Grid Strength Assessment for Inhomogeneous Multi-infeed HVDC Systems via Generalized Short Circuit Ratio

Guanzhong Wang, Huanhai Xin, Di Wu, Zhiyi Li, and Ping Ju

***Abstract*—Generalized short circuit ratio (gSCR) for grid strength assessment of multi-infeed high-voltage direct current (MIDC) systems is a rigorous theoretical extension of the traditional SCR, which enables SCR to be extended to MIDC systems. However, gSCR is originally based on the assumption of homogeneous MIDC systems, in which all high-voltage direct current (HVDC) converters have an identical control configuration, thus presenting challenges to applications of gSCR to inhomogeneous MIDC systems. To weaken this assumption, this paper applies matrix perturbation theory to explore the possibility of utilization of gSCR into inhomogeneous MIDC systems. Results of numerical experiments show that in inhomogeneous MIDC systems, the previously proposed gSCR can still be used without modification. However, critical gSCR (CgSCR) must be redefined by considering the characteristics of control configurations of HVDC converter. Accordingly, the difference between gSCR and redefined CgSCR can effectively quantify the pertinent AC grid strength in terms of the static-voltage stability margin. The performance of the proposed method is demonstrated in a triple-infeed inhomogeneous line commutated converter based high-voltage direct current (LCC-HVDC) system.**

***Index Terms*—Generalized short circuit ratio (gSCR), multi-infeed high-voltage direct current system, modal perturbation, static-voltage stability.**

I. Introduction

MULTIPLE line commutated converter based high-voltage direct current (LCC-HVDC) inverters connected to a common receiving end in proximity are defined as multi-infeed DC (MIDC) systems [1]. In MIDC systems, static-voltage instability issues may arise when the AC grid strength is insufficient to support a decrease in grid voltage through the integration of more LCC-HVDC inverters [2], [3].

AC grid strength plays a fundamental role in static-voltage stability. In addition, a simple measure known as the short circuit ratio (SCR) has long been used to quantify the grid strength in single-infeed LCC-HVDC (SIDC) systems. Specifically, the stability margin can be estimated entirely by calculating the SCR and critical SCR (CSCR), with $CSCR \approx 2$ in various SIDC systems [4]. To assess the grid strength of MIDC systems, several SCR-based methods that consider the interactions between HVDC inverters have been proposed [5]-[8]. These methods can be divided into two categories: empirical indices including the multi-infeed interactive SCR (MISCR) [5] and multi-infeed SCR (MSCR) [6] and theoretical indices including generalized effective SCR (GESCR) [7] and generalized SCR (gSCR) [8]. The advantage of empirical indices is that their calculation formulas are simple. However, they lack theoretical justification due to their empirical reasoning when the critical values of these indices vary in different power systems. Theoretical indices, e.g., GESCR, are theoretically proposed based on characteristic analysis of the Jacobian matrix. However, the calculation formula of GESCR is considerably more complicated because it depends on detailed system operation data. In addition, the critical GESCR is fixed at 1, which is significantly different from that of the SCR. Thus, the considerable experience derived from using SCR cannot be simply adapted to the application of GESCR.

Compared with the aforementioned indices, gSCR maintains a simple calculation formula with a fixed critical gSCR (CgSCR), i.e., $CgSCR = CSCR \approx 2$, in various MIDC systems. This is because it is originally proposed based on a theoretical analysis of the relationship between SCR and static-voltage stability in SIDC systems and by extending the results to MIDC systems [8]. This enables the gSCR to be used in the same manner as that of the SCR. In particular, the stability margin of MIDC systems can be entirely focused on the gSCR and CgSCR. However, the gSCR is original based on the assumption of homogeneous MIDC systems, where all HVDC converters have identical control configurations, thus limiting their applications to more general cases.

This letter extends the application of gSCR to inhomogeneous MIDC systems for grid strength assessment through

Manuscript received: December 22, 2021; revised: April 10, 2022; accepted: May 5, 2022. Date of CrossCheck: May 5, 2022. Date of online publication: July 26, 2022.

This work was jointly supported by the National Natural Science Foundation of China (No. 52007163) and China Postdoctoral Science Foundation (No. 2020M671718).

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DOI: 10.35833/MPCE.2021.000814

mode perturbation theory, which shows that the gSCR can remain valid without modification by deriving an approximate relationship between the gSCR defined for homogeneous MIDC systems and the singularity point of the Jacobian matrix. However, the CgSCR must consider the equivalent characteristic of a weighted sum of HVDC converter control configurations.

