

Multiple Renewable Short-circuit Ratio for Assessing Weak System Strength with Inverter-based Resources

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Abstract—Inverter-based resources (IBRs), such as wind and photovoltaic generation, are characterized by low capacity and extensive distribution, which can exacerbate the weak properties of power systems. Precise identification of weak system status is essential for ensuring the security and economic efficiency of IBR integration. This paper proposes the index of the multiple renewable short-circuit ratio (MRSCR) and its critical value calculated by the voltage (CMRSCR) to provide a comprehensive assessment of power system strength in the presence of high IBR penetration, enhancing the accuracy and reliability of system strength evaluation. First, we introduce a single-infeed equivalent model of the power system integrating multiple IBRs. We examine the factors associated with system properties that are crucial in the strength assessment process. Subsequently, the MRSCR is derived from this analysis. The MRSCR describes the connection between system strength and voltage variation caused by power fluctuations. This implies that voltage variation caused by IBR power fluctuations is more pronounced under weak grid conditions. Following this, the CMRSCR is proposed to precisely evaluate the stability boundary. The disparity between MRSCR and CMRSCR is utilized to evaluate the stability margin of the power system. Unlike a fixed value, the CMRSCR exhibits higher sensitivity as the system approaches a critical state. These indexes have been implemented in the PSD power tools and power system analysis software package, facilitating engineering calculation and analysis of bulk power systems in China. Finally, simulation results validate the effectiveness of the proposed indexes and the research findings.

Index Terms—Critical multiple short-circuit ratio, inverter-based resource, multiple renewable short-circuit ratio, system strength.

I. INTRODUCTION

INVERTER-BASED resources (IBR), such as wind and solar resources, are becoming increasingly integral to power grids due to their contributions to decarbonization and expanding customer needs. However, high-quality wind and solar resources are often located in specific locations that are

distant from load centers. An overcapacity of IBRs in a system can lead to various issues, including voltage instability [1], increased overvoltage [2], and power oscillation [3], [4]. Disparities in generation capacity, transmission location, and load size between regions complicate and introduce challenges in the development of transmission infrastructure for IBR. Therefore, considering the factors mentioned above, developing a comprehensive yet practical index is crucial for guiding the appropriate access position and ensuring sufficient integration capacity for IBRs.

The short-circuit ratio (SCR) is commonly employed for initial assessments of system strength, as recommended by researchers [5], [6] and organizations [7] such as the International Council on Large Electric Systems (CIGRE), the Australian Energy Market Operator (AEMO), and China Electric Power Research Institute (CEPRI). The SCR can balance the need for deep understanding with the time and cost burdens of rigorous electromagnetic model analysis. However, the system's stability can change rapidly with varying operations. As a result, the SCR has garnered considerable attention for its proactive and valuable role in assessing practical engineering scenarios.

In engineering practice, a critical or minimum SCR is specified for severe scenarios while ensuring stable operation. For instance, the line commutated converter-based high-voltage direct current (LCC-HVDC) transmission system faces a high risk of commutation failure under weak AC system conditions. In a typical scenario, the critical SCR is 2 on the inverter side [8] when operating at its maximum available power [9]. Additionally, the multi-infeed short-circuit ratio (MSCR) [10] is proposed and widely utilized for the multi-infeed LCC-HVDC transmission system to account for the interaction of various integrated DC links, with its critical value also set at 2. Moreover, the multi-infeed effective short-circuit ratio (MIESCR) [8] is proposed to account for the shunt compensation element required by the converter, with a critical MIESCR of approximately 1.5 for typical parameters and controls.

Several indexes have been proposed to evaluate the strength of systems with high IBR penetration, including the weighted short-circuit ratio (WSCR) [11], [12], the composite short-circuit ratio (CSCR) [13], and the equivalent circuit-based short-circuit ratio (ESCR) [14]. These indexes are based on practical engineering experience rather than rigorous theoretical

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derivation. Reference [15] introduces the site-dependent short-circuit ratio (SDSCR), with its critical value determined to be 1 based on the eigenvalue criterion. Additionally, reference [16] analyzes the relationship between the critical SCR and the system impedance ratio (SIR). However, [16] is only applicable to systems in critical states and does not guide assessing the strength of an ordinary system. Reference [17] proposes that conventional SCR is inapplicable and introduces voltage stiffness (VS) for evaluating the strength of VSC-penetrated power systems, suitable for resistance-inductive systems. Reference [18] proposes a semi-definite programming method to assess the maximal capacity of grid-following converters using the generalized short-circuit ratio, accounting for small signal stability constraints [19]. Reference [20] identifies the static voltage stability limit using the extended continuation power flow method, which requires simulation but lacks a critical index. Critical values for the indexes used to characterize weak systems are presented in Table I. The critical values of various short-circuit ratio indexes exhibit significant discrepancies, occasionally being overly conservative. Besides, bulk power systems with high IBR penetration lack theoretical derivation and empirical testing, considering systemic features and IBR characteristics, potentially hindering IBR development.

TABLE I
INDEXES OF SCR AND THEIR CRITICAL VALUES

Scenario	Index	Critical value
Power system with LCC-HVDC	SCR	2
	MSCR	2
	MIESCR	1.5
	ESCR	3
Power system with IBRs	SDSCR	1
	WSCR	1.5
	CSCR	1

Identifying the suitable access position and optimal integration capacity of IBRs is crucial for advancing IBR transmission to markets and maintaining stability. This paper proposes to use the multiple renewable short-circuit ratio (MRSCR), a novel index designed to assess system strength in the scenario of integrating IBRs into the existing transmission networks. Then, the practical applications of the proposed MRSCR and the critical index (CMRSCR) are explored in guiding decision-making processes related to IBR integration. The contributions of this paper are as follows:

- 1) Unlike previous indexes, which may focus on only one or a few aspects, the MRSCR offers a comprehensive assessment by simultaneously considering various factors such as access position, area load size, generation capacity, and IBR control method. The proposed index enhances the accuracy and reliability of system strength evaluation.
- 2) The MRSCR establishes mathematical relationships among system strength, static voltage stability, and the integration capacity of IBRs. It offers a deeper understanding of the interaction between these factors and facilitates. Also, it improves the decision-making efficiency in IBR integration.
- 3) By identifying the voltage stability limit and stability of IBRs considering control methods, the proposed critical index calculated by the voltage (CMRSCR) enhances the analysis

efficiency. It exhibits larger sensitivity near the collapse point, which is crucial under varying operating conditions.

The paper is structured as follows: Section II derives the MRSCR based on a single-infeed equivalent model considering systematic characteristics. Simultaneously, mathematical analysis is conducted to compare various short circuit ratio indexes. Subsequently, the MRSCR is reformulated as a formula to quantify voltage variation induced by IBRs, mathematically demonstrating its significance in weaker grids. Section III introduces the derivation of the CMRSCR through voltage sensitivity analysis alongside a comparison of some critical SCR index values. In Section IV, time domain verifications are performed to validate the proposed indexes' effectiveness in assessing voltage stability margins. Furthermore, a practical engineering application example in bulk power systems is provided. Concluding remarks are presented in Section V.

II. MRSCR FOR POWER SYSTEMS WITH MULTI-INFEED IBRS

The foundation of proposing the MRSCR lies in an equivalent analysis model of the engineering system, which captures the influence of generation capacity, transmission location, and load size. Furthermore, a novel alternative expression of the MRSCR using voltage variation is provided. We selected classical indexes commonly employed in engineering, resembling the multi-infeed interaction factor (MIIF) in structure, and compared their calculation methods to explain their differences.

A. Classical SCR Indexes

The SCR, MSCR, and WSCR are widely used experimental indices in engineering, while SDSCR is a derived index based on voltage stability. The calculation methods for each are outlined as follows.

1) SCR for a Single-infeed System

For the system with single-infeed equipment, the SCR is the ratio of the available system strength (measured in short-circuit MVA) to the MVA rating of the equipment:

$$S_{CR} = \frac{S_{ac}}{P} \approx \frac{1}{Z} \quad (1)$$

where S_{ac} is the short circuit capacity, P is the rated equipment capacity, and Z is the Thévenin equivalent impedance per unit.

