Generalized Short Circuit Ratio for Multi-Infeed LCC-HVDC Systems

Feng Zhang, Huanhai Xin, Zhen Wang, Deqiang Gan, Qian Xu, Pan Dai, Feng Liu

Abstract—The relationship between the short circuit ratio (SCR) and static voltage stability is analyzed in this paper. According to eigenvalue decomposition method, a concept named generalized short circuit ratio (gSCR) has been proposed for multi-infeed HVDC (MIDC) systems to mathematically measure the connected AC strength from the voltage stability point of view, which can overcome the rule-of-thumb basis of existing multi-infeed short circuit ratio (MISCR) concept. In gSCR, two indices, the critical gSCR (CgSCR) and the boundary gSCR (BgSCR) are developed to quantitatively evaluate if the connected AC system is strong or weak, in which CgSCR=2 and BgSCR=3 are two critical values for strength criterion. Finally, simulations are conducted to validate the effectiveness of the proposed gSCR. The results show that some system parameters like equivalent AC impedance angle have little effect on the two critical values.

Index Terms—Static voltage stability, multi-infeed HVDC system, multi-infeed short circuit ratio, generalized short circuit ratio

I. INTRODUCTION

Recently, the HVDC transmission is increasingly used as the power transmission way for widespread renewable energy generation [1]. In China, several ±800kV HVDC transmission projects have been particularly put into service for long-distance and sending-out electric power from large hydro-power plants and high-density wind farms to form the large North-, East- and Central China grid jointly with other ultra-high-voltage (UHV) AC transmission, while the total installed capacity will exceed 700GW by 2020 [2]. These close HVDCs constitute the multi-infeed HVDC system (MIDC) with AC power grid [3]. During the past decades, concerns on MIDC were mainly focused on the power transmission limitation and the voltage stability issues, e.g., stability mechanism, transient overvoltage (TOV) at the converter ac buses and harmonic instability were believed to be affected by voltage instability [5]-[7]. The SCR index was developed to evaluate the strength of connected AC system for single-infeed HVDC system. To consider the MIDC emerged later, the multi-infeed short circuit ratio (MISCR), as an extension of SCR was further proposed by CIGRÉ to give a quantitative assessment of the strength of AC/DC system considering the neighboring HVDC’s voltage influence [5]. However, MISCR is a rule-of-thumb extension of SCR concept and it is lacking of strict theory basis [7].

Several attempts have been made to give theoretical insight into physical mechanism of voltage stability, power system planning and terminal location selection of MIDC [7-12]. An analytic equivalent of the empirical index in [7] is derived to facilitate rigorous analysis of voltage/power interactions in MIDC systems, which is proposed to give theoretical explanation of the voltage stability. In [8], power system planning and location selection is solved by analyzing an optimal problem of dc-segmentation for MIDC systems based on stability performance, and so on. But these works haven’t essentially explained the physical mechanism of MISCR and the relationship between the MISCR and static voltage stability.

In this paper, a novel generalized short circuit ratio is proposed, which is derived by the eigenvalue decomposition method under several assumptions. Firstly, the characteristic equation is yielded by analyzing the analogy between SIDC and MIDC from the voltage stability point of view. Then the gSCR concept is developed to mathematically measure the AC system strength and the influences of the assumptions are discussed as well. Finally, the effectiveness of the proposed index is verified by simulations on the platforms of the Matlab and DigSILENT, respectively.

II. SHORT CIRCUIT RATIO AND VOLTAGE STABILITY

A. Definition and characteristics of SCR

In a SIDC system, the definition of SCR is

$$SCR = \frac{S_{\omega}}{P_{dc}} = U_x \cdot Z \cdot \frac{1}{(P_{dc} \cdot Z)} = \frac{1}{(P_{dc} \cdot Z)}$$ (1)

$$\frac{1}{(P_{dc} \cdot Z)}$$

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where $S_{sc}$ is the short circuit capacity, $P_{on}$ is the rated transmission power, $U_{sc}$ is the rated AC voltage where DC feeds in, $Z$ is the equivalent reactance, normally, the resistance part is neglected.

