rotor motion equation in RSG; such kinds of methods are conducive to studying the modeling, analysis, and control of system dynamic stability starting from the physical mechanism. With these approaches, the mechanism of system instability can be elaborated from a physical perspective.

The PAD model, SSG model, and impedance model are all frequency-domain analysis methods with the main advantage of obvious and clear physical meaning. For example, the PAD model is completely equivalent to sequence-domain impedance [83]. However, it is difficult to extend the PAD and SSG models to multi-VSC scenarios. For example, when analyzing the frequency and phase dynamics, it is usually assumed that the grid voltage amplitude remains unchanged. For this reason, the analysis is often performed in the single-machine infinite-bus (SMIB) frame [6], [79]. There is a crucial need to develop the PAD and SSG models with clear physical meaning and feasibility of dynamic analysis for multi-VSC systems. In addition, the inertia and damping control method aimed at improving system stability can be established, by exploiting the clear physical meaning.

III. Large-Signal Modeling and Stability

Due to the nonlinearity between the phase difference and transmission power in AC grids [93] and the VSC non-linear processes (e.g., switching operation, control switching [94], saturation limiting [95], etc.), the VSC dominated system suffers from the risk of instability in the case of large disturbances. Though the related study is still in its infancy, it is necessary to conduct research on large-signal modeling and stability analysis. Typical methods include the unsymmetrical fault analysis, bifurcation theory, energy function methods, graphical analysis, DP model-based methods, and detailed model-based numerical simulation. It is noted that the transient stability that is of concern currently is part of large-signal stability.

A. Energy Function Methods in Energy Domain

1) Basic Principle

The energy function methods in the energy domain, also known as Lyapunov function-based direct methods [96], exploit the Lyapunov's second method for stability and are used to analyze the dynamic stability of a system when it is subjected to a large disturbance. The methods view the system stability from the energy perspective, and the basic principle is described as follows [97]:

If there is an energy function $\boldsymbol{V}(\boldsymbol{x})$ such that $\boldsymbol{V}(\boldsymbol{x}) > 0$ if $\boldsymbol{x} \neq \boldsymbol{x}_0$, $\boldsymbol{V}(\boldsymbol{x}_0) = 0$, and $\dot{\boldsymbol{V}}(\boldsymbol{x}) \leqslant 0$ in the neighborhood of $\boldsymbol{x}_0$, the dynamic system $\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x})$ will have a stable operating point $\boldsymbol{x}_0$ [98].

This energy function that verifies these conditions is known as a Lyapunov's function. Besides, by building and comparing the transient energy function $\boldsymbol{V}$ and critical transient energy $\boldsymbol{V}_{\rm cr}$, the system transient stability and its stability margin can be evaluated. The system is stable while $\boldsymbol{V} \leqslant \boldsymbol{V}_{\rm cr}$, and the larger the difference, the greater the stability margin; otherwise, the system will lose its stability.

2) Key Features and Main Applications

Energy function methods are widely applied in traditional power grids as they have the capability to quickly and quantitatively analyze the system stability margin and assess the stability in the case of large disturbances. In recent years, these methods have also been introduced into the large-signal modeling and stability analysis of VSC-dominated power systems. By migrating the concepts, tools, and methods of the stability analysis of SG-dominated power systems, the power-angle curve-based equal area criterion (EAC) is successfully applied to the VSC-dominated power systems [6]. By focusing on the rotor speed control timescale, the generalized potential and kinetic energy of WTs is developed in [20], and the transient stability is analyzed by comparing the transient energy function versus critical transient energy that is based on the developed generalized energies. However, the generalized energies lack physical meaning [20], which is inconvenient for physically understanding the principle of energy conversion in VSCs with controllers and large disturbances. In [96], the energy function of the VSG-controlled VSC tied to the infinite grid is constructed by defining the virtual rotor kinetic energy, the rotor potential energy, the magnetic stored energy and the dissipated energy of line impedances. Based on the constructed energy function, the detailed procedure for determining the critical fault clearance time is successfully obtained. The Lyapunov function-based control utilizes local variables as its input signals and is successfully implemented on the series converter [99]. The large-signal stability of the interconnected microgrids is investigated in [100] and minimum stabilizing DC voltage criterion is proposed. In [101], [102], the Lyapunov function is considered to prove the transient stability of large-signal nonlinear models of VSC-based microgrids. The general processes for constructing the Lyapunov function are presented in [103] and the nonlinear model of islanded microgrid is established by employing a Lyapunov method, by which the attraction domain of paralleled VSCs is quantified.

