Small-Signal Strength Assessment Method for Flexible DC Transmission Systems from Renewable Energy Bases

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Abstract

The concept of system strength is commonly employed to characterize system voltage response performance and quantify security and stability levels, wherein strength quantification metrics based on short-circuit ratio exhibit simple and intuitive characteristics when describing renewable energy transmission limits. However, existing short-circuit ratio-based analysis fundamentally presupposes that synchronous machines provide short-circuit capacity or voltage support, rendering it unsuitable for renewable energy base flexible DC transmission systems lacking synchronous machine support. To address this, this paper investigates strength assessment and analysis issues for renewable energy base flexible DC transmission systems from a small-disturbance perspective. First, the sensitivity transfer function matrix of multi-port currents to bus voltages in such systems is derived, and the qualitative relationship between post-disturbance bus voltage response and system static voltage stability/small-disturbance synchronous stability is elaborated. Second, based on the sending-end flexible DC voltage source equivalent concept and incorporating the critical short-circuit ratio of renewable energy equipment, a source-grid separation assessment methodology for system strength is proposed, extending the generalized short-circuit ratio to all-power-electronic systems. The proposed method enables rapid analysis of static voltage stability/small-disturbance synchronous stability margins at system operating points, identification of weak links in system strength, and determination of optimization paths for system strength enhancement. Finally, the effectiveness of the assessment method is validated through a case study of multiple wind farms transmitted via flexible DC systems.

Full Text

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Small-Disturbance System Strength Assessment Method for Renewables VSC-HVDC Delivery System

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Abstract

System strength is commonly used to describe voltage response performance under disturbance and quantify stability margins. The short-circuit ratio (SCR) provides a simple and intuitive metric for describing renewable energy transmission limits. However, existing SCR-based analysis fundamentally assumes that synchronous generators provide short-circuit capacity and voltage support, making it unsuitable for renewables VSC-HVDC delivery systems without synchronous machine support. This paper addresses system strength assessment for such systems from a small-disturbance perspective. First, we derive the sensitivity transfer function matrix of bus voltage to multi-port current injection, establishing the qualitative relationship between post-disturbance voltage response and static voltage stability/small-disturbance synchronous stability. Second, based on voltage-source equivalent modeling of the sending-end VSC-HVDC and incorporating the critical short-circuit ratio of renewable energy devices, we propose a source-grid separation evaluation method that extends the generalized short-circuit ratio to all-power-electronic systems. The proposed method can rapidly analyze static voltage stability and small-disturbance synchronous stability margins at the operating point, identify weak links in system strength, and determine optimization paths for system strength enhancement. Finally, a case study of multiple wind farms delivered via VSC-HVDC validates the effectiveness of the assessment method.

Keywords: System strength, generalized short-circuit ratio, renewable energy base, multiband stability, transmission limit

0 Introduction

To achieve the "carbon peak and carbon neutrality" goals, China is constructing a new power system dominated by renewable energy sources [1]. To fully exploit regional wind and solar resources and promote renewable energy consumption, new transmission systems have emerged where renewable energy is collected and then delivered via voltage source converter-based high voltage direct current (VSC-HVDC) (hereinafter referred to as the "delivery system") [2]. This configuration is common in offshore wind power [3] and desert renewable energy bases, representing a typical architecture in modern power systems.

As the collection distance and capacity of renewable energy increase, the AC system's voltage support capability relatively weakens [4], potentially inducing voltage instability and oscillation stability issues that become major bottlenecks constraining renewable energy export levels [3]. Existing research has primarily analyzed these stability issues based on simplified interconnected systems of renewable energy stations and VSC-HVDC, identifying main influencing factors. For example, references [5] and [6] studied dominant eigenvalue trajectories of direct-drive wind power and doubly-fed wind farms interconnected with VSC-HVDC using time-domain state-space methods, showing that oscillation characteristics are strongly correlated with transmission power across the feed-in section. Reference [5] also indicates that increased grid connection distance can trigger oscillations. Furthermore, the dynamic characteristics of delivery systems are dominated by the full-power-electronic control of renewable energy converters and VSC-HVDC, posing new challenges for safe and stable operation. Reference [7] analyzed oscillation risks arising from coupling between VSC-HVDC AC voltage control and wind turbine phase-locked loop (PLL) control, while reference [8] discussed optimizing VSC-HVDC control to enhance system stability.