SCR is usually used to measure the connected AC system strength from the voltage stability point of view, where HVDC is controlled as constant power and constant extinction angle (CP-CEA) mode. There are two concepts involved in SCR, the critical SCR (SCR) [4] and the boundary SCR (BSCR) [13].

1. The SCR is called CSCR where the maximum available power (MAP) point coincides with the rated operation point, used to differentiate weak systems from strong systems.
2. The SCR is called BSCR where the MAP point coincides with the rated operation point where commutation overlap angle is 30°, used to differentiate very weak systems from weak systems.
3. The SCR is usually used to measure the connected AC system stability but its own capability.

If it is a strong system, the HVDC operation will not be limited: if SCR is less than 2 (CSCR), the AC system is considered as a very weak system. If SCR is between 2 and 3, the AC system is a weak system.

B. Derivation of Jacobian matrix

The characteristics of AC/DC voltage stability can be obtained by analyzing Jacobian matrix. In a SIDC system, the linearized matrix of AC/DC system can be expressed as

\[
\begin{bmatrix}
\Delta P / U \\
\Delta Q / U
\end{bmatrix} = \begin{bmatrix}
J_{p,p} & J_{p,q} \\
J_{q,p} & J_{q,q}
\end{bmatrix} \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]

where $J_{p,p}$, $J_{p,q}$, $J_{q,p}$, $J_{q,q}$ and $J_{p,p}$, $J_{p,q}$, $J_{q,p}$, $J_{q,q}$ are elements of AC and DC Jacobian matrix respectively.

According to the characteristics of LCC-HVDC, there is $J_{eq,p} = 0$, $J_{eq,q} = 0$.

In order to calculate $J_{eq,p}$ and $J_{eq,q}$, the equivalent circuit of HVDC is analyzed, given in Fig. 1.

![Fig. 1 Equivalent circuit of SIDC system](image)

The equations of inverter side are

\[
\begin{align*}
I_d & = P_i - I_d^2 R \\
U_{dc} & = 3\sqrt{2}\pi^2 N X_c U_p \cos \gamma - 3\pi^2 N X_c I_d \\
\cos \phi & = \cos \gamma - \frac{X_c I_d}{\sqrt{2}K U_p}
\end{align*}
\]

where $P_i$ is the in-feed HVDC power, $P_{dc}$ is the HVDC transmission power, $R$ is the HVDC transmission line resistance, $U_{dc}$ is the DC voltage, $K_1$ is the ratio of transformer, $I_d$ is the AC voltage, $X_c$ is commutation reactance, $\gamma$ is the extinction angle, $N$ is the number of cascading converter, $\phi$ is the power-factor angle. All variables with subscript $i$ imply that the variables are on inverter side.

The reactive power injection of HVDC is

\[
Q = -P \tan \phi + \omega B U^2
\]

where $Q$ is the reactive power injection, $B$ is the reactive power compensation capacitor.

Substituting $\phi(U) = \tan \phi$ into Eq (4) yields:

\[
\phi(U) = \tan \left[ \arccos \left( \cos \gamma - \frac{X_c I_d}{\sqrt{2K U_p}} \right) \right]
\]

Combining Eq (2) with Eq (3)-(7), the linearized matrix of DC system can be expressed as

\[
\begin{bmatrix}
\Delta P / U \\
\Delta Q / U
\end{bmatrix} = \begin{bmatrix}
0 & 0 \\
0 & PU^2 T(U, \xi)
\end{bmatrix} \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]

C. Relationship between SCR and static voltage stability

It can be derived that the elements of AC Jacobian matrix are [14]:

\[
J_{p,p} = -EZ^2 \cos \delta , \quad J_{q,q} = -P / U , \quad J_{p,q} = -P / U^2
\]

and $J_{q,q} = -Z$. Here $E$ is the Thevenin equivalent electric potential and $Z$ is the Thevenin equivalent reactance. At the rated operation point the reactive power absorbed by HVDC is compensated locally by compensation capacitor, so,

\[
U = E \cos \delta , \quad J_{p,q} = -U Z^{-1}
\]