3) Technical Challenges and Development Tendency

In VSC-dominated systems with their non-linear and high-order model, flexibility in control switching, and wide timescale range, great challenges are imposed in the application of energy function methods to the large-signal modeling and analysis [30].

a) Energy Function Construction: The biggest advantage of energy function methods is the capability of stability assessment of nonlinear systems. However, in many engineering and physical problems, it is quite difficult to find an energy function satisfying the classic LaSalle's invariance principle [104]. This difficulty has been a big drawback in the application of energy function methods to stability analysis of VSC-dominated systems with more realistic models. Hence, it is very important to find the general and detailed process to construct a candidate energy function for VSC systems.

b) System Simplification: For complex systems with multi-VSC interconnections, it is difficult to construct the system energy function based on the detailed model. This is unfavorable for analyzing the existence of the system steady-state operating point and limits the effective analysis of system stability before and after a large disturbance. Therefore, energy function methods are mostly used in SMIB system analysis. For example, to focus on the nonlinearity of grid synchronization and the resulting destabilization phenomenon, the VSC is often simplified into a low-order nonlinear differential-algebraic equations (DAE) model dominated by PLL [105]. Similarly, for the droop- and VSG-controlled VSCs, the system is often simplified into low-order DAE models dominated by droop or swing equations [95], [103]. By constructing the quasi-stationary (QS) model of the droop-controlled VSC, [98] and [106] obtain the Lyapunov functions of the VSC system when considering the dynamics of active and reactive power control. In addition, to obtain more accurate results, some works also consider the dynamic process of other control loops [96].

c) Instability Mechanism and Stability Improvement: The energy function methods are more applicable to low-order systems [107], and are attractive and powerful for physically understanding the instability mechanism and deriving suitable controllers that can counteract a wide variety of disturbances in the power system [108]. For instance, EAC-based energy function method in [6] is a powerful tool for physically understanding the transient response and theoretically analyzing the transient stability of VSCs, and has been widely used in recent works [96], [103]. Therefore, future development should focus on the design-oriented energy function methods, which are extremely important for detection algorithms [109], controller design [110], threshold determination [95], and stability improvement [105] of VSC-dominated systems.

B. Numerical Simulation in Time Domain

1) Basic Principle

Numerical simulation in time domain is most widely used and provides the most reliable results. The validity of results obtained from other methods is usually verified by numerical simulations. The general steps are:

a) The mathematical model reflecting the physical features of a VSC-dominated system is established in [111], encompassing

$$\mathbf{0} = g\left(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{l}, \boldsymbol{z}\right) \tag{40}$$

$$\dot{\boldsymbol{x}} = f\left(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{l}, \boldsymbol{z}\right) \tag{41}$$

$$\dot{\boldsymbol{l}} = h\left(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{l}, \boldsymbol{z}\right) \tag{42}$$

$$\dot{\boldsymbol{z}}\left(k+1\right) = d\left\{\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{l}, \boldsymbol{z}\left(k\right)\right\} \tag{43}$$

where $\boldsymbol{x}$ and $\boldsymbol{l}$ are state variable vectors of continuous and discrete processes, respectively; $\boldsymbol{y}$ and $\boldsymbol{z}$ are vectors of system algebraic and discrete variables, respectively. The algebraic equation (40) describes the equilibrium relationship within the system, e.g., Kirchhoff's laws of voltage and current; the differential equations (41) and (42) describe short- and long-term continuous processes respectively; the iterative, algebraic equation (43) describes the discrete processes in the system, such as actions of on-load voltage-regulating transformer, voltage and current over-limit protection, etc.

b) The equation array model (40)–(43) is converted into a discrete, iterative calculation model suitable for computer simulation, and programmed through a high-level language.

c) Various typical working conditions are selected for numerical calculation, and the system stability is analyzed and determined based on the numerical results.