When analyzing large systems containing multiple renewable energy stations, detailed electromagnetic transient simulations are generally required. Given that dominant stability issues exhibit strong correlation with transmission limits of renewable energy feed-in sections, grid planning and design stages often use short-circuit ratio (SCR) to assess system voltage support strength [10] (hereinafter referred to as "system strength"), enabling macroscopic understanding of system dynamic characteristics, rapid determination of stability margins under given operating conditions, and screening of high-risk instability scenarios. Various SCR indicators have been applied to assess system strength after large-scale renewable energy integration. For instance, reference [9] proposed a voltage stiffness index accounting for non-synchronous power sources based on SCR, physically characterizing grid strength during steady-state operation. Reference [10] proposed a multi-station short-circuit ratio indicator for renewable energy and calculated critical SCR values using power flow equations, though these critical values fluctuate dramatically with grid changes and lack objective standard values. Reference [11] considered the impact of renewable energy dynamic characteristics on stability and proposed a generalized short-circuit ratio (gSCR) from a small-disturbance stability perspective.

However, existing SCR calculations rely on the premise that synchronous machines provide short-circuit current/capacity [14]. Although some scholars have proposed SCR algorithms based on voltage variation [10], they still depend on synchronous machine grid equivalent models used in short-circuit calculations.

For example, in a single renewable energy machine-infinite bus system, the SCR at the grid-connection bus must be obtained by calculating the short-circuit current level provided by synchronous sources in the grid and comparing the AC system short-circuit capacity S_{short} with the connected equipment capacity S_B:

$$SCR = S_{short} / S_B = U_N^2 / (|Z| \cdot S_B) \quad (1)$$

where U_N is the rated bus voltage and Z is the grid equivalent impedance.

From a short-circuit calculation perspective, the renewable energy base VSC-HVDC delivery system shown in Fig. 1 exhibits full-power-electronic characteristics without synchronous sources providing short-circuit current. Moreover, the complex nature of short-circuit current in delivery systems, due to control switching and limiting nonlinearities of power electronic devices [9], makes system strength difficult to assess using the simple SCR method in (1) and poses challenges for rapidly quantifying stability margins.

Nevertheless, SCR essentially represents a sensitivity reflected by impedance or admittance. As shown in (1), SCR is equivalent to the inverse of grid equivalent impedance normalized to equipment capacity [11], describing the relative electrical distance between the renewable energy grid-connection bus and the equivalent voltage source bus: larger SCR indicates closer relative electrical distance, stronger voltage source support at the connection point, and less sensitivity of bus voltage to injected current. The association between traditional SCR and synchronous machine short-circuit capacity arises because short-circuit current precisely reflects this sensitivity [20].

From a sensitivity perspective, the SCR-based assessment approach can be extended to full-power-electronic systems without synchronous support. This raises the following question: How can the SCR concept be extended to assess delivery system strength and rapidly analyze/quantify static voltage stability and small-disturbance synchronous stability margins?

2 System Strength Description from a Sensitivity Perspective

To answer this question, this section first characterizes the sensitivity relationship between disturbed bus voltage and multi-feed current from renewable energy stations, establishing the qualitative relationship between post-disturbance voltage response and system stability.

2.1 Dynamic Modeling of Delivery Systems

The dynamics of the renewable energy base VSC-HVDC delivery system shown in Fig. 1 after a small disturbance can be described through linearized equations of each component. To conveniently represent post-disturbance bus voltage response, frequency-domain impedance/admittance transfer function modeling is adopted.

In the global synchronous rotating xy-coordinate system, a closed-loop system model can be established with disturbance current as input variables and bus voltage as output variables, as shown in Fig. 2. Here, $\Delta I_{per}(s)$ represents the small-disturbance current vector superimposed in parallel at the equipment grid-connection bus, $\Delta V_{xy}(s)$ represents the micro-increment of equipment grid-connection bus voltage, $\Delta I_{xy}(s)$ represents the micro-increment of equipment grid-connection port feed-in current, $Y_{NET}(s)$ represents the AC network admittance transfer function matrix, and $Y_{PE}(s)$ represents the admittance transfer function matrix of power electronic equipment including the sending-end VSC-HVDC and renewable energy stations. The analytical expressions of each transfer function matrix are introduced below.

The network admittance transfer function matrix $Y_{NET}(s)$ in Fig. 2 represents the multi-port sensitivity relationship between equipment feed-in current and bus voltage under certain assumptions [11]:

$$Y_{NET}(s) = Y_0 \quad [1\ 1;\ 1\ 1] + \mathrm{diag}\{0,\dots,0,Y_T(s)\} \quad (2)$$

where the subscript xy denotes the global synchronous rotating coordinate system with *$\omega 0 = 100\pi$ rad/s rotation frequency; Y_0 is the base network admittance matrix retaining the interconnection among n renewable energy stations and the sending-end VSC-HVDC at n+1 buses, with the sending-end VSC-HVDC located at node n+1; V*$\{xy\} = [V_{1xy},\dots,V_{nxy},V_{(n+1)xy}]^T$ is the bus voltage column vector; $I_{xy} = [I_{1xy},\dots,I_{nxy},I_{(n+1)xy}]^T$ is the equipment port current column vector;   denotes Kronecker product.

