A Review of System Strength Metrics for Inverter-based Power Systems

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***Abstract*—The increasing share of inverter-based resources (IBRs) in electrical power systems is causing a range of challenges related to maintaining power system stability. It is computationally challenging and time-intensive to evaluate the stability of power systems with high IBR penetration levels through time-domain simulation or small-signal analysis. Therefore, system strength metrics capable of screening systems for potential stability issues are valuable. The conventional grid strength metric, Short-Circuit Ratio (SCR), has proven useful. However, it is inaccurate when applied to power systems with high IBR penetration. To resolve this issue, a range of new metrics aimed at quantifying system strength have been proposed in the literature. In this paper, we provide a unified taxonomy and comparative evaluation of system strength metrics applicable to IBR-dominated power systems, identifying key limitations in their capabilities and future directions for system strength metric development.**

***Index Terms*—Grid strength, inverter-based resource, power system stability, short-circuit ratio, system strength.**

I. Introduction

Electrical power systems are seeing a significant increase in generation from inverter-based resources (IBRs), such as wind, photovoltaics, and battery-energy storage [1]. The development of IBRs is outpacing that of conventional synchronous generators (SGs), leading to power grids that are more reliant on IBRs than ever before. This increasing IBR penetration has brought a range of challenges for system operators and developers. One key challenge is to ensure power systems remain stable as IBR penetration increases.

The ability of power systems to maintain stable voltage and frequency under disturbances can broadly be referred to as system strength. The large-scale integration of IBRs with conventional grid-following (GFL) control has led to a decrease in the strength of the grid. IBRs and weak grids are associated with stability challenges such as subsynchronous oscillations [2], which have been observed in power systems repeatedly over the past decade.

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Metrics that reflect the strength of the grid have traditionally been used in offline planning studies to screen for weak system areas and identify potential instability issues. This is particularly important when new IBRs are connected to the grid. Electromagnetic transient (EMT) simulations can be used to assess their impact on grid stability, but these simulations can be computationally and time intensive. In operations, real-time monitoring of these metrics is becoming a priority for ISOs and utilities to identify stability margins, enabling operators to implement preemptive mitigating actions to maintain grid stability and improve system robustness. Therefore, there is a demand for metrics that can both be used to identify weak areas of the grid to focus EMT studies and serve as online indicators of grid strength [3]. Accessible and intuitive system strength metrics are essential for the reliable deployment and operation of systems with high levels of IBRs. However, the current literature lacks a clear consensus on which metric best characterizes system strength in such systems.

In this paper, we first discuss the concept of system strength in Section II. Then, we introduce a range of system strength metrics in Section III and categorize them as fault-current based or admittance-model based metrics. Section IV compares these metrics and Section V identifies gaps in existing metrics' capabilities and future directions for metric development. Finally, Section VI concludes the paper.

II. System Strength

System strength refers to the ability of an AC power system to maintain stable voltage and frequency under all operating conditions [4]. In the specific context of voltage stability, it relates to the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance [5]. In a strong system the sensitivity of the voltage to system disturbances is low, while in a weak system this sensitivity is higher. Areas identified as having a low system strength are more susceptible to instability [6]. With increasing IBR penetration, traditional boundaries in timescales used to decouple stability analysis of voltage and frequency are becoming less distinct and both mechanisms are increasingly influenced by faster dynamics [7]. Reflecting this, the term system strength has progressively come to encompass broader ideas of system stability over the years [8]. The work

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in [9] proposes a new classification of system strength: steady-state system strength and dynamic-state system strength. Specifically, steady-state system strength deals with operation around nominal operating values, while dynamic-state system strength deals with stability of the system when subject to large disturbances. In this paper, we focus on existing system strength metrics relating to the stability of the system when operating in steady-state and subject to small disturbances.