It is well known that when voltage instability occurs the Jacobian matrix becomes singular,

\[
\det \begin{bmatrix}
J_{p,p} & J_{p,q} \\
J_{q,p} & J_{q,q}
\end{bmatrix} = 0.
\]

Eq (10) is equivalent to the following equation:

\[
\det (J_{p,p} + J_{q,q} - J_{q,p} J_{p,q} J_{p,q}^T) = 0.
\]

Substituting Eq (8) and (9) into Eq (11), we have

\[
\left( \frac{P}{U^2 P_S} \right) T(U, \xi) + \frac{J}{P_S} + \frac{1}{P_S} \frac{P Z}{U U^2} = 0.
\]

let $P = P_{dc} U$, and as Eq (1) saying that, $\text{SCR} = \frac{1}{P_{dc}} = \frac{U}{U_1}$, so Eq (12) can be express in another form

\[
\Delta(O) = \rho T(U, \xi) + \rho^2 \text{SCR}^{-1} - \text{SCR} = 0.
\]

where $O$ represent operation point. It can be seen from Eq (13) that, SCR has a straight relationship with voltage stability.

Considering that $P_{dc} U = 1$ and $U = 1$ p.u. at the rated operation point, Eq (13) can be simplified as

\[
\Delta(O) = T(U, \xi) + \text{SCR}^{-1} - \text{SCR} = 0.
\]
where \( O_i \) represent the rated operation point. As the definition of critical SCR in Section II.A, it satisfies Eq (13) when MAP point coincides with the rated operation point.

Similarly, the boundary SCR is the SCR which satisfies Eq (15) when commutation overlap angle of HVDC is 30\(^\circ\).

\[
\Delta(O_i) = T(U_i, \xi_i) + \rho^2 SCR^{-1} - SCR = 0. \tag{15}
\]

where \( O_i \) represent the operation point where commutation overlap angle of HVDC is 30\(^\circ\).

It can be concluded from Eq (14), (15) that both CSCR and BSCR is related to voltage stability margin.

### III. MULTI-INFED GENERALIZED SHORT CIRCUIT RATIO

The original intention of SCR is to measure the strength and stability of AC/DC system. In order to make multi-infeed short circuit ratio having the same clear relevance to voltage stability of AC/DC system, this section continues to use the Jacobian matrix analyzing from the perspective of voltage stability.

All conclusions are derived from the equivalent circuit given in Fig. 2, and the following three assumptions are supposed:

![Fig. 2 Typical MIDC system](image)

**Assumption1**: The DC system is similar, which means that extinction angle and parameters of HVDC based on their individual power capacity have the same values. Besides, the control mode of all HVDC is CP-CEA.

**Assumption2**: The topology of AC system is connected and inductive. Namely, the node admittance determinant is reversible and symmetrical.

**Assumption3**: The reactive power absorbed by HVDC is compensated locally, namely, the tie-line power is much less than its limitation.

#### A. Linearization of HVDC system

The linearization of MIDC system can be written as

\[
\begin{bmatrix}
\Delta P/U \\
\Delta Q/U \\
\Delta U
\end{bmatrix} = \begin{bmatrix}
0 \\
\text{diag}(P_{ni}\rho T_i) \\
\text{Bdiag}(P_{ni}\rho T_i)
\end{bmatrix} \Delta \lambda
\]

where \( T_i = 2c_i K_i + \frac{2q_i b_i}{\rho_i} \), \( \rho_i = \frac{P_i}{P_{ni}^2}, i = 1, 2, \ldots, n \) is the compensation capacitor and \( P_{ni} \) is the rated capacity. Here, diag(\(a_i\)) represents diagonal matrix diag(\(a_1,a_2,\ldots,a_n\)).