2) WSCR for a System with Wind Plants

The WSCR primarily offers a consolidated measure established through mathematical statistics:

$$W_{SCR} = \frac{\sum_i^N S_{ac,i} \times P_i}{\left(\sum_i^N P_i\right)^2} \quad (2)$$

where i denotes the considered node number, $S_{ac,i}$ is the short circuit capacity at the node i , P_i is the rated equipment capacity at the node i , and N is the number of DC terminals.

The WSCR assumes full interactions among wind farms but does not consider actual electrical network connections among IBRs or calculate strength at each access position.

3) MSCR for a System with Multi-infeed DC and ESCR for a System with Wind Plants

In a multi-infeed IBR system, the accuracy of the SCR is diminished. The MSCR is an empirical formula. It extends the SCR to a multi-infeed HVDC system. The ESCR is identical to MSCR but applied to grids integrated with wind plants:

$$M_{SCR,i} = \frac{S_{ac,i}}{P_{dc,i} + \sum_{j=1, j \neq i}^N P_{dc,j} \times M_{IIF,j}} \approx \frac{1}{\sum_{j=1}^N P_{dc,j} \times Z_{ij}} \quad (3)$$

where i and j are the node number, $M_{SCR,i}$ is the MSCR at node i , $P_{dc,i}$ and $P_{dc,j}$ are the rated power, and Z_{ij} is the element in the bus-impedance matrix.

The MSCR can be explained using the fast decoupled load-flow (FDLF) method. The calculation assumptions of MSCR are as follows: i) The electrical resistance is neglected, and the phase-shifter effects are excluded from the bus-impedance matrix. ii) The physical coupling between active power and reactive power is assumed to be weak; hence, the reactive power is not considered.

The mentioned indexes involve numerous simplifications and assumptions, making them unsuitable for systems with multiple IBRs. IBRs typically connect to the system through the low-voltage transmission grid, where the resistance may not be significantly smaller than the reactance. Additionally, IBRs can supply reactive power to facilitate active power delivery. The coupling of active and reactive power introduces complexities. Therefore, neither MSCR nor ESCR is suitable for a system integrated with IBRs, as errors may occur if the impact of resistance or reactive power is disregarded.

B. Definition of MRSCR

1) A Single-infeed Equivalent Model for a Power System with Multi-infeed IBR

The topology of a practical power system includes many IBRs, synchronous generators (SGs), and loads. IBRs typically connect to the grid using phase-locked loop (PLL) technology, requiring sufficient system strength for reliable operation, as depicted in Fig. 1. The IBR is regarded as a current source for maximum short-circuit contribution. Considering the small scale of the IBR connected to the grid using grid-forming control, and simulating its characteristics, we temporarily treat it as a voltage source with a specific internal impedance.

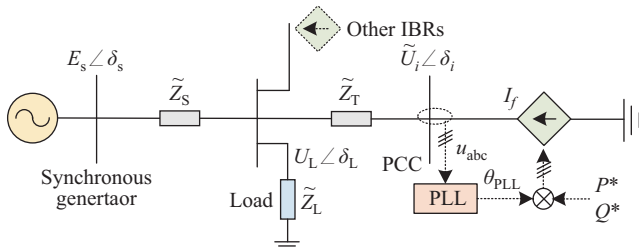


Fig. 1. The system structure of IBR with a grid-following converter.

The derivation of the equivalent model of the practical power system with IBRs is presented in Appendix A. The

voltage vector of buses connected with IBRs is:

$$\tilde{U}_R = \Phi(\tilde{I}_G + \tilde{I}'_G) + \Psi(\tilde{I}_R + \tilde{I}'_R) \quad (4)$$

where $\tilde{I}$ is the injection current vectors, $\tilde{I}'$ is the transformational vector of the connecting and load buses, $\tilde{U}$ is the bus voltage vectors, Φ and Ψ are impedance matrixes, the subscript G denotes SG bus, and R denotes IBR bus.

The element in represents the voltage at the node i :

$$\tilde{U}_i = \sum_k^M \Phi_{ik} \tilde{I}_{G,k} + \sum_k^M \Phi_{ik} \tilde{I}'_{G,k} + \sum_j^N \Psi_{ij} \tilde{I}_{R,j} + \sum_j^N \Psi_{ij} \tilde{I}'_{R,j} \quad (5)$$

where the italic represents the relevant element in the corresponding matrix, $\tilde{U}_i$ is the voltage at node i , M is the number of SGs, and N is the number of IBRs.

The Thévenin equivalent potential at node i reflects the influence of traditional SGs and loads:

$$\tilde{E}_i = \sum_k^M \Phi_{ik} \tilde{I}_{G,k} + \sum_k^M \Phi_{ik} \tilde{I}'_{G,k} + \sum_j^N \Psi_{ij} \tilde{I}'_{R,j} \quad (6)$$

where $\tilde{E}_i$ is the Thévenin equivalent potential of node i .

The final segment on the right signifies the voltage variation induced by the IBRs:

$$\tilde{U}_{d,i} = \sum_{j=1}^N \Psi_{ij} \tilde{I}_{R,j} \quad (7)$$

where $\tilde{U}_{d,i}$ is the voltage variation.

Consequently, following the Thévenin equivalent theory, a single-infeed equivalent model for a complex power system with IBRs is shown in Fig. 2. The variables in the voltage vectors remain unchanged. The expression for the equivalent current injected by all IBRs can be written as:

$$\tilde{I}_{e,i} = \frac{\tilde{E}_i - \tilde{U}_i}{\tilde{Z}_{ii}} \quad (8)$$

where $\tilde{Z}_{ii}$ is the Thevenin equivalent impedance.

Refer to (7), the equivalent current is:

$$\tilde{I}_{e,i} = \sum_{j=1}^N \frac{\Psi_{ij}}{\Psi_{ii}} \tilde{I}_{R,j} = \tilde{I}_{R,i} + \sum_{j \neq i}^N \frac{\tilde{Z}_{ij}}{\tilde{Z}_{ii}} \tilde{I}_{R,j} \quad (9)$$

where $\tilde{Z}_{ii} = \Psi_{ii}$ is the self-impedance, and $\tilde{Z}_{ij} = \Psi_{ij}$ is the mutual impedance. $\tilde{Z}_{ii}$ represents the electrical distance from the AC grid to node i . $\tilde{Z}_{ij}$ indicates the interaction between nodes i and j . $\tilde{I}_{e,i}$ is the equivalent current of node i , and $\tilde{I}_{R,i}$ and $\tilde{I}_{R,j}$ are the inject current provided by IBRs connected to node i and node j , respectively.

2) Calculation Method of MRSCR

The strength assessment for a power system with high IBG penetration considers two characteristics. The first involves calculating short-circuit capacity. According to the dual-infeed model, the short circuit capacity at node i is

$$\tilde{S}_{ac,i} = \frac{U_N \tilde{E}_i}{\tilde{Z}_{ii}} \quad (10)$$

where U_N is the rated voltage at node i .

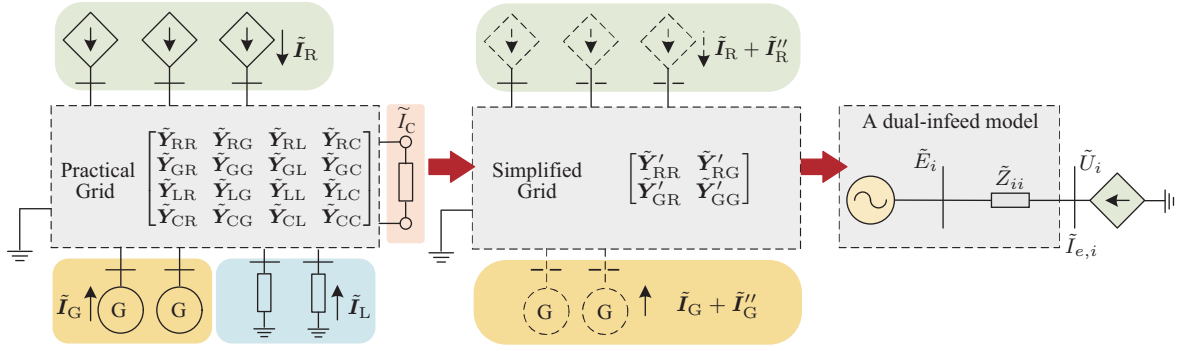


Fig. 2. Steps to establish the single-infeed equivalent model of a practical power system with IBRs.