2) Key Features and Main Applications

Time-domain numerical simulation based on a detailed model can accurately reflect complex system dynamics in the full time- and frequency-domain. It is widely used for dynamic analysis and control of VSC-dominated systems, in terms of harmonic analysis, controller design, short-circuit current calculation, relay protection verification, etc., and the simulation result is the baseline for correctness verification of all methods [2]. In [112], by numerical simulation, effects of different control schemes on the microgrid stability subsequent to fault-forced islanding are investigated, and simulation results show that the critical clearing time is highly dependent on the microgrid control strategy. The voltage support, transient stability, and frequency stability are investigated in [113] via numerical simulations and the mechanism for loss of synchronism of VSC systems caused by inadequate current injection is well explained based on the German grid code. In [114], the transient stability of the multi-VSG microgrid is evaluated by calculating the voltage angle deviations of generators.

As the most significant advantage of numerical simulation, regardless of the complexity in terms of system structure and dynamic interaction processes, each VSC device, load, and control loop can be modeled separately and all such models can be merged (e.g., as building blocks by the modular state-space model strategy in [115]). Complete models for VSC-dominated systems are quite accurate and are frequently found in literature. However, the modeling procedure and numerical computation becomes fairly burdensome when the number of VSCs in a grid is significantly large [116]. QS modeling, as an effective solution to this problem [2], [26], makes full use of timescale division (pertinent to the multi-timescale features in Fig. 2) for different dynamic processes.

The core idea of the QS model-based analysis is to concentrate on the timescale of interest, and to approximate the processes that weakly affect the target timescale processes as QS ones represented by algebraic equations [117]. Some examples are:

a) When focusing on a short-term process, it is considered that the variables $\boldsymbol{l}$ and $\boldsymbol{z}$ pertinent to the long-term timescale, cannot change accordingly. The relevant process is regarded as transient equilibrium point, and (42), (43) are rewritten as

$$\mathbf{0} = h\left(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{l}, \boldsymbol{z}\right) \tag{44}$$

$$\boldsymbol{z}(k+1) = \boldsymbol{z}(k) \tag{45}$$

The mathematical model at this time reflects the dynamic mechanism when the transient equilibrium point is perturbed, and is often used for the study of power angle stability.

b) When focusing on a long-term process, it is considered that there is a stable equilibrium point for the short-term dynamic process, and it is reached in a sufficiently short time, i.e., (41) can be reformulated as an algebraic equation:

$$\mathbf{0} = f\left(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{l}, \boldsymbol{z}\right) \tag{46}$$

The pertinent model reflects the system dynamic mechanism in the long-term timescale, and is often used for the stability study of long-term dynamic processes, e.g., long-term voltage and frequency stability [117]. Fig. 10 depicts the calculation procedure for long-term dynamic stability. The points in the figure represent the system transient equilibrium points, i.e., the solutions to (40) and (46). Processes A to A' and B to B' represent the sudden changes of the equilibrium point, describing large disturbances and discrete events such as power line switching and relay protection. Curves $A'B$ and $B'C$ describe the long-term processes formulated by (42). Obviously, QS modeling uses transient equilibrium points to replace the system transient processes, and only retains equations associated with long-term dynamic processes.

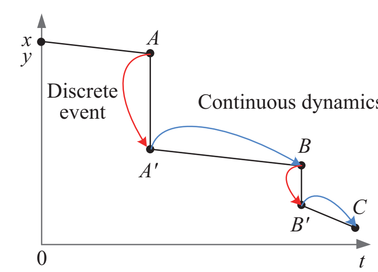

Fig. 10. Simulation principle of long-term dynamic processes.

The QS model of VSC-dominated systems can be obtained using the multi-timescale features or stability classification [2], i.e., by retaining the main factors that affect the system dynamic features of the target timescale and neglecting the secondary factors (with QS approximation). In [20], the dynamics of the VSC systems after disturbances are divided into AC current control timescale, DVC timescale, and rotor speed control timescale. In this manner, the electromagnetic timescale classified in traditional power systems is further divided into the two former types, while the electromechanical dynamics correspond to the rotor speed control timescale. In [118], an accurate reduced-order model is proposed for modeling VSC-based microgrids.