Notably, the AC grid model in (2) is universal and not limited to specific delivery system topologies such as chain or trunk types [5], enabling the analysis results to adapt to more diverse renewable energy delivery system configurations in the future.

2.1.2 Admittance Models of Sending-End VSC-HVDC and Renewable Energy Base

The admittance transfer function matrix $Y_{PE}(s)$ in Fig. 2 includes dynamics of multiple renewable energy stations and the sending-end VSC-HVDC, described sequentially below.

Based on references [5] and [15], the grid-connected circuit and control structure of the sending-end VSC-HVDC are shown in Fig. 3. Renewable energy power in the system is delivered to the collector bus, then stepped up through a transformer to the sending-end VSC-HVDC. The sending-end VSC-HVDC operates in rectification mode with V-F control structure, maintaining the grid-side AC voltage at rated value through voltage-current dual-loop control. In Fig. 3, L_{ac} is the converter inductance, C_f is the AC filter equivalent capacitance, and L_T is the step-up transformer leakage inductance. V_{abc} and I_{abc}

are the collector bus voltage and output current of the sending-end VSC-HVDC, V_{cabc} and I_{cabc} are the grid-side voltage and current, and U^*_{abc} is the desired output voltage. Considering the strong DC voltage control effect of the receiving-end converter station, its impact on sending-end AC system stability is small [5], so the DC side is simplified as a voltage source in Fig. 3. Additionally, focusing on the interaction between sending-end VSC-HVDC and renewable energy in weak systems rather than its internal dynamics, a two-level model is adopted for simplicity.

The admittance transfer function matrix of n renewable energy stations is:

$Y_{RE}(s) = S_B \quad Y_{CIG}(s)$ (3)

where $S_B = diag(S_{Bj})$ is the capacity ratio matrix with diagonal elements S_{Bj} representing the ratio of the j-th renewable energy station's rated capacity to system base capacity (taken as the sending-end VSC-HVDC rated capacity), and $Y_{CIG}(s)$ is the 2×2 admittance transfer function matrix of a single renewable energy device.

Regarding renewable energy modeling, numerous studies have discussed converter-interfaced generator (CIG) dynamic models. This paper adopts the admittance transfer function model from reference [16]. Without loss of generality, assuming all renewable energy generation devices are homogeneous and each station's dynamic characteristics are similar to a single device [7], each renewable energy station is equivalently represented as a single device scaled by capacity, yielding the admittance transfer function matrix in (3).

2.2 Qualitative Relationship Between Stability and Delivery System Strength

System strength is a qualitative concept describing system voltage response performance. According to frequency-domain theory [21], the bus voltage of each equipment grid-connection point after disturbance, as an output variable, reflects the closed-loop stability of the delivery system shown in Fig. 2. Specifically, small-disturbance stability is determined by dominant eigenvalues in the characteristic equation, focusing on sub/super-synchronous oscillation modes within the PLL bandwidth of grid-following renewable energy devices. Static voltage stability is a special case of small-disturbance stability at $s = 0$, concerning power frequency characteristics [11]. Both belong to structural stability or eigenvalue problems and can be uniformly described mathematically by the characteristic equation:

$\det\{Y_{NET}(s) + Y_{PE}(s)\} = 0$ (4)

where $\det\{\cdot\}$ denotes the matrix determinant function.

Notably, while observing bus voltage rise/fall before and after renewable energy integration represents an engineering understanding of system strength, voltage variation only affects power frequency circuit solution. The resulting system strength concept relates only to static stability and cannot reflect small-disturbance stability under the influence of multiple time-scale dynamic components in power electronic equipment.

3 System Strength Assessment Based on Generalized Short-Circuit Ratio

Based on the qualitative understanding of system strength, this section extends generalized short-circuit ratio theory to delivery systems and proposes a quantitative system strength assessment method.

3.1.1 Voltage-Source Equivalent Analysis of Sending-End VSC-HVDC

Considering that sending-end VSC-HVDC provides voltage support similar to synchronous machines in traditional power systems [9], this subsection proposes a sending-end VSC-HVDC equivalent method suitable for static voltage stability and small-disturbance synchronous stability analysis by analogy with synchronous machine classical equivalent circuits.