The other characteristic is the consideration of interaction among IBRs. It includes the power of the IBR directly connected to node i and the influence of other IBRs connected to the remaining nodes:

$$\tilde{S}_{e,i} = \tilde{U}_i \cdot \tilde{I}_{e,i}^* = \tilde{S}_i + \sum_{j \neq i} \omega_{ij} \tilde{S}_j \quad (11)$$

and

$$\omega_{ij} = \frac{\tilde{Z}_{ij}^* \tilde{U}_i}{\tilde{Z}_{ii}^* \tilde{U}_j} \quad (12)$$

where $\tilde{S}_{e,i}$ is the equivalent capacity, ω_{ij} is the multi-infeed interaction factor (MIIF) between the nodes i and j , the asterisk $*$ represents the conjugate operation, and $\tilde{S}_i$ and $\tilde{S}_j$ are the capacities of the equipment connected to nodes i and j .

The MRSCR at node i of the power system with multi-infeed IBRs is:

$$M_{\text{RSCR},i} = \frac{S_{\text{ac},i}}{S_{e,i}} \quad (13)$$

where $M_{\text{RSCR},i}$ is the MRSCR at node i . The equivalent capacity encompasses both the directly connected equipment capacity and the capacity from other feeding equipment, reflecting the mutual influence among multiple feeding units through the MIIF. Additionally, it equals (1) when the system has only a single-infeed IBR because $\tilde{Z}_{ij} = 0$. The MRSCR has the same physical interpretation as the SCR for the single-infeed system.

Comparing the MRSCR in (13) with the SCR in (2), the MSCR in (3) and indexes calculated by equivalent capacity [15], [22], [23], reveals that despite similar expressions, the calculation factors differ significantly, especially in grid matrix establishment. The MRSCR in (13) reflects the influence of network topology, considering the resistance, SG capacity, load size, and total IBR capacity.

3) Considering the Short-circuit Current From IBR

In the event of a short circuit at the point of common coupling (PCC), IBRs might provide a restricted short-circuit current, causing a modification of the short-circuit capacity. By considering the short-circuit current from IBRs, the maximum MRSCR is:

$$M_{\text{RSCR},i} \leq \frac{S_{\text{ac},i} + kU_N I_N}{S_{e,i}} \quad (14)$$

where I_N is the rated current of the IBR at node i , and k is the overcurrent ratio, typically $k \approx 1.1$.

Equation (14) is used to calculate the maximum value, considering the short-circuit current from IBRs. In the presence of large-scale IBRs, the equivalent capacity, considering the impact of multiple inputs, exceeds the short-circuit capacity of the IBR. Consequently, the short-circuit capacity from IBRs has a limited impact and is closely tied to control performance and fault depth. Therefore, it is recommended not to consider these chaotic short-circuit current supports in engineering.

C. Key Factors Affecting System Strength

The characteristics of the power system with high penetration of IBRs differ from those of the multi-infeed LCC-HVDC system. Ignoring the resistance and the reactive power generated by the IBRs may cause errors.

1) Reactive Power Supplied by IBR

With sufficient system strength and successful PLL synchronization, the power flow from the IBR to the grid can be managed. This paper sets the control parameters of the IBR to reasonable values to ensure stable operations. Reactive power control in IBR includes constant reactive power, constant voltage, and constant power factor (PF) control, as depicted in Fig. 3. Fig. 4 depicts the reactive power emitted by IBRs under different control methods, which significantly influences system strength.

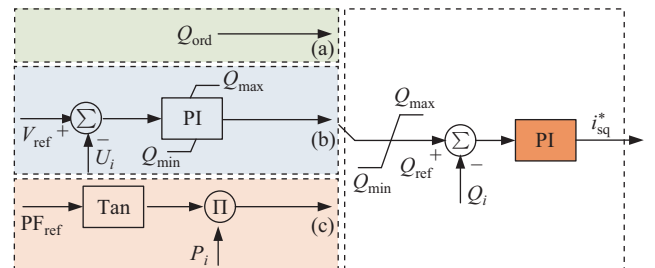


Fig. 3. Control methods for reactive power in IBR: (a) constant reactive power; (b) constant voltage; (c) constant power factor control.

2) System Equivalent Resistance Caused by Load

The presence of an active power load in the system leads to the inevitable generation of equivalent resistance. The load can be simplified into the admittance according to the U - I

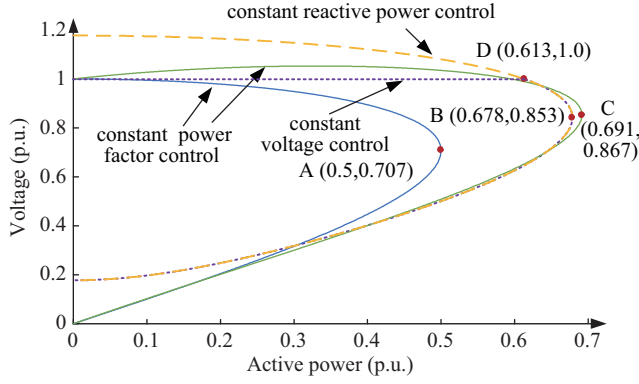


Fig. 4. P-V curves of IBR under different control modes.

characteristic. In Fig. 1, the system's equivalent impedance, considering no other IBRs, as seen from the PCC is:

$$\tilde{Z}_{ii} = \frac{\tilde{Z}_L \cdot \tilde{Z}_S}{\tilde{Z}_L + \tilde{Z}_S} + \tilde{Z}_T \quad (15)$$

where $\tilde{Z}_L = R_L + jX_L$ is the load impedance, $\tilde{Z}_S = R_S + jX_S$ is the system impedance without load, and $\tilde{Z}_T = R_T + jX_T$ is the impedance of the transmission line and transformer.

In various component impedance scenarios, the active load level R_L influences the system impedance ratio at PCC, as depicted in Fig. 5:

$$S_{IR} = \frac{(X_S + X_T)Z_L^2 + (X_T + X_L)Z_S^2 + 2X_T(R_S R_L + X_S X_L)}{(R_S + R_T)Z_L^2 + (R_T + R_L)Z_S^2 + 2R_T(R_S R_L + R_S X_L)} \quad (16)$$

where S_{IR} is the system impedance ratio, and it equals X_{ii}/R_{ii} .

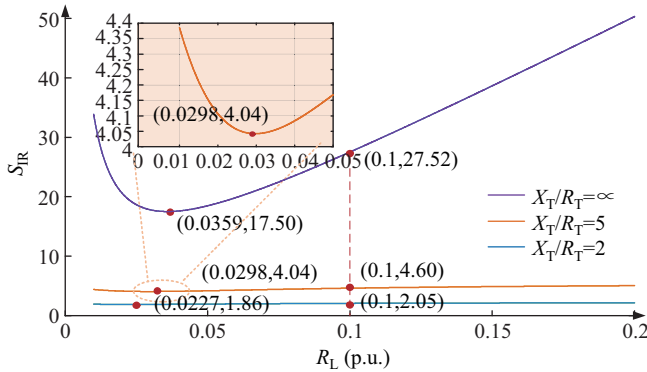


Fig. 5. Analysis of system equivalent impedance characteristics.

There is a relationship between the SCR and system impedance ratio of a critical system [16]:

$$M_{C,i} = 2 - 2 \frac{P_{em,i} + Q_{e,i} S_{IR}}{S_{em,i} \sqrt{1 + S_{IR}^2}} \quad (17)$$

where $M_{C,i}$ represents the MRSCR of node i in a critical system, $P_{em,i}$ is the maximum equivalent active power, $Q_{e,i}$ is the equivalent reactive power, and $S_{em,i}$ is the value of equivalent capacity corresponding to the critical state.

