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Boricic, Aleksandar; Torres, Jose Luis Rueda ; Popov, Marjan

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System Strength: Classification, Evaluation Methods, and Emerging Challenges in IBR-dominated Grids

Aleksandar Boričić
Faculty of EEMCS
Delft University of Technology
Delft, the Netherlands
A.Boricic@tudelft.nl

Jose Luis Rueda Torres
Faculty of EEMCS
Delft University of Technology
Delft, the Netherlands
J.L.RuedaTorres@tudelft.nl

Marjan Popov
Faculty of EEMCS
Delft University of Technology
Delft, the Netherlands
M.Popov@tudelft.nl

***Abstract*—To facilitate the increasing penetration of inverter-based resources, understanding and evaluating system strength becomes one of the central questions for the resilient operation of power systems. However, this is a very challenging and nuanced task, currently without a clear consensus in the industry and academia. This paper provides a comprehensive review of the proposed notion for system strength, followed by a consequent introduction of a novel classification. Furthermore, an exhaustive examination of present system strength evaluation methods is performed. Finally, a critical outlook on remaining and emerging challenges of system strength evaluation is presented, with several key recommendations for future research directions.**

***Index Terms*—System Strength, Inverter-based Resources, Classification, Voltage Stability, Weak Grids**

I. Introduction

Inverter-Based Resources (IBRs) are displacing Synchronous Generators (SGs) worldwide as the energy transition takes place. Unlike SGs, IBRs require a sufficiently strong grid at the point of connection to keep synchronism and ensure stable operation. Furthermore, instead of improving system strength like SGs, their proliferation typically leads to strength degradation. This presents a major challenge for the massive deployment and operation of renewable resources towards a 100% clean electricity supply [1-2].

Definitions of system strength vary across industry and academia. In conventional power systems, it was a synonym for short-circuit capacity (SCC). Presently, the most commonly used definitions express system strength as the sensitivity of voltage to variations in the current injection [1]. In other words, system strength can be understood as the *stiffness* of voltage [2], analogous to what inertia is to frequency deviations. Others define system strength as a broader strength term that comprises both inertia and voltage stiffness [3]. Finally, system strength is discussed both in terms of steady-state operation [4], and in the dynamic state as the size of the change in voltage following a disturbance [5]. Such a wide dispersion of definitions indicates that classification and understanding of system strength are still maturing. A classification of definitions is therefore needed to properly reflect the differences between steady- and dynamic-state power system strength and performance, which is addressed further in the paper.

When it comes to the first notions of system strength, it is at the very essence of voltage stability [2, 6]. Weak grids are more likely to exhibit various types of voltage instability, particularly in IBR-dominated systems [2]. Furthermore, the potential for IBRs' interactions with each other and other controllers in the grid increases as system strength drops [6], and IBRs maloperation and disconnection become more likely [7]. The challenges are emphasized for short-term stability, as the displacement of SGs leads to faster and larger voltage deviations [8-9]. Furthermore, low system strength introduces protection maloperation risks, as fault currents are lower and with very different characteristics [10, 11]. Finally, low system strength degrades power quality, which may cause further intensification of stability and protection challenges [2].

The challenges of stable and resilient system operation with low system strength therefore increase, and the ability to locate such "weak" buses and quantify their strength is of very high importance [12]. The available evaluation methods are abundant, nonetheless often inadequate for the challenges in IBR-dominated grids, as the concept of grid strength evolves and becomes less related to SCC provided primarily by SGs.

This paper offers several contributions to this field: (i) reflecting on the concept of system strength in IBR-dominated systems from different perspectives; (ii) a critical overview of the available evaluation methods and limitations; (iii) an introduction of a novel classification of system strength; and (iv) a comprehensive discussion on the challenges and research paths for quantifying system strength in IBR-dominated grids.

The paper is divided into four main sections. Section II provides a detailed overview and the theory of the currently available system strength evaluation methods. In Section III, a new classification of system strength is proposed, followed by a comprehensive discussion on the rationale and the emerging challenges of system strength evaluation. Finally, conclusions and future research paths are discussed in the last section.

II. System Strength and Evaluation Methods

The most common concept of assessing the system strength of a certain grid location is to calculate the short-circuit

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capacity. This is the typically applied method in the industry [13]. Figure 1 shows a single-line diagram of an IBR connected to the grid represented by a Thevenin source. The figure also depicts a load P_L (dashed line), assumed to be zero. The implications of a positive load are discussed in Section III.