The voltage support capability of sending-end VSC-HVDC under disturbance depends on main circuit and dual-loop control parameters, reflected through a controlled voltage source and equivalent impedance series circuit equation:

$$\Delta V = K_V(s)\Delta V_{ref} - Z_{VH}(s)\Delta I \quad (5)$$

where $\Delta V = \Delta V_x + j\Delta V_y$ and $\Delta I = \Delta I_x + j\Delta I_y$ represent the positive-sequence voltage and current dynamics at the collector bus; $K_V(s)$ is the transfer function matrix related to voltage control reference ($\Delta V_{ref} = \Delta V_{dref} + j\Delta V_{qref} = 0$ under small disturbance, making the left side a controlled voltage source term); $Z_{VH}(s)$ is the positive-sequence impedance transfer function of sending-end VSC-HVDC, comprising series-parallel combinations of capacitive filter impedance $Z_C(s)$, step-up transformer reactance $Z_T(s)$, and impedance transfer function $Z_L(s)$ containing dual-loop voltage control (detailed expressions in Appendix A).

Following this equivalent method, equivalent inductances under various parameter sets in Table 1 can be calculated. For example, parameter set 4 yields the equivalent reactance frequency characteristics shown by the dashed line in Fig. 4, with equivalent inductance $L_{eq} = 0.164$ p.u. Results for other parameter sets are summarized in Table 1. Since the equivalent inductance is a linear element, the sending-end VSC-HVDC AC-side impedance equivalent method can be mathematically viewed as a piecewise linearization result, approximating high-order models with lower-order dynamic elements within a certain range [17].

The equivalent model should primarily focus on the impact of sending-end VSC-HVDC dual-loop voltage control. However, actual sending-end VSC-HVDC internal dynamics are complex, containing multiple control loops that make impedance characteristics more variable and not necessarily inductive. Although linearization-based equivalent methods remain applicable, the error between equivalent results and actual impedance must be considered. An effective approach treats this error as model uncertainty, ensuring equivalent result reliability from a robust stability perspective [19].

Table 1 Equivalent inductance values under four VSC-HVDC PI control parameter sets

PI Parameters (K_{PV}, K_{IV})	PI Parameters (K_{PI}, K_{II})	Equivalent Inductance L_{eq}
(6, 10)	(0.8, 12)	0.114 p.u.
(3, 10)	(0.4, 20)	0.135 p.u.
(3, 50)	(0.3, 12)	0.144 p.u.
(2, 50)	(0.3, 20)	0.164 p.u.

Based on the above characteristics of sending-end VSC-HVDC AC-side impedance, equivalent inductance/reactance can approximate impedance characteristics within the concerned frequency band. First, assume the equivalent reactance analytical expression:

$$Z_{eq}(s) = sL_{eq} \quad (6)$$

where L_{eq} is the 待定 equivalent inductance parameter.

Then, letting $s = j\omega$, the process of approximately obtaining equivalent inductance from impedance sweep results can be described as a least-squares problem with inequality constraints:

$$\text{minimize: } \Sigma|Z_{VH}(j\omega) - j\omega L_{eq}|^2$$
$$\text{subject to: } |j\omega L_{eq}| \geq |Z_{VH}(j\omega)| \text{ for } \omega \quad [\omega_1, \omega_2] \quad (7)$$

where the frequency region $[\omega_1, \omega_2]$ is the neighborhood of potential oscillation frequency ω_c ($\omega_c \quad (\omega_1, \omega_2)$). Equivalent results near oscillation frequency are generally accurate [17], but obtaining potential oscillation frequency is beyond this paper's scope, so $\omega_1 = 0$ and $\omega_2 = 2\omega_0$ are taken to cover the concerned 0-100 Hz band. Subsequent simulation examples verify that this expanded analysis interval introduces small error. The constraint requiring equivalent inductance magnitude to be an upper bound of actual impedance magnitude ensures robustness in subsequent system strength assessment [21].

Physically, the sending-end VSC-HVDC equivalent model can be analogized to synchronous machine classical models considering excitation control. For synchronous machines, assuming constant excitation winding flux yields classical models described by synchronous or transient reactance [22]. After accounting for automatic voltage regulator (AVR) dynamics, excitation flux changes to control terminal voltage, making equivalent reactance vary naturally with AVR parameters. The sending-end VSC-HVDC equivalent model with dual-loop voltage control (Fig. 5) shares this characteristic: each voltage control parameter set corresponds to an equivalent inductance value, reflecting the electrical distance from the equivalent voltage source to the sending-end VSC-HVDC AC-side collector bus. Smaller equivalent inductance indicates closer electrical distance and stronger voltage support at the collector bus from sending-end VSC-HVDC control.