An increase in the load results in higher system equivalent resistance, thereby reducing the system impedance ratio and affecting system strength. The presence of the load increases the system's demand for transmission power from IBRs. Ignoring the influence of the load on resistance and its impact on system strength introduces errors. The MRSCR considers both reactive power and equivalent impedance, thereby enhancing accuracy, which enhances accuracy.

D. A Novel Expression for MRSCR Using Voltage Variation

Equation (13) provides a clear definition of the MRSCR. However, its analysis is challenging due to the numerous variables involved. A novel mathematical equivalent expression, based on voltage variation, is derived for efficient computation. Referring to (11), the MRSCR at node i is reformulated based on the voltage, as it shares the same expression with (13):

$$M_{U,i} = \frac{U_N E_i}{U_{d,i} U_i} \quad (18)$$

where $M_{U,i}$ is the node i in a critical system.

Equation (18) represents MRSCR from the perspective of voltage disturbance after integrating IBRs. This implies that a minor voltage variation indicates a strong system with a large MRSCR, while a large voltage variation indicates a weak system with a small MRSCR. The equation mathematically clarifies that voltage variations are more obvious in weak grids. A smaller MRSCR corresponds to a more considerable impact on voltage stability. Furthermore, (18) serves as the derivation base for CMRSCR.

III. THE CRITICAL INDEX OF MRSCR (CMRSCR)

Once MRSCR is defined, it is reasonable to inquire whether a critical value exists to discern weaknesses in the power system. In this section, CMRSCR will be derived to indicate critical stability. Physically, the disparity between CMRSCR and MRSCR values signifies the voltage stability margin of the power system.

A. Physical Interpretation of IBR Stability Indicated by CMRSCR

Given the impact of IBR control variables, the flow equation for a system in the critical state can be reformulated using the state vector $\mathbf{x}$ and the control vector $\mathbf{u}$:

$$\mathbf{g}(\mathbf{u}, \mathbf{x}) = 0 \quad (19)$$

$$\begin{cases} \mathbf{x} = [\cdots U_i \theta_i \cdots]_{i=1 \dots N} \\ \mathbf{u} = [\cdots P_i Q_i K_{con,i} \cdots]_{i=1 \dots N} \end{cases} \quad (20)$$

where $K_{con,i}$ represents the control parameters of IBRs, U_i is the voltage magnitude, θ_i is the voltage phase-angle.

If there is a small disturbance, a Taylor formula is derived:

$$\mathbf{G}\mathbf{u}_d + \mathbf{J}\mathbf{x}_d = 0 \quad (21)$$

where $\mathbf{G}$ and $\mathbf{J}$ are Jacobian matrices, $\mathbf{u}_d$ and $\mathbf{x}_d$ are the disturbance vector.

If there is a power disturbance, denoted as $P_{d,i}$, and other control parameters remain unchanged, it can be expressed as:

$$\frac{U_{d,i}}{P_{d,i}} = -(\mathbf{J}^{-1}\mathbf{G})_{ii} = -\left[\frac{\mathbf{J}^*}{\det(\mathbf{J})}\mathbf{G}\right]_{ii} \quad (22)$$

In a critical system state where $\det(\mathbf{J}) = 0$, (22) diverges, signifying that even a minor disturbance can lead to voltage collapse. The IBR's stable operation relies on the overall system stability. Using (22), we will deduce the CMRSCR to assess the power system's stability margin.

B. Definition of CMRSCR

Many critical values of the SCR index are empirical, as shown in Table I. The index describing the voltage stability margin has not been thoroughly researched. The simplified model in Fig. 2 enables the study of important phenomena by considering the influence of reactive power and equivalent resistance. The voltage instability point aligns with the maximum power. The critical voltage is:

$$U_{C,i} = \sqrt{\frac{E_i^2}{2} + (P_{e,i}R_{ii} + Q_{e,i}X_{ii})} \quad (23)$$

where $U_{C,i}$ is the magnitude of the critical voltage.

In normal conditions, the voltage drop between the node voltage and the system potential is smaller than the node voltage. As shown in Fig. 4, under maximum power conditions, the voltage drop equals the bus voltage:

$$\begin{cases} U_i > U_{C,i} > U_{d,i}, & P_{e,i} < P_{em,i} \\ U_i = U_{C,i} = U_{d,i}, & P_{e,i} = P_{em,i} \end{cases} \quad (24)$$

Ensuring power system stability requires the necessary condition that MRSCR is larger than CMRSCR. The MRSCR can be conveniently calculated using (18). Thus, the CMRSCR, expressed in terms of voltage, is established as:

$$C_{MRSCR,i} = \frac{U_N E_i}{U_i^2} \quad (25)$$

where $C_{MRSCR,i}$ is the CMRSCR at node i .

The comparison of MRSCR and CMRSCR is:

$$\frac{M_{RSCR,i}}{C_{MRSCR,i}} = \frac{U_i}{U_{d,i}} \quad (26)$$

When comparing MRSCR and CMRSCR, if $U_{d,i} < U_i$, $MRSCR > CMRSCR$, indicating system stability. When $U_{d,i} = U_i$, $MRSCR = CMRSCR$, the system is in a critical state. The CMRSCR serves as the inverse function of the voltage squared, relating to the system's operating state. It addresses the issue of low sensitivity indices as the system approaches the critical state.

C. Maximum Active Power Injected by IBRs

Using this model in Fig. 2, the quadratic equation for U_i^2 is:

$$U_i^4 - [2(P_{e,i}R_{ii} + Q_{e,i}X_{ii}) + E_i^2]U_i^2 + Z_{ii}^2 S_{e,i}^2 = 0 \quad (27)$$

When discriminant of (27) equals 0, the maximum equivalent active power injected by the IBRs is expressed as:

$$P_{em,i} = \frac{R_{ii}(E_i^2 + 2Q_{e,i}X_{ii}) + E_i Z_{ii} \sqrt{E_i^2 + 4Q_{e,i}X_{ii}}}{2X_{ii}^2} \quad (28)$$

The maximum transmitted power varies with different operation plans. The maximum active power of the IBR at node i is determined by isolating the influence of other IBRs:

$$P_{m,i} = P_{em,i} - \Re(S_{e,i} - P_i) \quad (29)$$

where $P_{m,i}$ the maximum transmitted power at node i , $\Re$ represents the calculation of the real part.

Under the same system equivalent impedance level, Fig. 4 shows PV curves of different control modes. Using equipment capacity as the reference, the power factor at the point B is 0.95, with the corresponding maximum power limit under the constant reactive power control as $P_B = 0.678$ p.u. Point C corresponds to constant power factor control at 0.95, with a limit of $P_C = 0.691$ p.u. Point D involves constant voltage control, and upon reaching the reactive power limit, it switches to constant reactive power control. In the three scenarios, the maximum allowable connection scale for the IBR is the smallest with constant reactive power control. In practical engineering, most of the IBRs adopt constant reactive power control ($Q = 0$, corresponding to PF = 1) due to the provision of reactive power compensation equipment. Therefore, we determine the maximum transmission scale based on the PV curve under constant reactive power control.

D. Relationship Between CMRSCR and Other Critical Values.

1) Relationship Between CMRSCR and Critical Values of SCR and MSCR

For a system with a single-infeed IBR, the maximum transmitted power equals the power injected by the IBR. If the Thévenin equivalent resistance and injected reactive power are both 0 according to (28), the critical value can be obtained:

$$U_{C,i} = 0.707E_i \quad (30)$$

By substituting (30) into (25), CMRSCR equals 2. This result aligns with the critical values of SCR or MSCR, as they ignore the impact of resistance and reactive power.

However, 2 is not accurate for power systems with multi-infeed IBRs, and the influence introduced by other IBRs should be considered. Comparing (17) with (25), we have:

$$\frac{C_{MRSCR,i}}{M_{C,i}} = \frac{U_N E_i S_{em,i} Z_{ii}}{2U_i^2 (S_{em,i} Z_{ii} - P_{e,i} R_{ii} - Q_{e,i} X_{ii})} \quad (31)$$

The potential of the critical system is derived from:

$$E_i = \sqrt{2U_{C,i}^2 - 2(P_{e,i}R_{ii} + Q_{e,i}X_{ii})} \quad (32)$$

By substituting (32) into (28), the relationship between the maximum power injected into the AC system and the voltage with critical stability for the node i is:

$$P_{em,i}^2 + Q_{e,i}^2 = \frac{U_{C,i}^4}{Z_{ii}^2} \quad (33)$$

When the system is in a critical state, (32) and (33) are established. Substituting them into (31), it equals 1. However, if the system is not in a critical state, the two indexes differ.