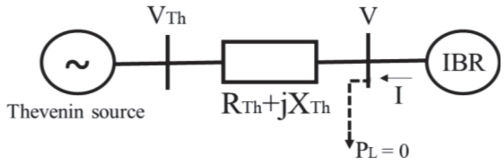

Figure 1. IBR grid connection, represented by a Thevenin equivalent.

The voltage at the point of connection of IBR can be expressed as a function of the Thevenin voltage and the voltage drop across the Thevenin impedance, as shown in (1):

$$V = V_{th} - Z_{th} * I \tag{1}$$

For a small change in current ΔI, the consequent change in voltage can be calculated as follows:

$$\Delta V + V = V_{th} - Z_{th} * (I + \Delta I) \tag{2}$$

$$\Delta V = -Z_{th} * \Delta I \quad => \quad Z_{th} = -\Delta V / \Delta I \tag{3}$$

From (3), it can be seen that the Thevenin impedance is directly linked to the relative change of voltage per change of current, which is often described as voltage sensitivity. Voltage sensitivity provides information on system strength; if $\Delta V/\Delta I$ is high, it means that the bus voltage is very sensitive to the changes in infeed current (power), often called a "weak bus". The other way to describe it is as pliable voltage, as opposed to stiff voltage [2]. Voltage sensitivity can be further expressed from the perspective of SCC, as shown in (4) and (5), where I_{SC} is the short-circuit current that would flow through the bus in the case of a three-phase short-circuit.

$$SCC = V_{th} I_{SC} = |V_{th}|^2 / Z_{th} \tag{4}$$

$$SCC \sim 1/Z_{th} \sim \Delta I / \Delta V \tag{5}$$

Equation (5) depicts inverse (direct) proportionality between SCC and voltage sensitivity (system strength), and the inverse proportionality between Thevenin impedance and SCC and system strength. Inherent approximations that follow this derivation will be further discussed in Section III.

SCC concept can be expanded further as the introduction and proliferation of IBRs takes place, by deriving various Short-Circuit Ratios (SCR). There are three fundamental challenges that an SCR-based method must meet: (i) evaluate the grid impact of connecting a single IBR; (ii) evaluate the grid impact of multiple IBRs; and (iii) consider transfer impedances between IBRs. These three challenges and methods that attempt to overcome them are discussed further.

A. Single-IBR Methods

The Short Circuit Ratio is generally used to evaluate the strength of an IBR's point of connection [13], defined in (6),

$$SCR = SCC / P_{IBR} \tag{6}$$

where SCC is the short-circuit capacity assuming a three-phase fault, and P_{IBR} is the nominal power of the connected IBR. It is important to note that SCC typically does not consider IBR's fault current contribution. It is generally assumed that SCR>3 means a strong grid, 1<SCR<3 a weak grid, and SCR<1 very weak grid where IBR connection is unstable [13].

However, as multiple IBRs are introduced in an area, SCR is unable to account for their interactions and consequent reduction of system strength. Therefore, new methods have been developed in an attempt to address this limitation.

B. Methods for Multiple IBRs

If there are multiple IBRs in proximity of each other, they will interact and effectively degrade system strength. In [14], the Weighted Short-Circuit Ratio (WSCR) is introduced, which is applied in the Texas grid where a large local penetration of IBRs is present. WSCR is defined in (7):

$$WSCR = \frac{\sum_i^N SCC_i * P_{IBR_i}}{\left(\sum_i^N P_{IBR_i}\right)^2} \tag{7}$$

where SCC_i is the short-circuit capacity at bus i, P_{IBR_i} is the active power output of the i_{th} IBR and N is the number of IBRs considered to fully interact with each other. ERCOT defines WSCR > 1.5, based on detailed EMT studies, as the minimum strength to ensure system stability. If WSCR is too low, IBRs' power is curtailed to preserve strength [14].

Another related method that accounts for multiple IBRs is the Composite Short-Circuit Ratio (CSCR), developed originally by GE [1]. CSCR method assumes a composite IBRs' bus by tying together low-voltage sides of plants' transformers. SCC is then calculated for such a composite bus.

WSCR and CSCR methods are an improvement compared to SCR, as they consider the impact of multiple IBRs. However, they do not take into consideration real electrical network connections between IBRs. In other words, they assume full interaction between selected IBRs. To deal with this approximation, several novel methods have been derived.