Fig. 5 Equivalent model of VSC-HVDC sending-end station

In summary, the equivalent model can reflect sending-end VSC-HVDC external characteristics during static/dynamic processes. The appropriate equivalent model can be selected based on the stability problem of interest:

1) For small-disturbance synchronous stability analysis: Calculate equivalent inductance L_{eq} or reactance Z_{eq}(s) near the delivery system oscillation frequency ω_c using the proposed method. Its magnitude closely relates to sending-end VSC-HVDC dual-loop voltage control characteristics, reflecting dynamic voltage support after disturbance.

2) For static voltage stability analysis: Since sending-end VSC-HVDC control achieves constant voltage target, the equivalent reactance at zero frequency ($\omega = 0$) equals the step-up transformer leakage reactance X_T = ω{0L}T, with equivalent inductance L{eq} = L_T.

3.1.2 Generalized Short-Circuit Ratio Calculation

In static or small-disturbance analysis, the voltage source bus (electrically equivalent to an infinite voltage bus) has zero dynamics and is treated as ground after linearization [11]. Therefore, the sending-end VSC-HVDC equivalent inductance in Fig. 5, as a shunt branch, can be incorporated into the grid side by modifying the grid node admittance matrix B:

B'{ii} = B{ii} + B_{eq} (8)

where B_{ii} is the (n+1)th diagonal element of admittance matrix B corresponding to the collector bus where sending-end VSC-HVDC is connected; B_{eq} = 1/(ω{{0L}}{{eq}}}) is the susceptance of sending-end VSC-HVDC equivalent inductance in the shunt branch for static voltage stability or small-disturbance synchronous stability analysis.

Based on the modified network admittance, the delivery system in (4) can be further decoupled into n renewable energy single-machine infinite-bus systems through equivalent characteristic equation transformation:

det{S_B · Y_{CIG}(s) + λ_j · I_2} = 0, j = 1,…,n (9)

where B' is the network matrix retaining only n nodes where renewable energy connects; I_n is the n-order identity matrix; λj are eigenvalues of matrix S{BB}' (ordered as λ_1 ≤ λ_2 ≤ … ≤ λ_n); Π denotes continuous product.

From (8)-(9), the electrical distance from each renewable energy grid-connection bus to the equivalent voltage source bus in the delivery system can be transformed into quantifying the electrical distance from n single renewable energy machines to the equivalent voltage source in modal coordinates, as shown in Fig. 6. Specifically, system stability depends on the single-machine subsystem corresponding to the minimum eigenvalue λ_1 of the matrix [11], physically meaning the renewable energy machine connects to the equivalent voltage source bus through the grid with lowest short-circuit ratio λ_1. This machine has the farthest electrical distance from the voltage source bus and is most prone to instability. According to reference [20], this short-circuit ratio λ_1 is a key parameter for quantifying system strength and represents the extension of generalized short-circuit ratio (gSCR) to delivery systems.

Generalized Short-Circuit Ratio: The minimum eigenvalue of matrix S_{BB}' shares the same mathematical properties and physical meaning as gSCR [11], expressed as:

gSCR = $\lambda\{min\}(S\{\mathrm{BB}\}`) = \sigma\{min\}^2(S\{\mathrm{BB}\}')$ (10)

where $\lambda\{min\}(\cdot)$ *and* $\sigma\{\mathrm{min}\}(\cdot)$ denote the minimum eigenvalue and singular value of a matrix, respectively.

Compared with existing SCR methods, the gSCR in (10) does not rely on short-circuit analysis but extends gSCR to delivery systems based on multi-port voltage-to-current sensitivity and matrix theory, reflecting the comprehensive electrical distance between renewable energy grid-connection buses and the equivalent infinite bus. Simultaneously, gSCR can account for static/dynamic voltage support characteristics caused by fast control response of sending-end VSC-HVDC, providing theoretical foundation for rapidly quantifying static voltage stability and small-disturbance stability margins.

Fig. 6 Derivation of gSCR for sending-end system

3.2 Source-Grid Separation Evaluation Method for Delivery System Strength

To enable gSCR-based system strength assessment to reflect stability margins, determining the critical generalized short-circuit ratio (CgSCR) at critical instability is key. For grid-following renewable energy single-machine systems, there exists a minimum grid short-circuit ratio SCR_0 that ensures the equipment adapts to the grid without instability after connection, called the equipment critical short-circuit ratio [20]. SCR_0 reflects renewable energy equipment tolerance to weak grids. From the previous section, delivery system stability is equivalent to the weakest single-machine system, physically corresponding to CgSCR reaching the single-machine equipment critical short-circuit ratio SCR_0 when the delivery system experiences static voltage instability or small-disturbance synchronous instability:

CgSCR = SCR_0 (11)

where $s_c = j\omega_c$ is the dominant eigenvalue at oscillation instability ($s_c = 0$ for static voltage instability).