In addition to modeling, another critical work is to develop algorithms for numerical calculation of the model. For the electric system solution, differential-discretization of the nodal equations is performed to obtain the component volt-ampere relationship and form the nodal conductance matrix [119]. For the solution of a control system with strong nonlinear features, the nonlinear problems are transformed into linear equations, or alternatively, the Newton iterative scheme is formed to improve the solution accuracy and numerical stability, by combining the linear and nonlinear control system equations [120]. In [121], the numerical oscillation problem is solved by using a two-and-a-half-step backward Euler method at the switching time. In [122], the new system topology and initial values after the switching action are obtained through the utilization of extrapolation and backward Euler method, and re-initialization is realized. In [123], to enhance the computational efficiency, the entire VSC system is partitioned into three parts, i.e., the transient stability subsystem, the electromagnetic transient subsystem, and the interface subsystem.

3) Technical Challenges and Development Tendency

Fully considering the detailed features of dynamic processes with all time- and frequency-scales can cause huge computational burden and unacceptable long time, especially when the power network is large in scale, complex to control, dispersive in timescale and contains a large number of VSCs with various functions. At this time, the calculation speed, numerical accuracy, and stability are the main obstacles to the application of time-domain simulation [124].

a) Dynamic Modeling: Using detailed models for all components in the system causes not only huge computational burden, but also difficulty in use for long-term stability analysis and simulation of complex systems. Accordingly, low-order models are usually used for numerical simulation, or the timescale features are used for hybrid simulations, to adequately simplify the calculation process and improve the calculation efficiency. Unfortunately, the reduced-order models may fail to predict some system instabilities, e.g., [118] finds that the network dynamics, despite their fast nature, appear to have major influence on stability of slower modes; [125] finds that though inner-loop dynamics are relatively fast, they seem to have an impact on power loops with slow dynamics, and neglecting them can lead to questionable results. Therefore, the choice of different timescales and dynamic processes has a significant effect on the analysis results, and it is particularly important to divide the timescales reasonably. In general, current modeling research on the problem is mainly concerned with the computational efficiency and model reduction. Future work should also value the model-order reduction in terms of error quantification as well as applicability [125].

b) Numerical calculation: Existing numerical simulation programs, mostly based on serial timing, have low calculation efficiency and require an unacceptably long time in the case of a large-scale system. To greatly improve the simulation efficiency, possible solutions include adopting a much larger time step, the model-order reduction technique, and the use of massively paralleled graphics processing units [126]. In addition, for a switching system represented by the VSC dominated power system, the numerical simulation method needs to solve several issues, including the inconsistency between the switching action and simulation step and the multiple switching problem caused by the fixed step size, the problem of synchronous switch operation, and the numerical oscillations associated with the trapezoidal method after the switching action.

c) Stability Assessment and Mechanism Comprehension: The biggest limitation of numerical simulation is its sole applicability to *white-box* systems whose information, e.g., topology, control, and parameters, are completely known. However, unpredictable random disturbances may make it difficult to obtain many parameters, and even the system topology can constantly change with different working conditions. Currently, the main approach is to explore all potential working conditions and establish fault sets. To this end, it is crucial to adopt the practice of traditional systems and propose a unified approach to transient stability contingency filtering, ranking, and assessment for the VSC-dominated system [127]. Obviously, the numerical simulation can only be used to obtain quantitative results under specific working conditions.

To obtain the stability boundary, it is necessary to explore the calculation for each working condition in the fault sets, however, this will cause huge computational burden and require long simulation time. In addition, this method is difficult to use in the analysis of the instability mechanism [23]. Therefore, numerical simulation should be combined with other methods to perform effective stability assessment and for understanding the instability mechanism.

C. Large-Signal Modeling and Stability Analysis Alternatives

Apart from the above methods, graphical analysis [100], DP methods [128], bifurcation theory [129], and other advanced methods [130] are also introduced into large-signal modeling and stability analysis of VSC-dominated systems. Among these, the graphical and DP methods have fruitful outcomes as they have been frequently used recently.