C. Methods for Multiple IBRs Considering Grid Impedances

To evaluate the actual interactions between various IBRs, authors in [15] introduced Site-Dependent Short-Circuit Ratio (SDSCR) as a generalization of SCR, which is defined by (8):

$$SDSCR_i = \frac{\left|V_{R,i}\right|^2}{(P_{R,i} + \sum_{j \in R, j \neq i} P_{R,j} w_{ij}) |Z_{RR,ii}|} \tag{8}$$

$$w_{ij} = \frac{Z_{RR,ij}}{Z_{RR,ii}} \left(\frac{V_{R,i}}{V_{R,j}}\right)^* \tag{9}$$

where $V_{R,i}$ is the voltage of the i_{th} busbar with IBR connection, $P_{R,i}$ is the IBRs' active power infeed at the i_{th} bus, and $Z_{RR,ij}$ the corresponding (i,j) element of the system impedance matrix [15]. SDSCR is able to quantify the level of IBRs' interactions by utilizing information on the actual transfer impedances and active power of IBRs. In [15], it is shown mathematically that SDSCR has the same stability thresholds as SCR. Since the metric can be time-demanding to calculate for large systems, a simplification is introduced in [16], where it was shown that transfer impedances play the central role in voltage sensitivity and IBR interactions, and hence system strength. Several other metrics, conceptually similar to SDSCR, have been proposed but are omitted for brevity.

Nevertheless, various diverse challenges remain and emerge with more IBRs, as discussed further in this paper, which is why a new classification of system strength is proposed in Section III, followed by a discussion on the implications.

III. Classification of System Strength With Emerging Challenges in IBR-dominated Grids

With the further proliferation of IBRs in power grids, the system strength concept evolves and brings distinctive operation and stability challenges that may require different considerations for modelling, evaluation, and mitigation.

This section proposes a new classification of system strength: (i) *steady-state* system strength; and (ii) *dynamic-state* system strength, described in Figure 2. The classification is proposed in a way that closely corresponds to the most recent system stability classification presented in [6]. The following two subsections, A and B, discuss the need for the proposed classification, implications for evaluation metrics, and remaining challenges in grids with a high penetration of IBRs.

A. Steady-state System Strength

Steady-state system strength deals with the operation around nominal voltage, assuming only small disturbances. Therefore, it can be linearized with Thevenin equivalence and described by SCR-based methods. However, several relevant steady-state factors, listed in Figure 2, are not necessarily considered by SCR-based methods. Implications of such assumptions and possible improvements are discussed next.

1) Presence of local load

In Figure 1, an illustrative single-line diagram of the IBR connection is depicted. However, with the widespread IBR integration, the load depicted in a dashed line is not necessarily zero. More load implies that less power is transferred towards the aggregate system, i.e. less power infeed from the perspective of the bulk power system [2]. This meaningfully changes the system strength and voltage stability limits of the system, which is exemplified in Figure 3. However, none of the methods presented so far considers this. As a result, they may be overly conservative and fail to describe the actual power transfer limit in terms of voltage stability and system strength. With IBRs adopted in both load-free and load-rich areas, consequent system strength differences ought to be considered.

2) Grid equivalence X/R ratio

While it is common to assume that the Thevenin impedance is predominantly reactive, it is not always accurate. IBRs are frequently integrated into grid locations where not only system strength is low, but also the X/R ratio. As the X/R ratio drops, $\partial V/\partial P$ increases, while $\partial V/\partial Q$ decreases, with all else equal. This implies that for buses in low X/R areas, the common P-θ and Q-V dependence changes. The (change of) active power affects the (change of) voltage magnitude more, and reactive power becomes less capable of controlling the bus voltage.

Methods presented in Section II generally do not consider the effects of the different X/R ratios on the stability limits. This simplification may affect the accuracy of the SCR-related metrics, particularly in weaker grids, as shown in [17, 18].

3) Operating voltage and secondary short-circuit support

SCR-based metrics are typically calculated utilizing nominal voltage [4, 13]. Nevertheless, higher (lower) operating voltage results in a higher (lower) active power transfer within the voltage stability limits. Furthermore, the impact of various FACTS devices and synchronous condensers (SC) on system strength is not always well-described by SCR-based methods. Such devices can, however, introduce a meaningful improvement in system strength and are common solutions applied in the industry [12]. Finally, on-load tap changers (OLTC) operation is ignored, which affects the voltage stability threshold and power transfer limits [17].