Therefore, system strength assessment can be achieved through source-grid separation: combining gSCR derived from grid information with equipment critical short-circuit ratio (CgSCR = SCR_0) to determine system stability and margins. If gSCR < CgSCR, the system has instability risk; if gSCR ≥ CgSCR, the system is stable, with larger values indicating greater stability margins. Furthermore, engineering applications generally require sufficient margins to stay far from instability boundaries. The relative value β% between gSCR and SCR_0 can be defined as a margin index to quantitatively construct system strength criteria as shown in (12)-(13).

System Strength Criterion: The margin index β% can quantify whether delivery system strength is sufficient to guarantee static voltage stability or small-disturbance synchronous stability. For example, requiring at least 20% margin means the system strength β% value should satisfy:

$$\beta\% = (\text{gSCR} - SCR_0)/SCR_0 \times 100\% \geq 20\% \quad (12)$$

The proposed method provides a universal approach for system strength assessment in various scenarios. For instance, in renewable energy base delivery through weak AC synchronous grids, external grids can be represented by multi-port Thevenin equivalents, extending single-bus equivalence to multiple buses/ports without increasing analysis complexity. The method can also be extended to microgrid scenarios without infinite buses, as delivery systems can be viewed as special grid-forming and grid-following hybrid systems. Notably, based on simplified system strength assessment models, equipment critical short-circuit ratio reflects station-level dynamic characteristics to some extent but has not yet considered auxiliary equipment within stations (e.g., static VAR compensators) or operating point differences under varying wind speeds. These factors make determining station-level critical short-circuit ratios difficult, requiring further research on delivery system strength assessment considering such complexities.

Fig. 7 Flow chart of system strength assessment based on gSCR in sending-end system

The system strength assessment can be performed separately on source and grid sides before combining results, simplifying system-level stability analysis. In (12) or (13), gSCR and CgSCR can be obtained independently: gSCR depends on AC grid parameters, sending-end VSC-HVDC equivalent inductance, and renewable energy equipment capacity; CgSCR equals renewable energy equipment critical short-circuit ratio SCR_0, which depends on equipment control parameters and can be easily obtained through manufacturer analytical calculations or simulation tests. Source-grid separation also clarifies system strength improvement paths, requiring optimization measures to increase gSCR and reduce SCR_0 [20] to ensure system strength meets (12) or (13).

Since renewable energy stations use single-machine scaling equivalence, the results can identify weak system lines and guide optimal allocation of grid-forming renewable energy/storage equipment [23] for precise system reinforcement.

The proposed method primarily focuses on small-disturbance synchronous stability and voltage stability modes strongly correlated with feed-in sections. Its application has limitations—for example, sub/super-synchronous oscillations involving series compensation capacitors and harmonic resonance/instability involving shunt compensation capacitors are not strongly correlated with system strength and cannot be analyzed using SCR methods.

4 Case Study

To verify the effectiveness of the proposed delivery system strength assessment method, this section analyzes a multi-wind-farm VSC-HVDC delivery system. The single-line diagram is shown in Fig. B1 of Appendix B. The renewable energy base contains 4 equivalent wind farms (n = 4), with each equivalent wind farm stepped up through 35/220 kV transformers before grid connection. Renewable power is delivered via transmission networks to the collector bus, then stepped up through 220/330 kV transformers to the sending-end VSC-HVDC station. Sending-end VSC-HVDC parameters and equivalent wind farm parameters are listed in Tables B1 and B2 of Appendix B, respectively, with line parameters in Table B3. All direct-drive wind turbines in the case have identical models and typical parameters, with station models obtained through single-machine capacity scaling, covering typical control structures of direct-drive wind turbines as shown in Appendix Fig. B2.

4.1 Theoretical System Strength Calculation

First, following the source-grid separation approach, a direct-drive wind turbine single-machine infinite-bus system with typical parameters from Table B2 is built in the simulation environment. By modifying the grid-connection line distance, the equipment critical short-circuit ratio is tested as SCR_0 = 3.30.

Second, four simulation cases are set up corresponding to the four VSC-HVDC control parameter sets in Table 1, with other parameters unchanged (all wind farms operate at rated conditions with identical steady-state operating points across the four cases).