II. Problem Statement

A. Static-voltage Stability Analysis for MIDC Systems

The linearized power flow equations at the converter side of an MIDC system consisting of HVDC1-HVDCn are shown in Fig. 1, where P_{aci} and Q_{aci} ($i=1, 2, \ldots, n$) are the active and reactive power injected into the inverter-end AC bus by HVDC and AC system, respectively; P_{di} and I_i are the DC power and current, respectively; Q_{di} is the reactive power of the HVDC together with the compensation capacitor; U_i is the AC voltage; ξ_i is the voltage angle of voltage source E; θ is the angle of line impedance Z_i or Z_{ij}; and b_{ci} is the reactive power compensation capacitor. The control mode is constant current-constant angle or constant power-constant extinction angle, which can be represented as [9]:

$$[\Delta \boldsymbol{P}_d \quad \Delta \boldsymbol{P} \quad \Delta \boldsymbol{Q}]^{\mathrm{T}} = \boldsymbol{J}_{MIDC} [\Delta \boldsymbol{I}_d \quad \Delta \boldsymbol{\delta} \quad \Delta \boldsymbol{U}/\boldsymbol{U}]^{\mathrm{T}} \tag{1}$$

where $\Delta \boldsymbol{P}_d$, $\Delta \boldsymbol{P}$, and $\Delta \boldsymbol{Q}$ are the vectors representing the perturbations of the DC power and active and reactive power at each converter-side AC bus, respectively; $\Delta \boldsymbol{I}_d$, $\Delta \boldsymbol{\delta}$, and $\Delta \boldsymbol{U}/\boldsymbol{U}$ are the vectors representing the perturbations of the DC current, voltage angle, and AC voltage percentage at each converter-side AC bus, respectively; and $\boldsymbol{J}_{MIDC}$ is the Jacobian matrix.

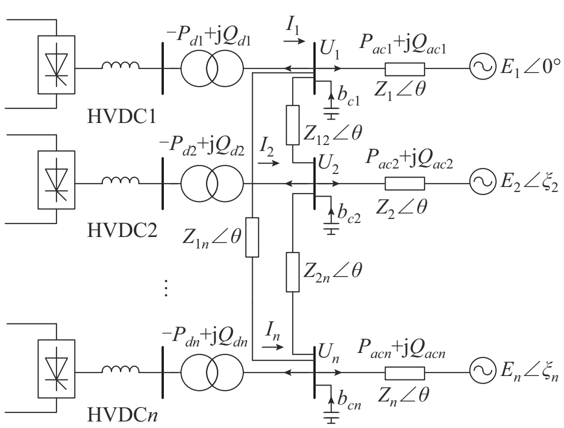

Fig. 1. MIDC system consisting of HVDC1-HVDCn.

The boundary condition for static-voltage stability in MIDC systems can be represented by the determinant of $\boldsymbol{J}_{MIDC}$ equal to zero, i.e., the saddle-node bifurcation.

$$\det(\boldsymbol{J}_{MIDC}) = 0 \tag{2}$$

In the planning studies [4], [8], the boundary condition in (2) can be simplified under the rated operating conditions, i.e., $U_i = U_N = 1$ p.u. and $P_i = P_{Ni}$ ($i = 1, 2, \ldots, n$).

$$\begin{cases} \det(\boldsymbol{J}_{MIDC}) = \det(\boldsymbol{J}_{sys}) = 0 \\ \boldsymbol{J}_{sys} = \mathrm{diag}(T_i) + \boldsymbol{J}_{eq}^{-1} - \boldsymbol{J}_{eq} \\ \boldsymbol{J}_{eq} = -\mathrm{diag}^{-1}(P_{Ni})\boldsymbol{B} \\ T_i = 2cK(c)/\{1 - 1/[(\cos\gamma)/c - 1]\} + 2\omega B_c U^2 \\ c = XI_d/\sqrt{2KU} \end{cases} \tag{3}$$

where P_{Ni} is the rated power injection into the AC grid from the i^{th} converter; $\boldsymbol{B}$ is the node susceptance matrix; $\boldsymbol{J}_{eq}$ is a weighted node susceptance matrix; T_i is the control parameter of the i^{th} converter; $K(c)$ is the function of c; I_d is the DC current; γ is the extinction angle; K is the ratio of the transformer; U is the voltage magnitude; X is the commutation reactance; B_c is the reactive power compensation capacitor; and ω is the angular velocity. More details can be found in [8].