2) Relationship Between CMRSCR and Maximum Active Power

When the system is in a critical state, the MRSCR and CMRSCR can be written as:

$$M_{\text{RSCR},i} = \frac{S_{\text{ac},i}}{\sqrt{P_{\text{em},i}^2 + Q_{\text{e},i}^2}} \quad (34)$$

$$C_{\text{MRSCR},i} = \frac{U_{\text{N}} E_i}{U_{\text{C},i}^2} \quad (35)$$

By substituting (33) to (35), the relationship between the maximum power injected into the AC system and the CMRSCR for the node i is:

$$C_{\text{MRSCR},i} = M_{\text{RSCR},i} = \frac{U_{\text{N}} E_i}{Z_{ii} \sqrt{P_{\text{em},i}^2 + Q_{\text{e},i}^2}} \quad (36)$$

Thus, the CMRSCR corresponds to the critical state including the information of the maximum transmission power.

3) Relationship Between CMRSCR and the Critical Value of SDSCR

The SDSCR [15] is proposed based on the Jacobian matrix,

which equals 0 when the voltage is at a critical stable state.

$$S_{\text{SDSCR},i} = \frac{U_i^2 / Z_{ii}}{\left| P_i + \sum_{j=1, j \neq i}^N \frac{\tilde{Z}_{ij}}{\tilde{Z}_{ii}} \left(\frac{\tilde{U}_i}{\tilde{U}_j} \right)^* P_j \right|} \quad (37)$$

The minimal SDSCR represented by r [15] is:

$$r = \frac{U_{\text{C},i}^2}{Z_{ii} S_{\text{e},i}} = 1 \quad (38)$$

It is the same as (33). Thus, the CMRSCR is consistent with r . The comparison between (38) and (25) is the same as the comparison between (37) and (13) when not considering the reactive power output by IBRs:

$$\frac{C_{\text{MRSCR},i}}{r} = \frac{U_{\text{N}} E_i}{U_{\text{C},i}^2} \quad (39)$$

The r equals the CMRSCR when the node voltage is always the rated voltage. Considering scenario as (30), when R_{ii} and $Q_{\text{e},i}$ equal 0, $C_{\text{MRSCR},i} = 2r$.

E. A Procedure of the Strength Assessment

The flow chart of the strength assessment procedure is shown in Fig. 6. The strength evaluation procedure, based on the criterion that the MRSCR exceeds the CMRSCR, is as follows:

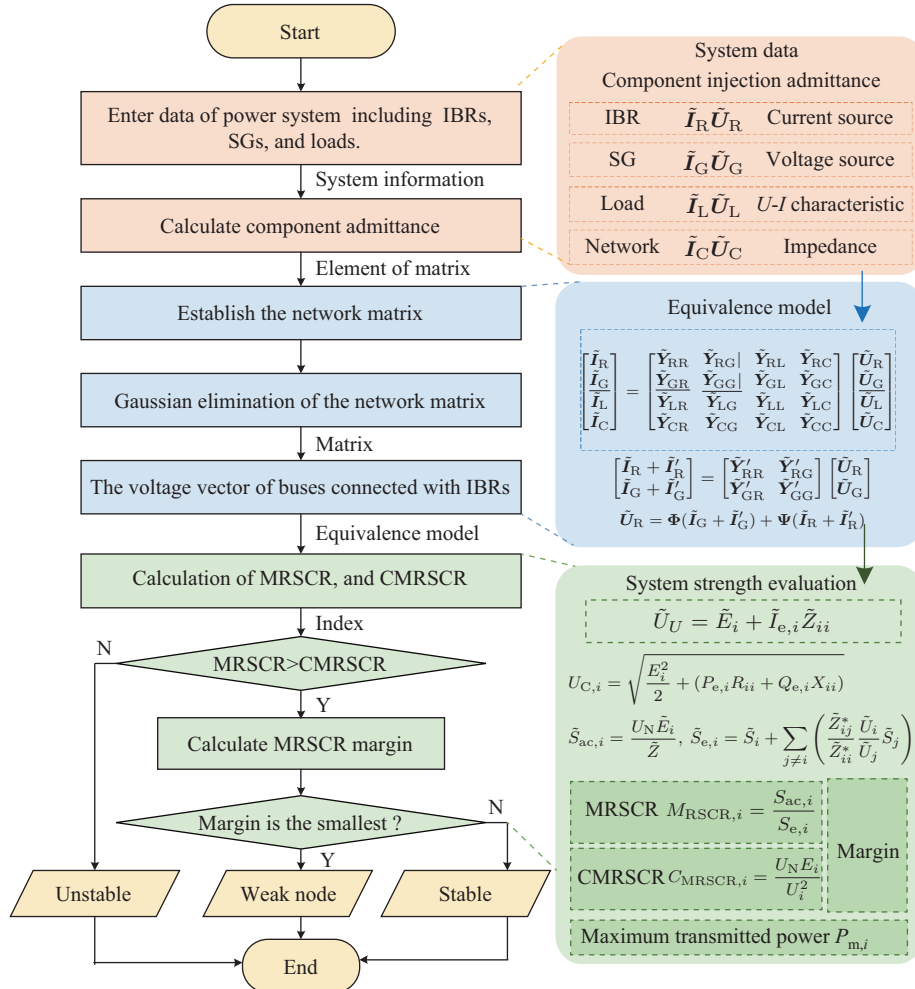


Fig. 6. The flow chart of the strength assessment procedure.

- 1) Prepare data for various integration schemes in the IBR-equipped system.
- 2) Calculate the network matrix.
- 3) Compute MRSCR and CMRSCR for these schemes.
- 4) Assess the system strength of different integration schemes. If all nodes meet the $\text{MRSCR} > \text{CMRSCR}$ criterion, further validation via voltage analysis may be employed to assess potential stability. If any node exhibits MRSCR less than or equal to CMRSCR, IBRs are likely to operate unstably and require additional electromagnetic validation.

5) For nodes meeting the $\text{MRSCR} > \text{CMRSCR}$ criterion, calculate the margin ($\text{MRSCR} - \text{CMRSCR}$) to evaluate the stability margin. A larger margin indicates greater stability.

The proportion of grid-forming converters is expected to increase in the near future. The nodal network matrix incorporating grid-forming converters can be derived using Gaussian transformation after comprehensive analysis and verification of the impedance model's characteristics, as grid-forming converters simulate the behavior of SGs. Therefore, this method is applicable to hybrid systems comprising both grid-following and grid-forming converters.

IV. CASE STUDIES

The MRSCR is the integral component of the short-circuit current calculation program (SCCP) in the PSD power tools (PSD) and power system analysis software package (PSASP) developed by CEPRI. It is widely used in bulk power system engineering projects across China for calculation and analysis. This study validates the effectiveness of MRSCR and CMRSCR in identifying critical states and comparing them with practical indexes such as SCR, WSCR, and MSCR. Additionally, two contingency cases and a practical engineering case are presented to validate the practicality of the proposed indexes.

A. Analysis of Stability Boundaries

Utilizing the IEEE 39 case system [21], we establish a power system integrated with IBRs, as depicted in Fig. 7. The SGs at nodes 30, 37, 38, and 39 are replaced with IBRs. The outputs of IBRs differ between Case A and Case B, with Case B emphasizing the influence of reactive power on system strength. The parameters are specified in Table II.

Taking node 39 as an example, the power of IBRs at Nodes 30, 37, and 38 remains constant while progressively increasing the power of IBR at Node 39 until the collapse point is reached. The proposed MRSCR is tested and compared with SCR, WSCR, and MSCR in Fig. 8. The error of the indexes is calculated as the ratio of the absolute error of the measurement to the true value. A positive error indicates that the measurement result is greater than the true value, while a negative error indicates the opposite. The magnitude of the error reflects the degree of deviation of the measurement result from the true value.