A novel method introduced in [17, 18] addresses some of the mentioned challenges by calculating voltage sensitivity $\partial Q/\partial|V|$ as a system strength metric. Detailed mathematical derivation is intricate and hereby omitted for brevity. Figure 3 shows how $\partial Q/\partial|V|$ visualizes system strength and the distance to voltage instability [17, 18]. For low active power with no load, $\partial Q/\partial|V| \approx$ SCR, while $\partial Q/\partial|V| = 0$ indicates voltage stability limit [2]. However, the green and red curves show that by adding load or SC, respectively, voltage sensitivity and the maximum power transfer significantly change relative to the base case (black curve in Figure 3). These two curve changes are a consequence of effectively reduced infeed power and

Proposed System Strength Classification	
Steady-state System Strength	**Dynamic-state System Strength**
Mainly deals with:	
• Steady-state system operation • Long-term stability and slow interactions • Stability when subjected to small disturbances • Linear operation around nominal voltage	• Dynamic-state system operation • Short-term (transient) stability and fast interactions • Stability when subjected to large disturbances • Non-linear operation with large voltage deviations
Factors that should be considered:	
• Short-circuit capacity (Thevenin impedance) • Influence of (multiple) IBR(s) and respective transfer impedances • Impact of loads, grid X/R ratio, and PLL parameters in weak grids • Secondary short-circuit support (e.g. synchronous condensers) • RMS modelling often sufficient (except in very weak grids)	• Impedances' non-linearity (converter saturation) • IBRs' FRT and interactions with post-fault voltage dynamics • Large-signal stability and interactions of control loops • Possible protection maloperation and unintended IBR tripping • Advanced RMS models needed (often supported by EMT models)

Figure 2. The proposed system strength classification, the scope of the two subclasses, and the relevant factors to be considered.

increased short-circuit capacity, respectively. Similar effects can be seen for varying X/R ratios and operating voltage [18].

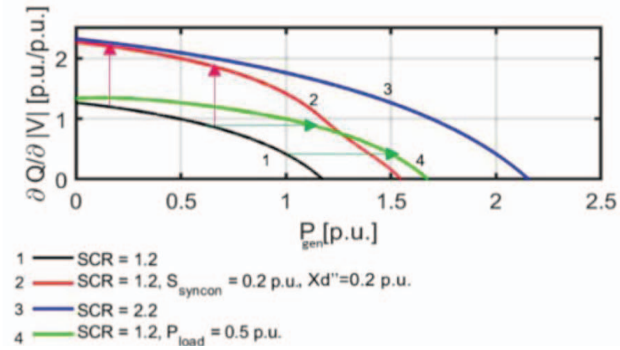

Figure 3. Voltage sensitivity $\partial Q/\partial|V|$ in four scenarios, adapted from [2].

These important differences are not always captured by SCR-based methods presented in Section II. Furthermore, $\partial Q/\partial|V|$ curves can offer continuous and more intuitive quantification of system strength, in comparison to SCR.

Nonetheless, while $\partial Q/\partial|V|$ addresses several challenges presented in this section, it is derived for a single IBR, unlike some of the methods shown in Section II. An interesting advancement would be to bridge the mathematical derivations of advanced SCR-based methods and the $\partial Q/\partial|V|$ method, to address all the challenges mentioned in Sections II and III simultaneously. This is a promising future work consideration for steady-state system strength evaluation.

4) Small-signal stability of control loops

The introduced methods determine system strength by identifying the maximum power transfer from the perspective of static voltage stability. This is, however, a theoretical limit, and it ignores the practical limitations of the phase-locked loop (PLL). PLL is a control loop used to synchronize IBRs with the grid, and it relies on the evaluation of voltage angle and frequency [6]. Therefore, IBRs inherently rely on the strength of the voltage waveform at the point of connection. In weak grids, before the static voltage stability limit is reached, PLL stability starts to play an important role in system strength, which is neglected in SCR-based methods. This role can be understood as either reduced steady-state system strength, or alternatively, increased IBR demand for system strength. The former perspective is taken in this paper. The PLL settings can therefore improve (degrade) small-signal stability, improving (degrading) steady-state system strength accordingly [17].

In [19], the approach of evaluating system strength in terms of small signal stability is taken. This differs compared to previous approaches, which generally focus on static voltage stability as a system strength boundary. The generalized SCR (gSCR) is introduced and showcased on multi-infeed power electronic systems such as LCC HVDC [20] or wind farms [21].

An alternative approach is taken in [22], where the authors introduced Short Circuit Strength (SCS) metric. SCS relies not only on short circuit capacity and impedances but also on PLL-relevant dynamic parameters such as controller gains and time constants, as well as expected protection clearing time, to complement SCR-based methods in locating weak buses.

B. Dynamic-state System Strength

The presented evaluation methods so far are steady-state system strength methods that focus on the small disturbance operation. Large disturbances are generally not considered. Consequently, they all assume that the Thevenin theorem and equivalence are applicable. In other words, there is an implicit assumption of system linearity, where impedances do not change with the operating point. This assumption is less accurate in (post-)disturbance operation, especially with the proliferation of IBRs, which is why this paper proposes the dynamic-state system strength subclass, shown in Figure 2. This subclass and the related challenges are discussed further.