B. Challenge for Grid Strength Assessment Based on gSCR

For a homogeneous MIDC system, the converters of all HVDC ties have the same control configuration. Thus, parameter T_i in (3) is an identical constant, i.e., $T = T_1 = T_2 = \ldots = T_i = \ldots = T_n$. $\boldsymbol{J}_{sys}$ can be rewritten as:

$$\boldsymbol{J}_{sys0} = T\boldsymbol{I}_n + \boldsymbol{J}_{eq}^{-1} - \boldsymbol{J}_{eq} \tag{4}$$

where $\boldsymbol{I}_n$ is an $n \times n$ identity matrix.

After (4) is eigen-decomposed, the boundary condition in (3) can be further represented as [8]:

$$\det(\boldsymbol{J}_{sys0}) = \prod_{i=1,2,\ldots,n} (T + \lambda_i^{-1} - \lambda_i) = 0 \tag{5}$$

where $T + \lambda_i^{-1} - \lambda_i$ and λ_i ($0 < \lambda_1 \leq \ldots \leq \lambda_i \leq \ldots \leq \lambda_n$) are the eigenvalues of $\boldsymbol{J}_{sys0}$ and $\boldsymbol{J}_{eq}$, respectively; and λ_i is defined as the gSCR such that the voltage stability margin of MIDC systems is quantified by the minimum eigenvalue of $\boldsymbol{J}_{eq}$.

Equation (5) is the product of the eigenvalues of $\boldsymbol{J}_{sys0}$, and each eigenvalue of $\boldsymbol{J}_{sys0}$ can represent an equivalent SIDC system for static-voltage stability analysis [8]. Because the stability of MIDC system depends primarily on the minimum eigenvalue of $\boldsymbol{J}_{sys0}$ or the equivalent SIDC system with λ_1, the boundary condition in (5) can be simplified as:

$$T + \lambda_i^{-1} - \lambda_i = 0 \tag{6}$$

This considerably reduces the burden of voltage stability analysis with the calculation of the determinant of $\boldsymbol{J}_{MIDC}$. In addition, CgSCR is defined as the critical value of gSCR that corresponds to the boundary condition in (6) and is represented by (7). In [4], CgSCR is found to be approximately equal to 2 (the same value as CSCR in SIDC systems), which overcomes the bottleneck of ambiguity of critical values in the applications of SCR-based methods in MIDC systems [5], [6].

$$CgSCR = T/2 + \sqrt{T^2/4 + 1} \tag{7}$$

where $CgSCR$ is the positive root of (6) with a single variable λ_i.

Note that gSCR can be analytically derived from the assumption that each T_i in (3) is equal in homogeneous MIDC systems. However, this assumption is false in inhomogeneous MIDC systems, which limits the application of gSCR to inhomogeneous MIDC systems.

III. GRID STRENGTH ASSESSMENT

SCR-based methods can be used to evaluate the stability margin of MIDC systems by focusing on the grid characteristics, i. e., network structure and parameters. For example, Section II introduces the concept of gSCR for quantitative analysis of the stability of homogeneous MIDC systems, where $gSCR$ is the eigenvalue of the weighted node susceptance matrix $\boldsymbol{J}_{eq}$. However, in practice, inhomogeneous MIDC systems, i. e., $T_1 \neq T_2 \neq \ldots \neq T_i \neq \ldots \neq T_n$, must also be investigated, and the method described in Section II is not applicable in these scenarios. To address this issue, the mode perturbation theory in [10] is employed to determine the relationship between the stability of MIDC systems (reflected by the minimum eigenvalue of $\boldsymbol{J}_{sys}$) and gSCR.

The following lemma provides the mathematical foundation for our proposed method.

Lemma 1 (Theorem 2.3 [10]): let λ_i be a simple eigenvalue of matrix $\boldsymbol{A}$ with right and left eigenvectors $\boldsymbol{x}$ and $\boldsymbol{y}$, and let $\boldsymbol{A}+\boldsymbol{E}$ be a perturbation of $\boldsymbol{A}$. Then, a unique eigenvalue $\tilde{\lambda}_i$ of $\boldsymbol{A}+\boldsymbol{E}$ can be derived as:

$$\tilde{\lambda}_i = \frac{\boldsymbol{y}^{\mathrm{T}}(\boldsymbol{A}+\boldsymbol{E})\boldsymbol{x}}{\boldsymbol{y}^{\mathrm{T}}\boldsymbol{x}} + O(\|\boldsymbol{E}\|^2) \tag{8}$$

where $O(\|\boldsymbol{E}\|^2)$ is the second-order small quality of $\boldsymbol{E}$.