#### B. Voltage stability condition

Similar to Eq (2), the linearization of AC system is

\[
\begin{bmatrix}
\Delta P/U \\
\Delta Q/U \\
\Delta U
\end{bmatrix} = \begin{bmatrix}
\text{Bdiag}(U_i) \\
-\text{diag}(P_{ni}U_i^2) \\
\text{B}
\end{bmatrix} \Delta \lambda
\]

here \( B \) is the node admittance determinant, \( B_i < 0 \). So the Jacobian matrix is as follow [15]:

\[
J_{eq} = \begin{bmatrix}
\text{Bdiag}(U_i) \\
-\text{diag}(P_{ni}U_i^2) \\
\text{B + diag}(P_{ni}\rho T_i)
\end{bmatrix}. \tag{18}
\]

Voltage instability implies the singularity of the Jacobian matrix, so by Schur decomposing Eq (18) can be changed to

\[
\det(\text{Bdiag}(U_i))\det(J_{eq}) = 0. \tag{19}
\]

where \( J_{eq} = B + \text{diag}(P_{ni}\rho T_i) - \text{diag}(P_{ni}U_i^2)B^{-1}\text{diag}(P_{ni}U_i^2) = B + \text{diag}(P_{ni}\rho T_i). \)

#### C. The generalized short circuit ratio (gSCR)

Multiplying \( J_{eq} \) left by \( \text{diag}^{-1}(P_{ni}) \), (19) is equivalent to

\[
\det[\text{diag}(\rho T_i) + \text{diag}(\rho i]\text{diag}(\rho) - J_{eq}] = 0. \tag{20}
\]

where \( J_{eq} \) is defined as the extended Jacobian matrix

\[
J_{eq} = -DB \tag{21}
\]

where \( D = \text{diag}^{-1}(P_{ni}) \).

**Lemma1** [14]: Since the MIDC satisfies **Assumption1** and can be represented by Fig. 2, which means the control mode of HVDCs is CP-CEA, thus the extinction angles of all HVDCs are the same. We can draw a conclusion that, \( \rho_i = \rho, c_i = c_j \) and \( B_i P_{ni}^{-1} = B_j P_{nj}^{-1} \) is satisfied, so long as the commutation overlap angle (COLA) are the same for all HVDCs, i.e. COLA=COLA\(_i\), while the operation point changes.

**Lemma2**: All Eigenvalues of the matrix \( J_{eq} \) are positive. And the minimum eigenvalue of \( J_{eq} \) is a simple eigenvalue [16], which means it is unique and its geometric multiplicity and algebraic multiplicity is one.

It can follow from the Lemma 1 that \( \rho = \rho_1 = \ldots = \rho_n \) and \( T(U_i, \xi_i) = \ldots = T(U_n, \xi_n) = T(U, \xi) \), so Eq (20) can be simplified as

\[
\det[\text{diag}(\rho T_i) + \rho^2 J_{eq}] = 0. \tag{22}
\]

Based on the Lemma2, there exists a nonsingular matrix \( W \) such that \( J_{eq} \) can be decomposed as follows.

\[
W^{-1}J_{eq}W = \text{diag}\{\lambda_1, \lambda_2, \ldots, \lambda_n\}. \tag{23}
\]

where the eigenvalues is sorted by \( 0 < \lambda_1 < \lambda_2 \leq \ldots \leq \lambda_n \).

Thus, Eq (22) and (23) lead to:

\[
\prod_{i=1}^{n} (\rho T(U, \xi) + \rho^2 \lambda_i - \lambda_i) = 0. \tag{24}
\]

Similarly, Eq (24) is equivalent to the following equation from the perspective of voltage stability.

\[
\Delta(O) = \rho T(U, \xi) + \rho^2 \lambda_i - \lambda_i = 0. \tag{25}
\]

It can be seen that Eq (25) is same as Eq (13) mathematically, so Eq (25) gives the condition of voltage stability of MIDC system. Therefore \( \tilde{\lambda} \) can be analogously defined as similar MISCR concept as follows.