In Fig. 8(a), the collapse point occurs at a maximum power of 1219.3 MW, with a critical voltage of 0.899 p.u. The results of the maximum active power calculated by (29) are presented in Table III. Using the continuous power flow method, the

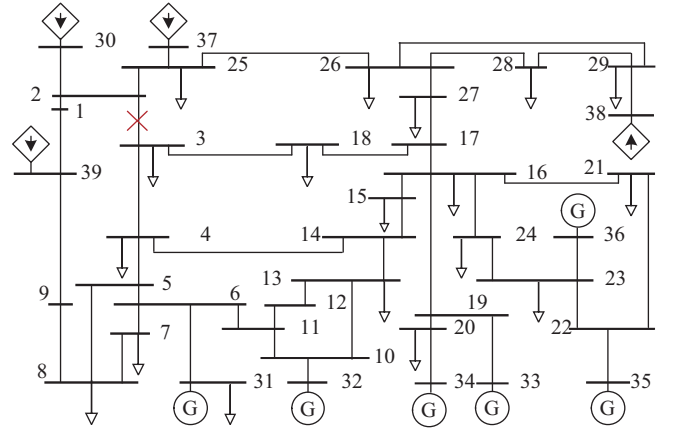


Fig. 7. System structure of IEEE 39 case.

TABLE II
IEEE 39 CASE PARAMETERS

Case	Node	P (MW)	Q (MVar)	$\bar{Z}_{ii}$ (p.u.)
A	30	200	0	$0.015+j0.045$
	37	300	0	$0.019+j0.052$
	38	400	0	$0.033+j0.069$
	39	600	0	$0.017+j0.054$
B	30	250	50	$0.015+j0.045$
	37	540	100	$0.019+j0.052$
	38	830	0	$0.033+j0.069$
	39	300	120	$0.017+j0.054$

TABLE III
MAXIMUM ACTIVE POWER AT NODE 39 IN IEEE 39 CASE (MW)

Case	Calculation value	Simulation value by CPF	Error (%)
A	1219.3	1219.1	0.016
B	1177.2	1176.1	0.094
C	996.1	998.7	-0.260

maximum active power injected to Node 39 is 1219.1 MW. The error between the calculation and the CPF is 0.016%. The MRSCR decreases with increasing power, as shown in Fig. 8(b). As the system approaches a critical state, the rate of voltage variation increases. Since SCR is the inverse function of power, using a constant value as a criterion result in a reduction in the rate of change of short-circuit margin. Unlike a constant value, the margin between MRSCR and CMRSCR is more sensitive to power evolution.

Additionally, the MRSCR calculated by (13) equals the M_U calculated by (18). At the critical point, the margin between MRSCR and CMRSCR equals zero, as illustrated in Fig. 8(c). The precise values of these indexes corresponding to the critical state are presented in Table IV. MRSCR and CMRSCR are more accurate than other indexes in indicating the critical stable condition, with minimal error between them at the collapse point. Fig. 8(d) and (e) reveal that MSCR and WSCR tend to underestimate the system strength as they are smaller than their critical values. Meanwhile, in Fig. 8(f), SCR tends to overestimate the system strength initially but ultimately underestimates it.

Case B is introduced to explore the scenario where the IBR provides reactive power. The analysis results by the MRSCR are depicted in Fig. 8(g) to (i), maintaining the same active

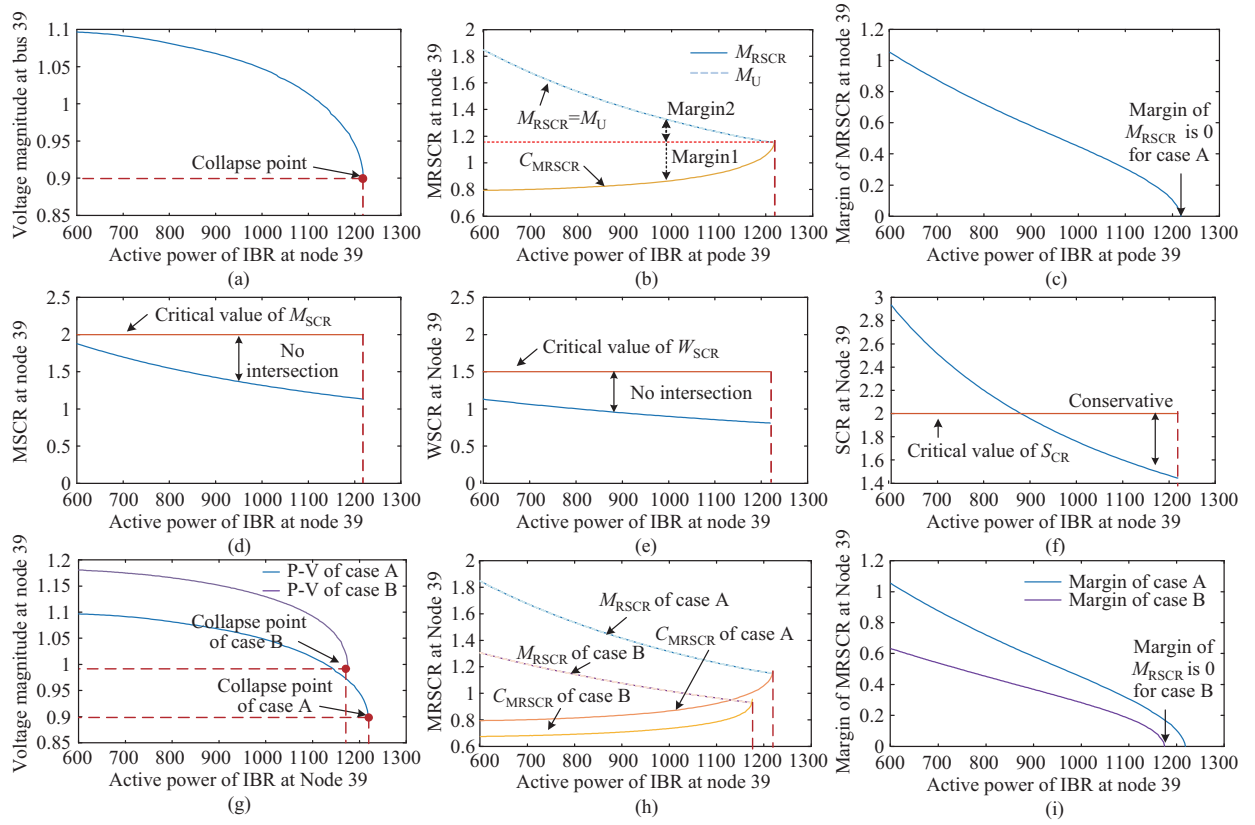


Fig. 8. Analysis results at Node 39 with increased active power: (a) voltage magnitude of Case A; (b) MRSCR, M_U , and C_{MRSCR} of Case A; (c) MRSCR margin of Case A; (d) MSCR of Case A; (e) WSCR of Case A; (f) SCR of Case A; (g) voltage magnitude comparison (Case A vs. Case B); (h) MRSCR, M_U , and C_{MRSCR} comparison (Case A vs. Case B); (i) MRSCR margin comparison (Case A vs. Case B).

TABLE IV
INDEX RESULTS IN THE CRITICAL STATE OF IEEE 39 CASE

Case	Index	Index value	Critical value	Error (%)
A	MRSCR	1.1540	1.1539	0.009
	SCR	1.4444	2	-27.8
	MSCR	1.1325	2	-43.4
	WSCR	0.8106	1.5	-18.9
B	MRSCR	0.9284	0.9279	0.054
	SCR	1.4825	2	-25.9
	MSCR	0.9782	2	-51.1
	WSCR	0.5876	1.5	-60.8
C	MRSCR	1.0530	1.0529	0.010
	SCR	1.5321	2	-23.4
	MSCR	1.0566	2	-47.2
	WSCR	0.7404	1.5	-50.6

power increase as in Case A. The two cases exhibit different operational states corresponding to distinct P-V curves. According to the continuous power flow simulation, the maximum active power at Node 39 is 1176.1 MW. Concurrently, the maximum active power calculated by (29) is 1177.2 MW, presented in Table III. The error between the calculation and simulation is 0.094%. Aligned with the critical state, the precise values of SCR, MSCR, WSCR, and MRSCR are detailed in Table IV. This reaffirms the accuracy of MRSCR and C_{MRSCR} when assessing the strength, considering the reactive power of IBRs.