It is worth noting that the terms system strength and grid strength are often used interchangeably [3], [9]–[11]. However, we propose that these two terms relate to different insights. System strength refers to the stability of the whole system composed of the IBR devices and the power network, while grid strength refers to the sensitivity of the grid based only on the network characteristics. For example, Short-circuit Ratio (SCR) is a metric commonly used to quantify grid strength in terms of voltage stability [11], [12]. SCR is defined as

$$\mathrm{SCR} := \frac{S_{\mathrm{SCMVA}}}{P_{\mathrm{RMW}}}, \tag{1}$$

where S_{SCMVA} denotes the short-circuit apparent power at a point of interconnection (POI); P_{RMW} represents the rated power of the connected IBR device. Typically, an SCR greater than 3 implies a strong grid, an SCR between 2 and 3 implies a weak grid, and an SCR below 2 indicates a very weak grid [13]. However, a low SCR does not necessarily imply an IBR connected at that POI will be unstable. To evaluate the system strength in terms of its stability, both the power network and device dynamics need to be considered. Thus, the SCR needs to be compared with its critical value, i.e., the critical short-circuit ratio ($\mathrm{SCR}_{\mathrm{crit}}$), which depends on IBR device dynamics, control mode, control parameters, and dispatch. The system is considered stable when $\mathrm{SCR} > \mathrm{SCR}_{\mathrm{crit}}$ and unstable when $\mathrm{SCR} < \mathrm{SCR}_{\mathrm{crit}}$. The difference between these two values can be referred to as the stability margin.

III. System Strength Metrics

SCR can not capture interactions between an IBR device and the rest of the system including other IBRs. When multiple IBRs are connected to a power system electrically close to each other, the short-circuit level of the system in that area is shared between the IBRs. This results in the grid strength being significantly less than the SCR calculated for a single one of these IBRs would imply [4]. Further, conventional GFL inverters are prone to instability in weak grids, while grid-forming (GFM) inverters are prone to instability when connecting to strong grids [14]. Thus, applying conventional SCR to systems with high IBR penetrations can lead to inaccurate measures of system strength. This section provides an overview of other system strength metrics proposed in the literature to address this challenge.

In the literature, system strength metrics can generally be categorized into two groups: fault-current based metrics and admittance-model based metrics. Fault current based metrics are defined using short-circuit fault currents. To determine the system strength with these metrics, their value must be compared to its critical value. Industry experience informs approximate ranges for critical values, but their true critical value must be found through EMT simulation. This has led to recent efforts to develop metrics based on admittance models. Admittance-model based metrics use equivalent frequency-domain admittance/impedance models of devices and the power network in their formulation which capture the small-signal characteristics of the system around a steady-state operating point through frequency-domain analysis.

A. Fault-current based Metrics

1) Weighted Short-circuit Ratio: The Weighted Short-Circuit Ratio (WSCR) [15]- proposed by the Electric Reliability Council of Texas (ERCOT) - is found by assuming the electrical distance between IBRs can be ignored but interactions between these devices must be considered. It is defined as

$$\mathrm{WSCR} := \frac{\sum_i^{N_{\mathrm{IBR}}} S_{\mathrm{SCMVAi}} \cdot P_{\mathrm{RMW},i}}{\left(\sum_i^{N_{\mathrm{IBR}}} P_{\mathrm{RMW},i}\right)^2}, \tag{2}$$

where the subscript i indicates the value relating to the i-th of the N_{IBR} IBRs. This approach provides a conservative measure of SCR for the aggregated group of IBRs.

2) Composite Short-circuit Ratio: The Composite Short-Circuit Ratio (CSCR) [16] - proposed by General Electric (GE) - assumes the IBRs of interest are electrically close and connects them all to a common bus while neglecting their electrical distance. The short-circuit MVA at this common bus excluding current contributions from IBRs, S_{CSCMVA}, is then calculated. CSCR is defined as

$$\mathrm{CSCR} := \frac{S_{\mathrm{CSCMVA}}}{\sum_i^{N_{IBR}} P_{\mathrm{RMW},i}}. \tag{3}$$