Remark 1: let $\delta = |\lambda_1 - \lambda_i|\,(i=2,3,\ldots,n)$ $\boldsymbol{Y}^{\mathrm{T}}\boldsymbol{A}\boldsymbol{X}$, and ε be the distance between the minimum eigenvalue λ_1 and the other eigenvalues $\lambda_i\,(i=2,3,\ldots,n)$ of $\boldsymbol{A}$, the Jordan canonical form of $\boldsymbol{A}$, and the upper bound of $\|\boldsymbol{Y}\|\|\boldsymbol{E}\|\|\boldsymbol{X}\|$, respectively. If $\boldsymbol{E}$ is so small that $16n\varepsilon^2/\delta^2 < 1$, $\tilde{\lambda}_1$ is located uniquely on a Gerschgorin disk centered at $\boldsymbol{y}^{\mathrm{T}}(\boldsymbol{A}+\boldsymbol{E})\boldsymbol{x}/(\boldsymbol{y}^{\mathrm{T}}\boldsymbol{x})$ with the radius bounded by $4n\varepsilon^2/\delta$ (as can be observed in the proof of Theorem 2.3 [10]).

The minimum eigenvalue of $\boldsymbol{J}_{sys}$ for inhomogeneous systems can be derived by perturbing the minimum eigenvalue of $\boldsymbol{J}_{sys}$ for homogeneous systems based on Lemma 1, which is summed in the following theorem.

Theorem 1: condition ①: the minimum eigenvalue of $\boldsymbol{J}_{sys}$ for inhomogeneous systems can be approximated as (9); condition ②: the boundary condition $\det(\boldsymbol{J}_{sys})=0$ can be simplified as (10).

$$\lambda_{\min}(\boldsymbol{J}_{sys}) = \boldsymbol{\mu}_1^{\mathrm{T}}(\mathrm{diag}(T_i) + \boldsymbol{J}_{eq}^{-1} - \boldsymbol{J}_{eq})\boldsymbol{v}_1 = \sum_{j=1}^{n}\mu_{1,j}v_{1,j}T_j + \lambda_1 - \lambda_1^{-1} \tag{9}$$

$$\lambda_{\min}(\boldsymbol{J}_{sys}) = \sum_{j=1}^{n}\mu_{1,j}v_{1,j}T_j + \lambda_1 - \lambda_1^{-1} = 0 \tag{10}$$

where $\mu_{1,j}$ and $v_{1,j}$ are the j^{th} elements of the left and right eigenvectors $\boldsymbol{\mu}_1$ and $\boldsymbol{v}_1$ of λ_1, respectively. In addition, $\sum_{j=1}^{n}\mu_{1,j}v_{1,j} = 1$ and $\mu_{1,j}v_{1,j} > 0$ [8].

Proof: $\mathrm{diag}(T_i) + \boldsymbol{J}_{eq}^{-1} - \boldsymbol{J}_{eq}$ can be considered as a perturbation of $\boldsymbol{J}_{sys0}$ whose eigenvectors are the same as those of $\boldsymbol{J}_{eq}$. Therefore, it follows from Lemma 1 that its minimum eigenvalue can be approximated by $\boldsymbol{\mu}_1^{\mathrm{T}}(\mathrm{diag}(T_i) + \boldsymbol{J}_{eq}^{-1} - \boldsymbol{J}_{eq})\boldsymbol{v}_1$, i.e., condition ① is satisfied. In addition, because the determinant of a matrix is equal to the product of its eigenvalues, condition ② is also satisfied. This concludes the proof.

Remark 2: the distance between converter control parameters is generally smaller than the distance between λ_i in prevalent MIDC systems [4]. This means that the corresponding ε and δ in Theorem 1 satisfy the condition $16n\varepsilon^2/\delta^2 < 1$ in Remark 1, and the approximation error of Theorem 1 is bounded by $4n\varepsilon^2/\delta^2 \approx 0$. Moreover, if $16n\varepsilon^2/\delta^2 < 1$ is not satisfied, (9) is still a good approximation in inhomogeneous systems. This can be illustrated by the cases described in Section IV, where $\varepsilon \approx 0.2\delta$ and $16n\varepsilon^2/\delta^2 \approx 1.92$.