1) Graphical Methods

The graphical methods consist of power-angle curves, frequency-angle curves, voltage-angle curves, EAC, and phase portraits that are mostly used in SMIB systems [100]. In [6], the concepts, tools, and methods of transient stability analysis of SG-dominated power systems (such as power angle, power-angle curves, and EAC) are firstly migrated to investigate the dynamic behavior and stability issues of the VSC system; the proposed methodology has been widely used in recent literature [109], [110], [131]. The frequency-angle curve is proposed in [5] for illustrating the effect of grid strength on the dynamic performance of the DC voltage control in DFIG. The power-angle curves and EAC are exploited to analyze large-signal DC voltage stability of the VSC-based SMIB system [6]. Similarly, the EAC and phase portrait-based methods are also adopted to investigate the large-signal synchronization stability of VSC-based SMIB systems under severe faults [110], [131]. In [94] and [95] it is proposed that synchronous instability can occur when the VSC current is saturated under large disturbances, and the instability mechanism is physically explained by using the power-angle curves of VSC-based SMIB systems. In [96] and [103], the power-angle curve is also adopted to investigate the transient angle stability of single- and double-VSC systems. By constructing voltage-angle curves, [105], [109], and [110] focus on VSC-based SMIB systems and analyze whether equilibrium points are present under large disturbances, using power synchronization control, droop control, and VSG control. Using the I–V plane, the effects of grid voltage, equivalent reactance, and q-axis current control gain on the equilibrium of the WT system is also physically investigated in [30]. Besides, by establishing the P–V curves of VSC-based SMIB systems, the impact of system dynamic behavior on short-term voltage stability has been well investigated [132]. The mechanisms of voltage-frequency-coupled transient instability are investigated by the voltage-vector-triangle graphic method [133].

Obviously, the significant advantage of graphical methods is that the physical meaning is intuitive and easy to understand. This helps to provide a direct explanation of the physical nature behind the destabilization process. However, they are only suitable for analyzing low-order (mostly SMIB) systems, e.g., the phase portrait is only applicable to behavioral analysis of the two-dimensional autonomous system.

2) *DP Model-based Methods*

The frequency decomposition-based DP model, which is a time-varying large-signal model between the phasor model and detailed model [128], uses several time-varying Fourier coefficients (known as dynamic phasors) to continuously approximate the system time-varying variables. In [116], it is proved that the DP model can accurately predict the stability margins of droop-controlled VSCs, while the reduced-order small-signal model fails. The DP model for the interfaces of VSC and AC grid subsystems is adopted in [123] to improve the accuracy and efficiency of hybrid simulations. Based on the multi-frequency shift transformation [134], the typical DP model is successfully extended to the system-level models for a variety of power converters. To analyze the transient response of an unbalanced microgrid, the complete system DP model is obtained in [135] by combining the DP model of each submodule at a time-variable frequency. In [136], the DP model of grid-tied VSC shows that the large-signal stability of PCC voltage is governed predominantly by the dynamics of the load and the PLL, simultaneously. Besides, the DP methods are also introduced into the SSR analysis [137] and system short-circuit calculations [128]. Obviously, the DP model also requires the art of compromise—with more frequency components retained, the accuracy of the model increases, however, the complexity and computational burden of the model increase as well [64].

IV. Discussion of Future Development Trends

In conclusion, further research works on the following eight subjects are expected:

A. *Stability Definition and Classification*

Though the definition and classification of power system stability issues have been addressed earlier by several CIGRE and IEEE Task Force reports [117], they fail to reflect current industry needs, practices, and understanding of VSC-dominated systems in terms of preciseness and completeness, e.g., they do not fully encompass practical, VSC-related instability scenarios [2] such as the harmonic instability [138]. Furthermore, due to possible contradictions in relevant reports, much work remains to be done before consensuses can be reached and international standards established. For instance, the IEEE PES Task Force on microgrid stability definitions, analysis, and modeling released its achievements on system stability including the definition, classification, analysis, and examples, in its technical report [2], whereas different definition of stability and classification have been recently reported by the IEEE Power System Dynamic Performance committee [130] (see Fig. 11).