3) Equivalent Short-circuit Ratio: To account for the electrical distances between IBR devices, the Equivalent Short-Circuit Ratio (ESCR) - also referred to as SCR with interaction factors (SCRIF) [11] - is introduced in [17]. ESCR uses interaction factors defined as the observed change in the voltage at bus i for a given change in voltage at bus j, $IF_{ij} = \Delta V_i / \Delta V_j$, to determine the level of interaction between IBRs. ESCR is defined as

$$\mathrm{ESCR}_i := \frac{S_{\mathrm{SCMVA},i}}{P_{\mathrm{RMW},i} + \sum_j (IF_{ji} \cdot P_{\mathrm{RMW},j})}. \tag{4}$$

ESCR gives a value at each bus, which differs from WSCR and CSCR that provide a single value for an area.

4) Site-Dependent Short-circuit Ratio: The Site-Dependent Short-circuit Ratio (SDSCR) [18] considers how the IBRs in a multi-infeed system interact through their power injections. In deriving this metric the authors define the equivalent power injection at bus i, using Thevenin equivalent models, as $S_{\mathrm{eq},i} = P_{\mathrm{RMW},i} + \sum_{j \neq i} P_{\mathrm{RMW},j} \cdot w_{ij}$ where the power injections from other IBRs are considered through the interaction factor $w_{ij} = \frac{Z_{\mathrm{RR},ij}}{Z_{\mathrm{RR},ii}} \left(\frac{V_{\mathrm{R},i}}{V_{\mathrm{R},j}}\right)^*$, which depends on the ratio of the electrical distances and the ratio of the bus voltages of the i-th and j-th IBR resource. Using the static voltage stability

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limit and combining it with the change in voltage due to the equivalent power injection, SDSCR is then defined as

$$\text{SDSCR}_i := \frac{|V_{\text{R},i}|^2}{|S_{\text{eq},i}||Z_{\text{RR},ii}|}. \tag{5}$$

SDSCR measures the system strength in terms of the distance to the static voltage stability limit of each bus; when SDSCR_i is smaller than 1, there is a heightened risk of voltage stability.

5) Inverter Penetration Short-circuit Ratio: The Inverter Penetration Short-circuit Ratio (IPSCR) [19] - proposed by Electranix - is calculated solely using fault infeed data from short-circuit analysis and does not require the calculation of interaction factors. IPSCR is defined at each bus as the ratio of the short-circuit apparent power provided by conventional generators to that provided by IBRs:

$$\text{IPSCR}_i := \frac{S_{\text{SCMVA,SG},i}}{S_{\text{SCMVA,IBR},i}}, \tag{6}$$

where $S_{\text{SCMVA,SG},i}$ and $S_{\text{SCMVA,IBR},i}$ are the short-circuit powers evaluated on bus i with all IBRs turned off and with conventional generators turned off, respectively. In the IBR only case, each IBR's source impedance is adjusted until it contributes 1 p.u. S_{SCMVA} at its POI based on its rated capacity. This approach naturally considers IBR electrical distances and their power injection interactions.

6) Normalized Short-circuit Ratio: Taking into consideration the impact that the power dispatch, control parameters, and control mode can have on the stability margin of an IBR, the Normalized Short-circuit ratio (NSCR) [20] is defined based on the stability margin found from comparing SCR to the critical SCR value of an IBR. NSCR is defined at bus i as

$$\text{NSCR}_i := \frac{\text{SCR}_i - \text{SCR}^{\min}_{\text{crit},i}}{\text{SCR}^{\max}_{\text{crit},i} - \text{SCR}^{\min}_{\text{crit},i}} \tag{7}$$

where $\text{SCR}^{\min}_{\text{crit},i}$ and $\text{SCR}^{\max}_{\text{crit},i}$ are the minimum and maximum critical SCR values for the IBR connected at bus i as its active power dispatch varies from $0.0 \to 1.0$ p.u. These critical SCR values are obtained through EMT simulations or small-signal analysis based on a single-machine/IBR infinite-bus system.