Following the gSCR-based delivery system strength assessment flowchart in Fig. 7, gSCR, CgSCR, and system strength index $\beta\%$ values are analytically calculated for the four cases and listed in Table 2 (for simplicity, the threshold is set as $\beta\_0\% = 0$, where $\beta\% \geq 0$ indicates stable system 判定). For example, when sending-end VSC-HVDC control parameters use set 1 from Table 1, the equivalent reactance is 0.114 p.u. Using this as a boundary condition combined with network parameters and equipment capacity information yields gSCR = 3.44. With known critical generalized short-circuit ratio CgSCR = SCR_0 = 3.30, $\beta\% = 4.18\% > \beta\_0\% = 0$, analytically 判定 that current parameters meet small-disturbance synchronous stability requirements with a stability margin of $\beta\% = 4.18\%$. Similar calculations are performed for the other three cases.

Table 2 Results of system strength assessment in four cases

Case	Equivalent Inductance L_{eq}	gSCR	CgSCR = SCR_0	System Strength $\beta\%$
1	0.114 p.u.	3.44	3.30	4.18%
2	0.135 p.u.	3.23	3.30	-2.50%
3	0.144 p.u.	3.13	3.30	-5.12%
4	0.164 p.u.	2.95	3.30	-10.5%

4.2 Time-Domain Simulation Verification

Comparing the system strength assessment results in Table 2 with subsequent time-domain simulations verifies whether the proposed method accurately captures delivery system strength.

Table 3 lists the dominant eigenvalues of the delivery system for the four cases obtained through time-domain small-signal analysis. Results show a pair of weakly damped modes in the 0-100 Hz range, which may experience insufficient damping during parameter variations and cause oscillation instability. Case 3 has zero damping ratio, indicating critical instability. Correspondingly, Fig. 8 shows electromagnetic transient simulation waveforms for cases 1-4. A 2% terminal voltage sag is applied at the sending-end VSC-HVDC connection node at simulation time T = 4.0 s as a small disturbance, cleared after 0.02 s, with response curves of grid-connection bus voltage amplitudes for wind farms 1-4 observed: cases 1 and 2 show oscillations decaying with different damping ratios (case 1 has larger stability margin); cases 3 and 4 show sustained bus voltage oscillations, with case 4 exhibiting divergent oscillations (oscillation frequency 18.7 Hz within PLL bandwidth), indicating system instability.

Comparison shows that time-domain simulation trends are consistent with system strength assessment trends in Table 2. Smaller $\beta\%$ values shift dominant eigenvalues further toward the right half-plane, while time-domain voltage response waveforms are more prone to oscillation instability, indicating poorer system stability. Notably, case 3 shows constant-amplitude oscillations with zero damping ratio, representing actual critical instability. At this stability boundary, the assessment result $\beta\%$ = -5.12% < β_0% = 0 already 判定 instability, showing the proposed method is slightly conservative at the stability boundary. The error originates from the sending-end VSC-HVDC voltage source equivalent process, but the small error demonstrates that the proposed method meets engineering requirements. In practice, additional margins should be considered for engineering reference.

Furthermore, simulation analysis shows that delivery system gSCR is sensitive to sending-end VSC-HVDC equivalent inductance, varying monotonically:

as equivalent inductance increases from 0.114 p.u. to 0.164 p.u., gSCR decreases from 3.44 to 2.95. This indicates that the influence of sending-end VSC-HVDC voltage-current control loop parameter variations on small-disturbance synchronous stability can be analyzed from a system strength perspective. VSC-HVDC control parameters should be tuned to increase gSCR, avoiding oscillation instability caused by inappropriate parameter sets that weaken grid support.

Table 3 Results of dominant eigenvalues in four cases

Case	Equivalent Inductance L_{eq}	Dominant Eigenvalue
1	0.114 p.u.	-2.23 ± j116.7
2	0.135 p.u.	-0.75 ± j117.2
3	0.144 p.u.	±j117.3
4	0.164 p.u.	1.85 ± j118.2

Fig. 8 Voltage amplitude of grid-connected bus of each wind farm in four time-domain simulation cases

Appendix A Derivation of Sending-End VSC-HVDC Impedance/Admittance

Based on Fig. 3, the AC-side linearized equations of sending-end VSC-HVDC in dq rotating coordinates include:

V_{cabc} = V_{abc} - sL_{{{acI}}*{{cabc}}} (A1)*
I{abc} = I_{cabc} + sC_{{{fV}}*{{cabc}}} (A2)*
I{cdref} = G_I(s)(V_{dref} - V_{cd}) (A3)
I_{cqref} = G_I(s)(V_{qref} - V_{cq}) (A4)

where G_I(s) = K_{PI} + K_{II}/s is the current inner-loop PI control transfer function, and G_V(s) = K_{PV} + K_{IV}/s is the AC voltage outer-loop PI control transfer function. I_{cdref} and I_{cqref} are inner-loop current dq-axis reference values, with ΔV_{dref} = ΔV_{qref} = 0; step-up transformer admittance is Y_T(s) = Z_T^{-1}(s).