Consistent use of terminology is required for developing system design and operating criteria, standard analytical tools, and study procedures. However, due to the lack of standards

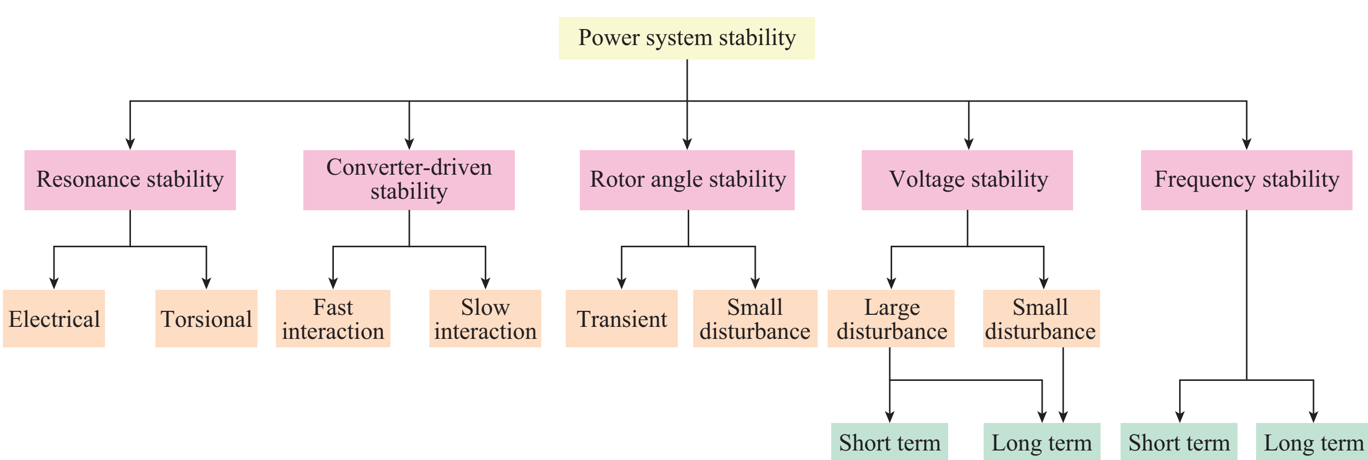

Fig. 11. Classification of stability for VSC-dominated power systems according to the IEEE Task Force on stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic-interfaced technologies.

in stability definition and classification, different terms have emerged for the same stability type. For instance, some concepts in existing literature, including grid-synchronization stability [53], first-swing stability [80], synchronous instability [94], transient angle stability [103], and synchronization stability [105], are all counterparts of angle stability in traditional power grids.

B. Physical Understanding of Instability Mechanism

A clear understanding of different types of instability and how they are interrelated is essential for the satisfactory design and operation of power systems. While detailed models are available, they are both computationally expensive and not transparent enough to provide an insight into the instability mechanism or factors, hindering the development of stability control strategies based on the physical mechanism. In particular, the dynamic process of VSC under fault condition often involves saturation limiting and control switching; the control strategy (especially the LVRT strategy), if not properly designed, is likely to cause deterioration of control performance, over-current/over-voltage faults, and even instability issues and disconnection from the grid [30], [133]. Therefore, understanding the evolution process, occurrence mechanism, influencing laws, and dominant factors of the above physical phenomena is of great importance for designing reasonable control schemes, limiting thresholds, and switching conditions. If mechanism analysis or process anatomy is the aim, a reduced-order model should be used as a benchmark for developing a simplified model that holds the main physical process features, based on which the leading factors for instability can be effectively identified and target strategies can be developed. Existing literature use stability classification and multi-timescale features for model aggregation [36] or simplification [84]. It is noted that the model-order reduction is focused on particular problems: the reduced-order model for one scenario cannot be directly used for another, otherwise a significantly lower accuracy is expected [48], [139].

C. Accurate Prediction of Stability Boundary

The system structure, parameter, and protection threshold designs rely on accurate prediction of the system stability boundary, without which a sufficiently large safety and stability margin is needed to assure normal system operation at the expense of cost-effectiveness. Detailed models should be used as the benchmark for modeling and stability analysis aimed at accurate predictions. Especially in the case of large disturbances when measures (e.g., using protection control, saturation limiting, and control switching) are taken to avoid the VSC equipment damage, accurate prediction results of the nonlinear dynamics for the VSC-dominated system (essentially characterized by wide timescales and frequency coupling) [10] can only be obtained with difficulty via quantitative analysis, since most reduced-order analytical models can only linearize the system without reflecting the above switching processes. At this time, the prediction is dependent on the continuous-discrete mixed detailed model with multi-timescale features jointly given by (40)-(43), which mathematically prohibits the deviation of an analytical solution. Therefore, it is crucial to develop efficient and stable numerical calculation algorithms and corresponding software to achieve accurate prediction of the stability boundary.