**Definition1**: The minimum eigenvalue of the extended Jacobian matrix \( J_{eq} \) is defined as the generalized short circuit ratio (gSCR):


\[ g_{SCR} = \min \lambda \left( J_{\varphi} \right). \]  

(26)

**Definition 2.** The gSCR is called the critical gSCR (CgSCR) if the MIDC’s rated operation point satisfies Eq (25). The gSCR is called the boundary gSCR (BgSCR) if the MIDC’s operation point satisfies Eq (25) and its corresponding commutation overlap angle is 30°.

According to Lemma 1, the extinction angle and commutation overlap angle of multiple HVDCs can be kept equivalent respectively by proper control measures, then mathematically the following conclusion can be drawn: \( C_{gSCR} = C_{SCR} \approx 2 \), \( B_{gSCR} = B_{SCR} \approx 3 \). Therefore, from the definition of gSCR, the strength of the AC system can be measured exactly by gSCR. Namely, if gSCR is less than 2, the AC system is a very weak system, which means it can’t support all HVDCs operating at the rated operation point. If gSCR is greater than 3, the AC system is a strong system, which can guarantee all the HVDCs to approach to their limit conditions (i.e., the maximum commutation overlap angle is 30°). If gSCR is between 2 and 3, the AC system is a weak system, which means it can support all HVDCs operating at the rated operation point but can’t support all HVDCs operating at the point where the commutation overlap angle is 30°.

IV. INFLUENCES OF SYSTEM PARAMETERS

As analyzed above, the properties of the gSCR are investigated under three assumptions which may be not satisfied in a practical system. In this section, some system parameters, such as equivalent AC impedance angle and tie-line power, are analyzed to reveal that CgSCR and BgSCR can still measure the connected AC system strength with small deviation.

When **Assumption 3** is not satisfied, which means the tie-line power should be considered, and the resistance part of Thevenin equivalent impedance cannot be neglected, the elements in (17) is as follows,

\[
\begin{align*}
J_{p_{ij}} &= -U_i \left( G_{ij} \sin \theta_j - B_{ij} \cos \theta_j \right) \\
J_{q_{ij}} &= -U_i \left( G_{ij} \cos \theta_j + B_{ij} \sin \theta_j \right) \\
J_{p_{i\varphi}} &= Q_i \left( U_i + B_i U_i \right) \\
J_{q_{i\varphi}} &= -P_i U_i^2 - G_i \\
J_{p_{\varphi\varphi}} &= U \left( G_{\varphi} \cos \theta_j + B_{\varphi} \sin \theta_j \right) \\
J_{q_{\varphi\varphi}} &= -P_{\varphi} U_{\varphi}^2 + \varphi \\
J_{p_{\varphi\varphi}} &= -Q_{\varphi} U_{\varphi}^2 + \varphi
\end{align*}
\]

(27)

where \( \theta_j \) is the voltage angle between \( i \)th and \( j \)th HVDC converter bus, \( G_{ij} \) and \( B_{ij} \) are the real and imaginary parts of Thevenin equivalent impedance respectively. Considering low \( R/X \) for transmission line, let \( X = |Z| \) when calculating gSCR.

The procedure to calculate the CgSCR and BgSCR with the effect of equivalent AC impedance angle and tie-line power can be generally summarized as follows,

Step 1) Select appropriate parameters of AC-DC system so that gSCR=2 is satisfied.

Step 2) Conduct simulations on the case system to calculate the MAP and the current at MAP operation point.

Step 3) Compare the MAP and current at MAP operation point with the rated power and rated current. If the MAP and current at MAP operation point are larger than the rated power and rated current, then increase the impedance proportionally by 0.002 p.u.; If the MAP and current at MAP operation point are less than the rated power and rated current, then decrease the impedance proportionally by 0.002p.u.; Otherwise, move to Step 6.

Step 4) Stop the iteration if the deviation between the current at MAP operation point and the rated current is less than 0.005p.u., and the gSCR is the critical gSCR; Otherwise, repeat Step 2-3.

![Fig. 3 The flowchart of calculating the critical gSCR](image)

For clarity purpose, the flowchart of calculating the critical gSCR is given in Fig. 3, the BgSCR calculation procedure is similar and ignored here.