Equation (10) shows that the boundary condition for both homogeneous and inhomogeneous MIDC systems in (3) can be unified into (9), i.e., replacing T_i by T in (9) yields (6). Therefore, if $gSCR = \lambda_1$, and a modified $CgSCR^*$ in (11) is redefined for inhomogeneous systems, the voltage is stable if $gSCR > CgSCR^*$ and the voltage stability boundary can be approximated by the curve of $gSCR = CgSCR^*$.

Similar to (7) for the homogeneous system, it follows from (10) that the $CgSCR^*$ for the inhomogeneous MIDC system can be defined as:

$$CgSCR^* = T_*/2 + \sqrt{T_*^2/4 + 1} \tag{11}$$

where $CgSCR^*$ is the positive root of (10) with a single λ_1 variable; and $T_* = \sum_{j=1}^{n}\mu_{1,j}v_{1,j}T_j$ is the weighted sum of T_i of all HVDC converters in the MIDC systems.

It should be noted that T_* is, in essence, an equivalent HVDC control parameter in the corresponding SIDC system whose $CSCR = CgSCR^*$, and the extreme value of T_* is determined by the existing T_i in the MIDC system.

IV. NUMERICAL STUDIES

In this section, the effectiveness of $gSCR$ and $CgSCR^*$ in (11) for grid strength assessment of inhomogeneous MIDC systems is demonstrated in an inhomogeneous triple-infeed HVDC system. The benchmark model proposed by CIGRE in 1991 [5] is applied, where the corresponding control configuration $T=1.5$. To highlight the inhomogeneity, when the commutation reactance, power-factor angle, and transformer ratio of the benchmark model are changed, three HVDC inverters with different control parameters T_i, e. g., $T_1 = 1.24$, $T_2 = 1.5$, $T_3 = 1.75$, are constructed. In addition, in the triple-infeed system [8], the Thevenin equivalent reactance is set to be $z_1 = 1/1.5$ p.u., $z_2 = z_3 = 1/3$ p.u., and $z_{12} = z_{13} = z_{23} = 1/1.5$ p.u..

First, we must choose to verify the applicability of $gSCR$ and $CgSCR^*$ to assess grid strength in terms of static-voltage stability margin. When P_{N2} increases and P_{N1} and P_{N3} remain constant, the $gSCR$ and $CgSCR^*$ can be evaluated. The changes in $gSCR$ and $CgSCR^*$ with P_{N2} are shown in Fig. 2. The figure shows that $gSCR$ decreases and $CgSCR^*$ tends to remain constant as P_{N2} increases. Thus, the static-voltage stability margin, quantified by the distance between $gSCR$ and $CgSCR^*$, decreases as P_{N2} increases. When P_{N2} increases to $P_{d\max}$ such that the determinant of $\boldsymbol{J}_{MIDC}$ in (2) is equal to zero, $gSCR$ coincides with $CgSCR^*$. This indicates that a static-voltage stability limit occurs and thus the stability margin is equal to zero.

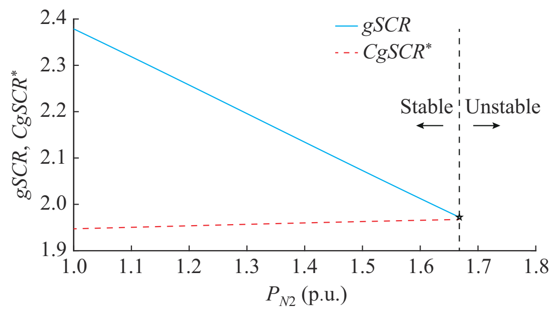

Fig. 2. Trajectories of *gSCR* and $CgSCR^*$ with P_{N2} for a triple-infeed system.

The curves with different *gSCR* values (2.0, 2.1, and $CgSCR^*$) are shown in Fig. 3, where the circles denote the static-voltage stability boundary ($\boldsymbol{J}_{MIDC}$ in (1) is singular). To draw the curves, the rated power injections P_{N1}, P_{N2}, and P_{N3} from the three HVDC ties are set up as follows: P_{N3} maintains 1 p.u., P_{N2} varies from 1 to 1.4 p.u., and P_{N1} changes to make $\boldsymbol{J}_{MIDC}$ singular or to have *gSCR* coincide but with different values. Figure 4 shows that the static-voltage stability boundary and curve with $gSCR = CgSCR^*$ are very close. In particular, the largest relative error between the points on the static-voltage stability boundary and those on the curve with $gSCR = CgSCR^*$ is only 0.41% when P_{N1} is fixed and when different P_{N2} in the curves are compared. In summary, the voltage-stability boundary can be well approximated by the curve of $gSCR = CgSCR^*$. In addition, a larger *gSCR* value indicates a larger stability margin because the curve with a larger *gSCR* is closer to the origin point than those with a smaller *gSCR*.