B. Admittance-model based Metrics

1) Generalized SCR: A natural extension of SCR to a multi-infeed system that reflects the interaction of IBRs led to the definition of generalized SCR (gSCR) in [21]. The approach is based on dividing the IBR system into decoupled subsystems using eigenvalue decomposition and then focusing on the weakest of these subsystems. Later studies have linked gSCR to small-signal stability [22], addressed heterogeneous IBR control [23], and considered GFM IBRs [24]. The gSCR value can be calculated from the steady-state system values as

$$\text{gSCR} := \min_{i=1,..,n_{\text{GFL}}} \lambda_i(\boldsymbol{Y}_{eq}) \tag{8}$$

where $\boldsymbol{Y}_{eq} = \boldsymbol{S}_b^{-1}\boldsymbol{B}$ with $\boldsymbol{S}_b$ being a diagonal matrix containing the rated capacity of each GFL and $\boldsymbol{B}$ representing the reduced node susceptance matrix after eliminating passive and infinite buses. gSCR provides a single value that represents the grid strength of a multi-infeed system; the grid strength of each POI can be further quantified based on the participation factor of the j-th device to the equivalent weakest equivalent subsystem, i.e., $p_{1j} = \boldsymbol{W}_{1j}\boldsymbol{W}_{j1}^{-1}$, where $\boldsymbol{W}$ contains the eigenvectors of $\boldsymbol{Y}_{\text{eq}}$. Calculating gSCR only requires phasor-domain parameters and GFM voltage support can be considered by embedding IBR device dynamics into network parameters [24]. The critical gSCR value can be obtained by either small-signal analysis or EMT simulations based on the weakest equivalent single-IBR subsystem.

2) Grid Strength Impedance Metric: The Grid Strength Impedance Metric (GSIM) defines a metric using a ratio including the eigenloci of the system admittance, $\boldsymbol{Y}_{\text{sys}}(s)$, and the base impedance of the system, $\boldsymbol{Z}_{\text{b}}(s)$ [10]. The dq-axis GSIM values are calculated as

$$\begin{bmatrix}\text{GSIM}_{\text{q}}(s)\\ \text{GSIM}_{\text{d}}(s)\end{bmatrix} = \vec{\lambda}(\boldsymbol{Y}_{\text{sys}}(s)) \odot \vec{\lambda}(\boldsymbol{Z}_{\text{b}}(s)) \tag{9}$$

where $\vec{\lambda}(\boldsymbol{Y}_{\text{sys}}(s))$ and $\vec{\lambda}(\boldsymbol{Z}_{\text{b}}(s))$ are the eigenloci of the system admittance and base impedance, respectively, and $\odot$ represent the element-wise multiplication of two vectors. GSIM is then defined by combining values from (9) as

$$\text{GSIM}(s) := \sqrt{\frac{\text{GSIM}_{\text{q}}(s)^2 + \text{GSIM}_{\text{d}}(s)^2}{2}}. \tag{10}$$

This metric is defined across the frequency spectrum and can vary significantly when evaluated at different frequencies. Interpreting GSIM can be challenging as it is has no direct relationship to the stability margin of a system. However, a larger GSIM generally indicates a greater system strength.

3) Impedance Margin Ratio: The Impedance Margin Ratio (IMR) [25] uses the fact that a change in the equivalent impedance of a device connected at a bus will result in a change in the modes of the system. A low IMR identifies buses where a perturbation in the equivalent device impedance at that bus is associated with a large sensitivity in one of the system's modes. This modal sensitivity is shown in [26] to be $\partial\lambda/(\partial\boldsymbol{Z}_{Ak}(\lambda)) = -\text{Res}_{\lambda}\boldsymbol{Y}^{\text{sys}}_{kk}$, where $\text{Res}_{\lambda}\boldsymbol{Y}^{\text{sys}}_{kk}$ is the residue of the whole-system admittance matrix [27] measured at the POI of bus k, evaluated at the mode of interest, $\lambda = \sigma + j\omega$. This sensitivity is used to determine an impedance margin, which is defined as the maximum allowable change in impedance of a device such that the dominant mode will remain stable, as $\|\Delta\boldsymbol{Z}_{Ak}(\lambda)\|_{\max} = |\sigma|/\|\text{Res}^{*}_{\lambda}\boldsymbol{Y}^{\text{sys}}_{kk}\|$, where $\|\cdot\|$ indicates the Frobenius norm of a matrix. IMR is defined as the magnitude of this impedance margin divided by the magnitude of the original impedance of the device,