D. Multi-Method Integration Based Stability Prediction

Based on previous discussions, the existing approaches have their inherent prerequisites, advantages, limitations and applications, as comparatively listed in Table I. The conservativeness associated with different stability criteria varies greatly, and the analysis results given by different methods can even conflict. Thus, for a complex nonlinear system represented by the VSC-dominated large-scale power system, it is currently difficult to establish a set of simple, accurate, and versatile stability analysis theories, methods, and tools. Based on the existing theoretical basis and analysis methods, an intelligent expert analysis system should be developed, integrating a variety of typical analysis methods, to achieve complementary advantages and mutual verification, and to comprehensively interpret the system dynamic features and stability mechanism from different perspectives.

E. Design-Oriented Stability Analysis

Guidance for system design is one of the main functions of stability assessment and instability mechanism analysis [95]. However, existing design methods are usually based on the SMIB system. When the VSC is tied to the actual power grid, various stability issues may occur due to the complex grid structure and variable working conditions. For example, several studies show that in the weak grid condition, a stronger coupling effect between the coupling loops increases the probability of system instability [37]. Therefore, it is necessary to carry out research on the stability analysis methods for system structure, control, and protection design, which in turn affects the system stability and stability margin [94].

F. Operation-Oriented Stability Analysis

During operation, the loads in a power system are constantly switching; the system topology is constantly changing, and the disturbance is difficult to determine. Accordingly, it is difficult to match the results based on the *white-box* model to the actual operating condition completely. It is thus necessary to derive real-time, online safety and stability analysis methods based on measurement data (e.g., real-time measurement data based on phasor measurement unit devices). Data-driven stability assessment methods for online applications need to be developed for complex, multi-VSC large systems that are difficult to effectively analyze and evaluate using conventional methods.

G. Benchmarks Development for Typical Stability Issues

To promote the development of stability analysis and control technologies, it is critical to adopt the practice of traditional SG-dominated grids in terms of development of representative examples and benchmarks for typical stability problems and instability phenomena. Detailed information of benchmarks (disturbance, topology, control schemes, and pertinent parameters) should be provided for easy access, so that testing, comparison, and plan selection of relevant research results

TABLE I
ADVANTAGES, LIMITATIONS, AND APPLICATIONS OF DIFFERENT APPROACHES FOR SYSTEM MODELING AND STABILITY ANALYSIS

Method	Advantages	Limitations	Applications
State-space model-based methods	• Mature theories and rich tools for modeling & stability analysis. • Suitable for single-, multi-, and system level-VSC-dominated power systems. • Prominent modularity and scalability for multi-VSC systems.	• Only suitable for LTI systems in theory. • Only suitable for *white-box* systems. * • The nonlinear features of VSCs are neglected by linearization. • Difficult to physically understand the instability mechanism.	• Derive the complete LTI model and provide small-signal stability prediction for multi-VSC *white-box* systems. • Analyze small-signal dynamic features such as oscillation frequency, attenuation factor, critical eigenvalues, etc.
Impedance model-based methods	• Suitable for *black-box* systems. • Port impedance for stability prediction can be obtained by on-line measurement.	• Unable to predict stability issues of inner subsystems. • Stability criteria highly conservative. • Difficult to physically understand the instability mechanism.	• Subsystem port impedance measurement • Interaction process analysis of two cascaded VSC subsystems. • Small-signal stability prediction of *black-box* systems.
PAD/SSG model-based methods	• Low-order model with major behaviors and familiar physical concepts. • Powerful for physically understanding the instability mechanism.	• Difficult to describe the multi-timescale and frequency-coupling dynamics. • Difficult to be extended to multi-VSC scenarios.	• Modeling mainly concerned with dynamic features with clear physical meaning. • Physically understand the instability mechanism of the SMIB system.
Numerical simulation-based methods	• Suitable for single-, multi-, and system level VSC-dominated power systems. • Detailed features modeled with full time- and frequency-scales. • Provides the most accurate and reliable quantitative results.	• Unable to model *black-box* systems • Difficult to physically understand the instability mechanism.	• Provide numerical results and stability prediction for *white-box* systems. • Model & stability verification of other analysis methods for a *white-box* system. • Design and verification of system parameters and control strategies.
DP model-based methods	• Suitable for nonlinear & time-varying systems. • Suitable for large-signal stability assessment.	• Increased model complexity and computational burden. • Inevitable compromise between accuracy and complexity.	• Modeling of the nonlinear and time-varying system. • Prediction of large-signal stability for low-order (mostly SMIB) VSC systems.
Energy function methods	• Suitable for large-signal stability prediction of nonlinear systems. • Powerful for physically understanding the instability mechanism.	• Difficult to find an energy function satisfying LaSalle's Invariance Principle. • Difficult to be extended to multi-VSC scenarios.	• Prediction of large-signal stability for low-order (mostly SMIB) VSC systems • Design suitable system parameters and derive powerful control strategies counteracting large disturbances.
Graphical methods	Graphical models mainly concerned with behaviors and clear physical concepts.	Only suitable for low-order (mostly SMIB) systems.	Physically comprehend the physical process and the instability mechanism.