V. SIMULATION VALIDATION

In order to validate that \( C_{gSCR} \approx 2 \) and \( B_{gSCR} \approx 3 \) are two critical values for strength evaluation in MIDCs, as stated in **Definition 2**, simulations are conducted on both Matlab platform and DIgSILENT platform based on benchmark.

First of all, a dual-infeed system is constructed and simulated on Matlab platform. By changing the rated transmission power of one HVDC, keeping other network parameter unchanged, the system CgSCR and BgSCR are then calculated and plotted in Fig. 4, in which the CgSCR value is about 2 while the BgSCR value is about 3, the same as the values of CSC and BSC. Besides, it can be observed that, the deviation of CgSCR and BgSCR is small when the rated power varies. The deviation of CgSCR is about 2.0%, while the deviation of BgSCR is about 2.7%. This means that for a MIDC the characteristics of the voltage stability and the strength of the AC system can be described accurately by the proposed gSCR index.
rated and critical point while confirming the deviation of angle between the boundary point and 30°.

Seven simulations have been made and the results are given in Table 2 and Table 3. The voltage instability point is estimated by the divergence condition of power flow on DlgSILENT platform.

### Table 2 Critical gSCR and critical power

| Case     | Quantity of infeed | gSCR | Pd1/sw | Pd2/sw | Pd3/sw |
|----------|-------------------|------|--------|--------|--------|
| Case1    | Single            | 3    | 1037.40| 1056.07| 1104.66| 998.07 |
| Case2    | Dual              | 3    | 1024.21| 1009.76| 998.07 |
| Case3    | Triple            | 3    | -      | -      | 1088.49|

When the point where the commutation overlap angles are 30°, the MAPs of all the HVDCs are around the rated operation point, the deviation of power is less than 0.3%. Furthermore, if gSCR is around 3, the MAPs of all the HVDCs are around the point where the commutation overlap angles are 30°, the deviation of commutation overlap angle is less than 0.7°, which is given in Table 3.

When the equivalent AC impedance angle and the tie-line power are independently changed, the trajectories of CgSCR and BgSCR are given in Fig. 5 and Fig. 6, respectively.

### Table 3 Boundary gSCR of MIDC system

| Quantity of infeed | Case4/Single | Case5/Dual | Case6/Dual | Case7/Dual | Case8/Triple |
|--------------------|--------------|------------|------------|------------|--------------|
| gSCR               | 3            | 3          | 3          | 3          | 3            |
| Pd1/sw             | 1037.40      | 1056.07    | 1104.66    | 998.07     |
| Pd2/sw             | -            | 1024.21    | 1009.76    | -          |
| Pd3/sw             | -            | -          | -          | 1088.49    |
| OLA1               | 30.03        | 30.49      | 30.34      | 30.71      |
| OLA2               | 30.62        | 30.68      | 30.36      | 30.37      |
| OLA3               | -            | -          | -          | -          |

It can be seen from Fig. 5, the actual CgSCR and BgSCR decrease when the impedance angle decreases, but the deviations of CgSCR and BgSCR are both less than 2.5% as the impedance angle is 75°. Similarly, it can be seen from Fig. 6, the actual CgSCR and BgSCR decrease approximately when the tie-line power increases, but the deviations of CgSCR and BgSCR are both less than 3% when the tie-line power is 0.5p.u.. Therefore, the equivalent AC impedance angle and tie-line power have little effect on these two critical values, namely, CgSCR and BgSCR can still measure the connected AC strength with small deviation when considering these system parameters.

### VI. CONCLUSION

The gSCR is proposed to quantitatively measure the strength and stability of AC/DC system. Theoretical analysis and simulations show that if gSCR<2, the AC system is a very weak system; if gSCR>3, the AC system is a strong system; otherwise if gSCR is between 2 and 3, the AC system is a weak system. Moreover, it is shown that the influences of AC impedance angle and tie-line power in Thevenin equivalent electric on the CgSCR and BgSCR are small. Exploring the variety of gSCR under weaker assumptions will be our future work.

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