$$\text{IMR} := \frac{\|\Delta\boldsymbol{Z}_{Ak}(\lambda)\|_{\max}}{\|\boldsymbol{Z}_{Ak}(\lambda)\|}. \tag{11}$$

To calculate IMR the modes of the system must first be identified and the strength of a bus is determined by the minimum IMR over the range of modes observed at that bus. The Admittance Margin (AM) is defined in [28] as a complement to IMR used to define grid strength at buses without any devices connected yet.

TABLE I
COMPARISON OF SYSTEM STRENGTH METRICS. '-' IMPLIES A VALUE IS UNSPECIFIED OR UNDEFINED. (YES ✓, NO ✗)

Category	System Strength Evaluation					Applicable to IBR Dominated Systems		Metric Scope	Ease of Industry Adoption
	Metric		Critical Value						
	Name	Data Required for Calculation	Voltage Stability	Small-Signal Stability		Considers IBR Control	Considers IBR Interactions		
				Approx.[1]	Accurate[2]				
Fault-current based	SCR [11]	Phasor-domain Parameters	1	1-3	EMT	✗	✗	Bus	★★★
	WSCR [15]	Phasor-domain Parameters	-	1-3	EMT	✗	✓	System	★★★
	CSCR [16]	Phasor-domain Parameters	-	1-3	EMT	✗	✓	System	★★★
	ESCR [17]	Phasor-domain Parameters	-	1-3	EMT	✗	✓	Bus	★★★
	SDSCR [18]	Phasor-domain Parameters	1	-	-	✗	✓	Bus	★★★
	IPSCR [19]	Phasor-domain Parameters	-	-	EMT	✗	✓	Bus	★★★
	NSCR [20]	Phasor-domain Parameters & EMT	-	0-1	-	✓	✗	Bus	★★☆
Admittance-model based	gSCR [24]	Phasor-domain Parameters	1	-	FDA or EMT[3]	✓	✓	System	★★☆
	GSIM [10]	Device Admittance Models	-	-	-	✓	✓	System	★☆☆
	IMR [25]	Device Admittance Models	-	-	0[4], FDA	✓	✓	Bus	★☆☆
	DIM [29]	Device Admittance Models	-	-	EMT	✓	✗[5]	Bus	★★☆

[1]This column indicates approximate critical values of the metric based on industry experience or its formulation.
[2]This column indicates whether the true critical value of a metric is determined using electromagnetic transient (EMT) simulation or frequency-domain analysis (FDA).
[3]The critical gSCR value of a system can be obtained by simulating the weakest equivalent single-inverter infinite-bus subsystem instead of the full system model.
[4]IMR does not define a critical value, but estimates the permissible impedance variation to maintain small-signal stability. IMR is zero when an eigenvalue's real part is zero.
[5]Interactions through the PV analysis are considered; however, IBR control interactions cannot be modeled with such an approach.

4) Dynamic Impedance Margin: The authors of [29] proposed the Dynamic Impedance Margin (DIM) to address a gap between steady-state analysis tools and dynamic models. DIM provides insights into the dynamic voltage stability of systems by modeling generation resources using their *dynamic impedance* values. These values are extracted from the sensitivity of the current injected by a resource to changes in the voltage at that POI. The dynamic impedance varies, particularly for GFL IBRs, over the range of frequencies, so to evaluate the dynamic impedance requires selecting a perturbation frequency. Each device is then represented with a Thevenin equivalent model - an ideal voltage source behind its dynamic impedance value - in a steady-state power flow study and the systems power transfer limits are tested using P-V analysis. The authors show that the power transfer stability limit predicted using DIM is typically conservative compared to results found from EMT studies. DIM extracts information from admittance models; however, it does not directly consider the small-signal stability of the system.