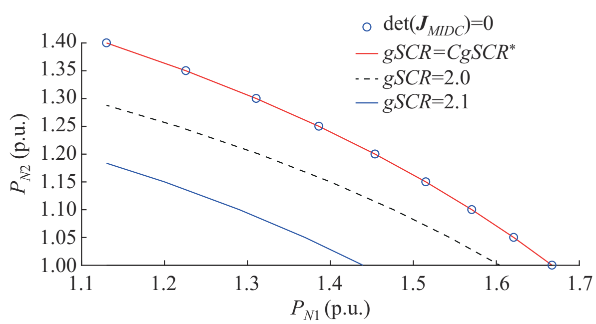

Fig. 3. Trajectories of P_{N2} with P_{N1} responding to different *gSCRs* and a singular Jacobian matrix.

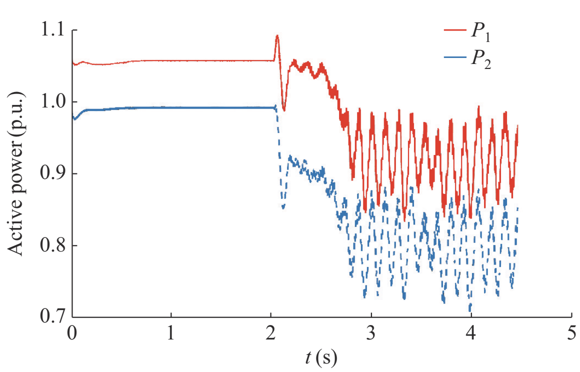

Fig. 4. Active power of dual-converter multi-infeed system.

The relative error between $CgSCR^*$ and *gSCR* at the stability boundary is further analyzed when the inhomogeneity level in the HVDC inverters changes in the system. The inhomogeneous level is quantified by the standard deviation of control parameters T_i $(i = 1, 2, 3)$ of the three HVDC inverters. Table I presents the largest percentage errors and standard deviations of T_i when T_1 and T_3 change while T_2 remains constant, which shows that the approximation error of the stability boundary when using $CgSCR^*$ is insensitive to the changes of the control parameters. This is because the largest percentage error is small even when $T_1 = 1.0439$ and $T_3 = 1.9245$ are significantly different from the benchmark model with $T = 1.5$ $(\varepsilon \approx 0.2\delta)$.

TABLE I
ERROR ANALYSIS FOR TRIPPLE-INFEED SYSTEM

T_1	T_3	Standard deviation of T_i	Error level (%)
1.2444	1.7455	0.2505	0.33
1.1786	1.8056	0.3135	0.52
1.1118	1.8652	0.3768	0.75
1.0439	1.9245	0.4400	1.01

To further validate the proposed method using the numerical calculation presented in the previous sections, dynamic simulations are also performed using the PSCAD/EMTDC program. For this purpose, a dual-converter multi-infeed system shown in Fig. 1 is used to verify the effectiveness of the *gSCR*. The CIGRE benchmark model and corresponding modified model are located at two buses with *CgSCR* values of approximately 2.1 and 1.8 in the SIDC system, respectively. The two HVDC links are connected to the same AC network with a *gSCR* of approximately 1.9, which is the approximate critical value of the static-voltage stability. The active power of the inverters finally collapses if we continue to increase the DC current after 2 s, as shown in Fig. 4. This means that the dual-converter multi-infeed system is now located in the unstable operational region, and the value of *CgSCR* is between those of the two SIDC systems.

III. CONCLUSION

Modal perturbation theory is used to extend the application of the *gSCR* previously defined for homogeneous MIDC systems to inhomogeneous MIDC systems. The letter demonstrates that the difference between the *gSCR* and a modified $CgSCR^*$ can effectively assess the grid strength of an inhomogeneous HVDC in terms of the static-voltage stability margin. In addition, the proposed $CgSCR^*$ represent a promising means of estimating the static-voltage stability limit with various HVDC control parameters, which is a topic for a future study.

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