B. Contingency Case

Case C demonstrates the application of MRSCR in a con-

tingency state with an outage of lines 2–3, as illustrated in Fig. 7. Comparisons between basic Case A and contingency Case C, including the P-V characteristic, MRSCR indices, and the margin of MRSCR, are presented in Fig. 9. The stability boundary of Node 39 retreats from the position in Case A. As indicated in Table III, the maximum power that can be transmitted decreases from 1219.1 MW to 998.7 MW. OP2 represents the collapse state of the contingency case. The values of MRSCR, SCR, MSCR, and WSCR for Node 39 are detailed in Table IV. In contrast, other indices exhibit significant errors. When the power of Node 39 is 996 MW, the voltage at Node 39 is 0.949 p.u., as shown in Fig. 9(a). The combination of MRSCR and C_{MRSCR} accurately detects the critical state, as depicted in Fig. 9(b) and (c).

Transmission outages are temporal network modifications that may weaken the MRSCR at the interconnection point. Considering additional power output changes, we further verify the stability boundary of Case C at OP2. A power disturbance of 0.1 p.u. lasting 0.4 s leads to voltage collapse, as shown in Fig. 9(d). The existence of an equilibrium point, a prerequisite for stable system operation as derived from (22), is confirmed. Interestingly, reducing Node 39's output to 900 MW from its original operation maintains stability under the same disturbance.

Weak systems are more prone to instability following disturbances. In Case A, the output of Node 39 can reach 1219 MW at OP1 in Fig. 9(a). In the event of an outage on lines 2–3

at 2 s, as shown in Fig. 9(e), a voltage collapse occurs in a system with the original state at OP1. Calculating the MRSCR considering the outage of lines 2–3, the maximum output of bus 39 for Case C is only 996 MW at OP2. The system remains stable when the output of Node 39 is 970 MW during the outage of lines 2–3. Therefore, a comprehensive and accurate preliminary assessment by MRSCR would be beneficial.

C. Practical Case for Identifying Weak Nodes

This case illustrates the practical application of SCCP in identifying vulnerable nodes in the ZB region.

Figure 10 illustrates the structure and parameters of the ZB

area. The system structure is simplified for security reasons. IBRs integrated into a PCC operate consistently. Table V presents the rated installed capacity, MRSCR, CMRSCR, and margin. ZP1 exhibits the smallest MRSCR margin, indicating it as the weak node prone to voltage instability. Subsequently, the static voltage analysis of ZP1 is conducted through continuous power flow simulation, as shown in Fig. 11. The fundamental application of SCCP is effective in identifying weak nodes for practical engineering analysis. The capacity represents the rated capacity to illustrate P-V curves ranging from 1 p.u. for different IBRs. This confirms ZP1 as the weakest node.

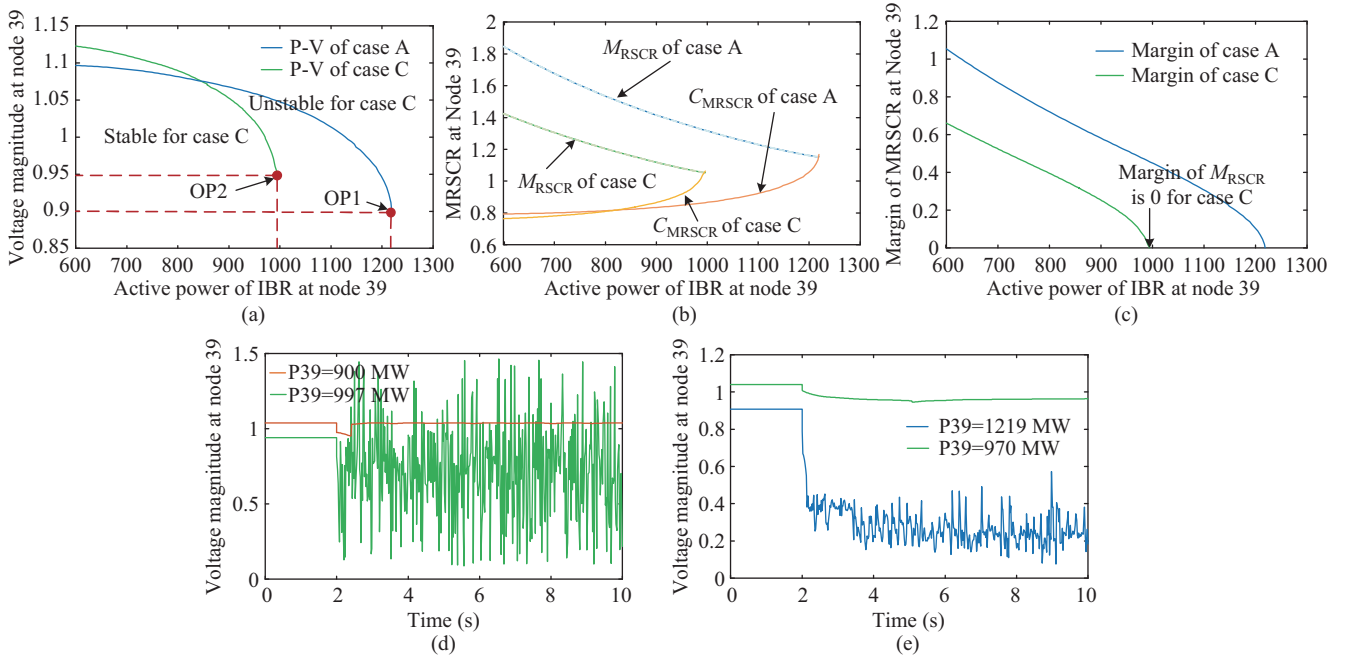


Fig. 9. Analysis results at Node 39 in contingency case. (a) Voltage magnitude comparison. (b) M_{RSCR} , M_U , and C_{MRSCR} comparison. (c) M_{RSCR} margin comparison. (d) Node voltage variation with power disturbance. (e) Bus voltage variation with line 2–3 outage.

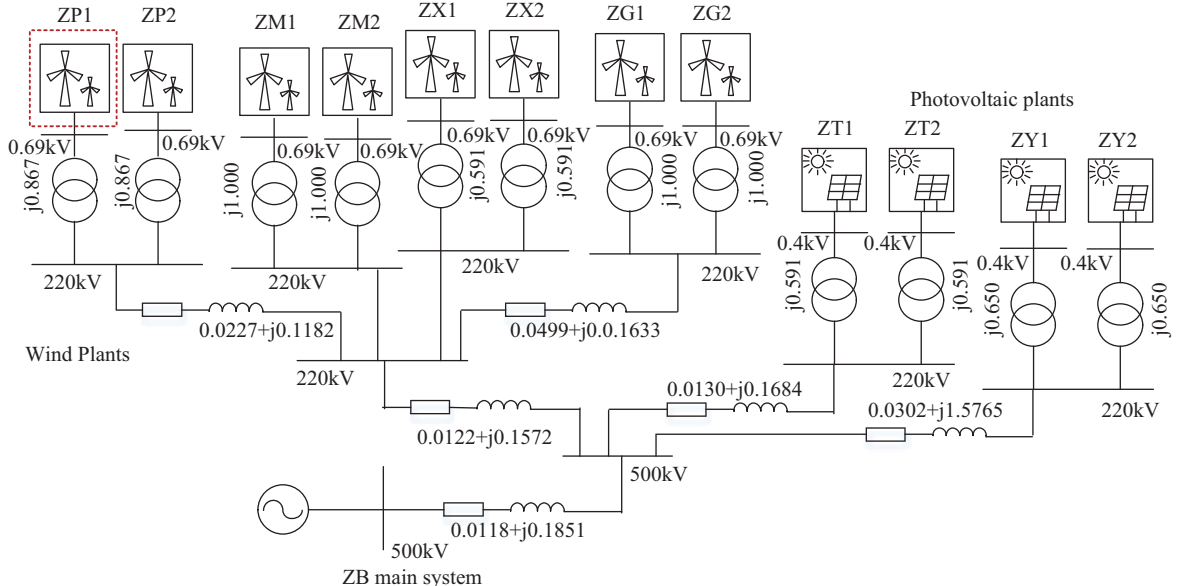


Fig. 10. The system structure of ZB renewable energy area.