IV. COMPARISON OF METRICS

In this section, we compare the reviewed grid strength metrics in terms of their characteristics, advantages, and limitations. Table I summarizes the characteristics of each metric.

The first distinction between the metrics presented aligns with our categorization. Fault-current based metrics cannot consider IBR control modes or GFM voltage support, except when compared to critical values obtained from EMT simulation. In contrast, admittance-model based metrics inherently consider device dynamics. This benefit of using admittance-model based metrics comes at the cost of acquiring admittance models, compared to fault-current based metrics which only require more readily available phasor-domain system parameters used in short-circuit analysis. Admittance models can be extracted from analytical models of device dynamics, which are not typically available from vendors, or can be obtained via frequency scanning techniques in black box scenarios [30]. Implementing frequency scanning in real time may need additional hardware, such as phasor measurement units, which complicates practical implementation. In this regard, gSCR is different from the other admittance-model based metrics as it is derived based on admittance models but its calculation only requires phasor-domain system parameters.

While all admittance-model based metrics consider the interactions between devices via equivalent admittance modeling, fault-current based metrics differ significantly in their consideration of IBR interactions. SCR ignores other IBRs, while WSCR and CSCR assume IBRs are connected at the same bus, thus ignoring the the IBR interaction via the network. The fault-current based metrics can consider inverter interactions to some extent, but they cannot fully consider control interactions between IBRs that can lead to small-signal stability issues, such as subsynchronous oscillation. Admittance-model based approaches inherently reflect these control interactions.

To assess system stability, most metrics are interpreted relative to a critical value, which can be defined empirically (from industry experience), theoretically (based on voltage stability or small-signal stability theory), or via simulation (from EMT results). Most fault-current based metrics have approximate ranges indicating when a system is susceptible to instability based on industry experience. However, to accurately determine the critical value of these metrics, one must run EMT simulations of the full system being considered. Admittance-model based methods can instead use frequency-domain analysis to determine accurate critical values without requiring EMT simulation of the full system. Notably, IMR differs from this approach of defining a stability margin based on a critical value and instead considers the sensitivity of a system's eigenvalues to convey system strength.

Lastly, in Table I, we compare the scope and the ease of industry adoption of each metric. A metric's scope determines if it calculates a value for each bus in the system or a

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single value for the whole system being considered. Its ease of industry adoption gives an idea of how easily the metric can practically be implemented in an industry setting and is qualitatively rated out of three stars based on the modeling effort, required data availability, and ease of integration into existing short-circuit analysis programs.

V. Gaps and Future Directions for Metrics

Current gaps and challenges related to system strength metrics and possible future directions for research are as follows:

1) Fault-current metrics have not been developed to consider voltage support from GFM IBRs. The development of fault-current metrics that better consider GFM IBR capabilities would benefit IBR connection studies.
2) Fault-current and admittance-based metrics do not all provide clear critical values relating to system stability and practical approaches for calculating these critical values. Researchers should ensure metrics are developed such that they have clear definitions of critical values or other intuitive methods for interpreting metric values that can help inform system operator decisions.
3) Admittance-model based metrics lack industrial documentation and guidance on their implementation. Collaboration between industry and academia to apply these metrics to real-world systems, and the development of tools to automate or simplify the process of acquiring admittance models and implementing these metrics could accelerate adoption.

VI. Conclusion

This paper provides an overview of the existing system strength metrics. By comparing these metrics, gaps and future directions for the development of new metrics are identified. We categorize existing metrics as fault-current based or admittance-model based metrics, and discuss the advantages and limitations of each approach. Reviewing existing literature, we identified that there is a lack of fault-current based metrics that can consider support from GFM IBRs and that admittance-model based metrics have not been adopted in industry. Further, tools to automate the process of implementing admittance-model metrics could accelerate adoption.

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