* A *white-box* (*black-box*) system indicates a system whose topology, control, and parameters are all known (unknown).

can be based on the same benchmark. In addition, standard dynamic or reduced-order models for each type of stability phenomenon need to be provided, assuming that the research on each type of stability problem has a correspondingly reasonable model that is as simple as possible, on the basis of accurately reflecting the problem features.

H. Grid Code Developments for Stability Issues

Improper grid code requirements can increase the risk of system instability [113]. For example, grid frequency stability is essentially a type of engineering problem, i.e., if the frequency exceeds a certain range, it will cause a series of system protection actions to avoid oscillatory or divergent destabilization and may even lead to a major power outage that must be avoided. With an increasing number of VSCs in power systems, the system inertia level and damping capacity gradually decrease. The indicators in conventional power systems, including the frequency nadir, the QS frequency deviation, and the rate of change of frequency, can thus easily exceed the thresholds and cause relay actions. This makes threshold selection of stability issues related to the grid code requirements of paramount importance. For system operation safety and stability, it is necessary to study the system structure, control strategy, as well as software and hardware protection system design specifications based on the general conclusions given by stability analysis, and formulate specific provisions on protection thresholds, triggering conditions, and switching logic for key physical parameters.

V. CONCLUSION

VSC-based equipment has been rapidly applied in modern power systems, gradually leading to the rise of VSC-dominated power systems. Due to several features of the models, including high order, strong coupling, various controls, multiple coupling paths and saturation processes, and significant switching nonlinearity, many traditional modeling and stability analysis methods, tools, models, and conclusions are no longer fully applicable. This paper summarizes the current research status and key technical issues in terms of dynamic modeling and stability analysis for VSC-dominated systems, and discusses the main challenges and future research directions in this field.

To conclude, the state-space model-based time domain analysis is particularly suitable for small-signal stability issues of large power systems. It is the most widely used and mature stability analysis method, however, it is only applicable to small-signal stability analysis in LTI systems. The impedance model-based frequency-domain stability analysis is favorable for cascaded systems, however, the port impedance measurement of the large power system needs to be improved, and its predicted stability boundary is relatively conservative. The main advantages of the PAD and SSG model-based frequency-domain methods encompass the obvious physical meaning, which helps in analyzing the system instability mechanism, and the compatibility of core concepts and methods with conventional power grids, which helps in better understanding the dynamic stability problems and solutions of VSC-dominated systems. Though the conclusions derived from large-signal stability analysis have wider applicability, there is a lack of effective and unified large-signal modeling methods and stability criteria. Among a few techniques, the main energy function methods currently used for single VSC design and analysis can quickly and quantitatively analyze the system stability margin and are suitable for large-signal stability analysis, although it is difficult to build energy functions for complex systems. The detailed model-based numerical simulation has the significant advantage of accurate and reliable results, however, it is inconvenient for interpreting the system instability mechanism. Besides, this method, is mainly applied to the analysis and calculation of specific *white-box* systems, and it is difficult to obtain general conclusions.

With joint efforts of worldwide experts, fruitful theoretical and practical results have been obtained. Nevertheless, there are still many theoretical and engineering problems to be investigated in depth, including stability definition and classification, physical understanding of the instability mechanism, precise stability boundary prediction, multi-method integration-based intelligent analysis, design- and operation-oriented stability analysis, as well as benchmark and grid code development for typical stability issues.

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