1) Non-linearity of IBR-dominated grids

For conventional systems, the Thevenin impedance derived in steady-state conditions is not meaningfully affected by the intensity of the disturbance. It is instead primarily related to the inherent physical characteristics of SGs and passive grid components. Therefore, the assumed grid linearity holds true.

This situation is different in IBR-dominated grids. Instead of underlying physics, IBR response is primarily driven by the applied controls. Therefore, steady-state $\Delta V/\Delta I$ values from (5) would be only applicable to steady-state operation. The system can no longer be linearized, as impedances change with the voltage. Consequently, the system may be strong in the steady-state, but simultaneously exhibit dynamic-state weakness, further justifying the need for the classification in Figure 2.

To address this, the impedance mapping is introduced in [23], where the system impedance is not a single value, but a non-linear spectrum of values based on the operating point. It is, however, also shown that the non-linearity leads to non-differentiability in the complex space, i.e. V/I relationship is not analytical (holomorphic). Therefore, a deterministic mathematical method does not seem to be derivable. This is a challenge that requires further research to describe non-linearity and its impact on dynamic-state system strength.

2) Large-signal stability of control loops

The weak grid operation during and after large disturbances is a major and distinctive challenge for IBRs. Firstly, faults may lead to even weaker grid conditions if an important element gets disconnected. Furthermore, during faults, voltage waveforms that PLL relies on can be notably disturbed. In IBR-dominated systems, faults induce larger voltage angle jumps and rate of change of frequency (RoCoF), due to reduction of fault currents and inertia, respectively. This poses risks to the stability of IBR control loops and may lead to oscillations, disconnections, and converter-driven instability [6]. Such events stress a grid further, inducing vulnerability to cascading [24]. Finally, with more IBRs in a grid, the likelihood of post-disturbance interactions increases, especially in weaker grids [2].

3) Maloperation and unintentional disconnections

It is common that some IBRs may exhibit undesired fault-ride-through (FRT) behaviour and enter momentary cessation mode or even disconnect during (or following) a disturbance. They may be also (incorrectly) disconnected due to protection maloperation, which is much more likely in IBR-dominated grids [10-11]. Inverter blocking or disconnection is particularly concerning as it tends to happen during severe disturbances, where a power system is already very vulnerable, exacerbating the issue [24]. The recent experience with massive IBR disconnections in the (post-)fault period stresses the importance of this [25]. Based on practical experience, AEMO shows that there is a strong correlation between fault intensity and the amount of distributed IBRs likely to trip [26]. MIGRATE project demonstrates that the loss of devices in the FRT period is one of the larger stability challenges for European TSOs [4]. Furthermore, dynamic load (post-)fault behavior may contribute to the probability of nearby IBR disconnection by introducing fault-induced delayed voltage recovery (FIDVR), or other complex voltage deviations [24]. Therefore, it is prudent to assume that some IBRs will not operate as expected, which reduces dynamic-state system strength. No available system strength methods explicitly consider this.

Grid-forming converters (GFMC) may help to ease some of these challenges [27, 28]. However, they are not a solution to all of them. PLL-specific challenges might be alleviated, as GFMC do not rely on PLL to synchronize with the grid. However, for power transfer challenges where voltage and angle stability are the bottlenecks, GFMC are unlikely to provide further benefits compared to advanced grid-following weak-grid controls [28]. Furthermore, converter-driven instabilities and interactions are likely to remain an issue. As GFMCs have limited fault currents by the semiconductor ratings, their support of dynamic-state system strength is also limited [29]. Therefore, many stability and system strength challenges are still relevant for GFMC, especially as the overall IBR (SG) penetration increases (decreases). GFMC are currently an actively researched topic, with several pilot field applications [28]. The research on system strength evaluation with many GFMCs in a grid is an important future work topic.

The challenges of steady- and dynamic-state system strength presented in this section are fundamentally different. This may require a tailored evaluation approach, further justifying the introduced classification and need for innovative solutions to tackle all the present and emerging challenges.

IV. Conclusion

The importance of understanding and evaluating system strength increases as more IBRs are integrated into grids. The new classification presented in this paper, which fundamentally corresponds to the latest stability classification, provides a necessary framework for analysing the existing and emerging system strength challenges. Furthermore, the available system strength evaluation methods are shown to be often inadequate in IBR-dominated grids. Several research gaps and promising future improvement paths are highlighted, to help tackle the growing steady- and dynamic-state system strength challenges. The topic of system strength evaluation remains focal in enabling the massive deployment of renewables worldwide.

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