Combining dynamic equations (A1)-(A4), the admittance transfer function matrix Y_{ac}(s) of the sending-end VSC-HVDC control part is:

Y_{ac}(s) = [I_{cd}; I_{cq}] = G_I(s)G_V(s) [V_{cd}; V_{cq}] (A5)

Considering the sending-end VSC-HVDC controller dq coordinate rotation frequency equals the global xy coordinate synchronous rotation frequency ω_0 = 100π rad/s, the admittance transfer function matrix viewed from the collector bus in (4) is expressed as:

Y_{VSC}-HVDC(s) = Y_{ac}(s) + Y_T(s) + sC_f (A6)

Furthermore, through linear transformation from synchronous rotating coordinate system dq-domain to sequence-domain [17], the sequence impedance transfer function viewed from the collector bus in (7) is obtained:

Z_{VH}-PN(s) = T · Y_{VSC}-HVDC^{-1}(s) · T^{-1} (A7)

where Z_{VH}-PN(s) is the 2$×$2 sequence impedance transfer function matrix of sending-end VSC-HVDC, and T is the coordinate transformation matrix. Since the sending-end VSC-HVDC dual-loop voltage control structure is symmetric in dq axes, the sequence impedance matrix Z_{VH}-PN(s) has diagonal form [17]:

Z_{VH}-PN(s) = diag{Z_{VH}-P(s), Z_{VH}-N(s)} (A8)

where Z_{VH}-P(s) and Z_{VH}-N(s) are the positive- and negative-sequence impedance transfer functions, respectively.

Frequency sweep measurement results in Figs. A1 and A2 verify the correctness of the admittance/impedance analytical models in (A7) and (A8). Using parameters from Appendix Table B1, the analytical models match simulation measurements, proving modeling correctness.

Additionally, (A6) can be written as:

Y_{VSC}-HVDC(s) = Y_L(s) + Y_T(s) + sC_f (A9)

Thus, the positive-sequence impedance in (A8) has the corresponding form:

Z_{VH}-P(s) = Z_L(s) // Z_T(s) // Z_C(s) (A10)

where Z_C(s) = 1/(sC_f) is the capacitive filter positive-sequence impedance, and Z_T(s) is the transformer positive-sequence reactance, yielding (8).

Fig. A1 Frequency curves and measured values of VSC-HVDC dq-domain admittance in synchronous rotating frame

Fig. A2 Frequency curves and measured values of VSC-HVDC sequence-domain impedance in synchronous rotating frame

Appendix B Simulation System Parameters

Fig. B1 One-line diagram of wind plants with VSC-HVDC

Fig. B2 Control scheme of the grid-side inverter of the direct-drive wind turbine

Table B1 Parameters of VSC-HVDC in sending-end system

Parameter	Value
Rated active power	240 MW
Rated collector bus voltage	220 kV
Rated DC bus voltage	$±$320 kV
Step-up transformer leakage inductance L_T	0.107 p.u.

Parameter	Value
Converter inductance L_{ac}	0.05 p.u.
AC filter capacitance C_f	0.04 p.u.
Current inner-loop PI parameters	$K_{PI} = 0.8$, $K_{II} = 12$
AC voltage outer-loop PI parameters	$K_{PV} = 6$, $K_{IV} = 10$
Control mode	V-F control

Table B2 Control parameters of grid-side inverter of wind turbine (under its own base value)

Parameter	Value
Control mode	DC voltage control - reactive power control
Rated active power	1.5 MW
Rated AC voltage	0.69 kV
Rated DC voltage	1.1 kV
DC voltage outer-loop PI parameters	0.8, 20
Reactive power outer-loop PI parameters	0.5, 40
Current inner-loop PI parameters	0.3, 10
PLL PI parameters	121, 7306
Voltage feedforward filter time constant	0.01 s
Station step-up transformer leakage reactance L_{Tw}%	0.0675 H
Power factor	Unity (reactive power command $Q_{ref} = 0$)

Table B3 Network data of wind farms with VSC-HVDC

Line No.	Value	Line No.	Value	Line No.	Value
L1	0.0471 F	...	...	...	...

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Note: Figure translations are in progress. See original paper for figures.