TABLE V
THE MRSCR AND CMRSCR CALCULATED BY SCCP

Node	Rated active power (MW)	MRSCR	CMRSCR	Margin
ZP1	75	1.912	1.656	0.256
ZM1	50	2.894	1.831	1.063
ZX1	50	2.851	1.832	1.019
ZG1	25	2.331	1.742	0.590
ZT1	50	3.283	1.856	1.427
ZY1	50	3.408	1.957	1.451

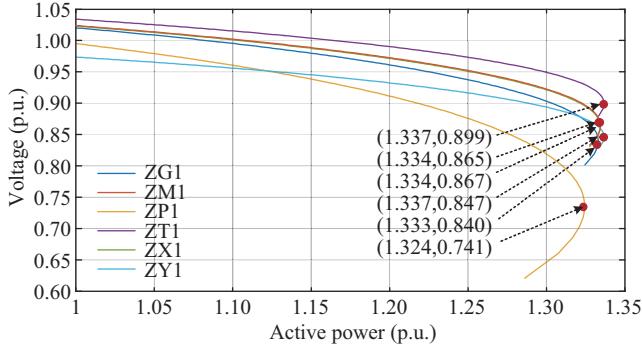


Fig. 11. The weak node location analyzed by CPF simulation.

Moreover, when MRSCR equals CMRSCR according to (29), the maximum transmitted power of ZP1 is 96.2 MW. In the simulation, it is 99.3 MW in the critical state. The error in the maximum active power between calculation and simulation is 3.1%. SCCP application remains valid in weak node analysis for practical engineering.

V. CONCLUSION

This paper introduces MRSCR and CMRSCR indexes, derived from an equivalent single-infeed model, for evaluating the comparative strength between the power system and integrated IBRs. The equivalent expressions of MRSCR, illustrating voltage variation with IBR power fluctuations, facilitate fast analysis. Furthermore, the difference between MRSCR and CMRSCR describes the system stability margin. Subsequently, we propose a procedure to evaluate the comparative strength of a power system with high IBR penetration using the suggested indexes. Improved the issue of difficulty in identification when the system approaches the critical state due to the excessively small change in indicators. Case studies validate the effectiveness of the proposed comparative system strength evaluation indexes. This demonstrates that MRSCR is effective not only for assessing comparative strength between the power system and integrated IBRs but also for indicating the system's static voltage stability and identifying weak nodes. The proposed indices can compare and optimize different schemes for IBR plans.

APPENDIX

A. Derivation of the Equivalent Model of the Practical Power System

In a real power system, there are numerous Inverter-based resources (IBRs), synchronous generators (SGs), and loads.

When analyzing and selecting a connection node, a single-infeed model can be established using Gaussian elimination of the network matrix. The key factors are formulated as follows.

The load can be simplified to the admittance based on the voltage-current relationship:

$$\tilde{y}_L = \tilde{S}_L^* / U_L^2 \quad (A1)$$

where $\tilde{y}_L$ represents the admittance, $\tilde{S}_L$ represents the load power, and U_L represents the voltage of the load bus.

In the system, the injection current at each node is the sum of the power supply current and the load current. The injection current at some connecting buses is zero. To account for the impact of IBRs, the grid matrix is established using the admittance matrix:

$$\begin{bmatrix} \tilde{I}_R \\ \tilde{I}_G \\ \tilde{I}_L \\ \tilde{I}_C \end{bmatrix} = \begin{bmatrix} \tilde{Y}_{RR} & \tilde{Y}_{RG} & \tilde{Y}_{RL} & \tilde{Y}_{RC} \\ \tilde{Y}_{GR} & \tilde{Y}_{GG} & \tilde{Y}_{GL} & \tilde{Y}_{GC} \\ \tilde{Y}_{LR} & \tilde{Y}_{LG} & \tilde{Y}_{LL} & \tilde{Y}_{LC} \\ \tilde{Y}_{CR} & \tilde{Y}_{CG} & \tilde{Y}_{CL} & \tilde{Y}_{CC} \end{bmatrix} \begin{bmatrix} \tilde{U}_R \\ \tilde{U}_G \\ \tilde{U}_L \\ \tilde{U}_C \end{bmatrix} \quad (A2)$$

where the bold variables represent matrices or vectors, $\tilde{I}$ represents the injection current, $\tilde{U}$ represents the bus voltage, $\tilde{Y}$ represents the admittance matrix, the subscript G denotes the SGs bus, R denotes the IBR bus, C denotes the connecting bus, and L denotes the load bus.

By applying Gaussian elimination, (A2) can be simplified into a system where all connecting and load buses are eliminated, retaining all IBRs and SGs:

$$\begin{bmatrix} \tilde{I}_R + \tilde{I}'_R \\ \tilde{I}_G + \tilde{I}'_G \end{bmatrix} = \begin{bmatrix} \tilde{Y}'_{RR} & \tilde{Y}'_{RG} \\ \tilde{Y}'_{GR} & \tilde{Y}'_{GG} \end{bmatrix} \begin{bmatrix} \tilde{U}_R \\ \tilde{U}_G \end{bmatrix} \quad (A3)$$

where

$$\begin{bmatrix} \tilde{I}'_R \\ \tilde{I}'_G \end{bmatrix} = - \begin{bmatrix} \tilde{Y}_{RL} & \tilde{Y}_{RC} \\ \tilde{Y}_{GL} & \tilde{Y}_{GC} \end{bmatrix} \begin{bmatrix} \tilde{Y}_{LL} & \tilde{Y}_{LC} \\ \tilde{Y}_{CL} & \tilde{Y}_{CC} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{I}_L \\ \tilde{I}_C \end{bmatrix} \quad (A4)$$

and

$$\begin{bmatrix} \tilde{Y}'_{RR} & \tilde{Y}'_{RG} \\ \tilde{Y}'_{GR} & \tilde{Y}'_{GG} \end{bmatrix} = \begin{bmatrix} \tilde{Y}_{RR} & \tilde{Y}_{RG} \\ \tilde{Y}_{GR} & \tilde{Y}_{GG} \end{bmatrix} - \begin{bmatrix} \tilde{Y}_{RL} & \tilde{Y}_{RC} \\ \tilde{Y}_{GL} & \tilde{Y}_{GC} \end{bmatrix} \begin{bmatrix} \tilde{Y}_{LL} & \tilde{Y}_{LC} \\ \tilde{Y}_{CL} & \tilde{Y}_{CC} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{Y}_{LR} & \tilde{Y}_{LG} \\ \tilde{Y}_{CR} & \tilde{Y}_{CG} \end{bmatrix} \quad (A5)$$

Equation (A3) describes a system that all the connecting and load buses have been eliminated, and all IBRs and SGs are retained. The voltage vector of buses connected with IBRs is:

$$\tilde{U}_R = \Phi(\tilde{I}_G + \tilde{I}'_G) + \Psi(\tilde{I}_R + \tilde{I}'_R) \quad (A6)$$

The components Φ and Ψ in the voltage vector are:

$$\begin{cases} \Phi = [\tilde{Y}'_{GR} - \tilde{Y}'_{GG} \tilde{Y}'_{RG}{}^{-1} \tilde{Y}'_{RR}]^{-1} \\ \Psi = -[\tilde{Y}'_{GR} - \tilde{Y}'_{GG} \tilde{Y}'_{RG}{}^{-1} \tilde{Y}'_{RR}]^{-1} \tilde{Y}'_{GG} \tilde{Y}'_{RG}{}^{-1} \end{cases} \quad (A7)$$

Using the voltage-current relationship, the load admittance model is established, with the SGs acting as the voltage source. The node impedance matrix of the system is formulated, reflecting the influence of these two parameters on the system's equivalent impedance and equivalent potential through matrix transformation.

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