# ASSESSMENT OF SYSTEM STRENGTH METRICS FOR SMALL-SIGNAL STABILITY ANALYSIS IN POWER ELECTRONICS DOMINATED GRIDS

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## Introduction

As more renewable energy sources are introduced into the electric grid using power electronics, known as Inverter-Based Resources (IBRs), the system is experiencing a substantial reduction in the system short circuit level and intrinsic system strength, creating challenging "weak grid" conditions in many areas [1]. Unlike Synchronous Generators (SGs), which inherently resist frequency and voltage changes, IBRs rely on fast electronic control systems, such as the Phase-Locked Loop, which are prone to complex, converter-driven small-signal instabilities when operating in weak networks [2], [3].

For modern power systems, the system strength definition has evolved and is generally understood to be the sensitivity of the voltage magnitude, phase angle, and voltage waveform at any given transmission grid location with respect to the change in active/reactive power in every possible system condition [4]. The conventional metric for assessing grid strength, the Short Circuit Ratio (SCR), is now recognized as insufficient and outdated because it fails to capture the dynamic behavior of IBR controls across a wide frequency range, overlooks multi-infeed interactions, and cannot accurately represent converter-driven stability concerns, leading to potentially inaccurate or optimistic estimations of power system security [2], [3], [4]. Therefore, there is need for new metrics that can assess system strength in a modern power grid and provide insight into grid operation, diagnostics, stability analysis and planning.

### *System Strength Metrics*

Amongst the metrics derived from SCR, the Equivalent Short Circuit Ratio (ESCR) is one that has been widely adopted by TSOs as a quick scan tool, as it considers not only the short circuit level at the bus being tested, but also the power contribution from nearby converters by applying an interaction factor that assigns different weights to other buses in a meshed grid [3], [5]. However, newer impedance-based metrics like the Impedance Margin Ratio (IMR), take into account the stability provided from a Grid Forming (GFM) inverter versus a Grid Following (GFL) inverter [2]. The IMR is particularly interesting because it correlates a change in the impedance to a change in the poles of the system, ensuring the damping values always stay positive, and providing a margin of small-signal stability [2]. In essence, it observes how much the impedance of a unit can change until the system becomes potentially unstable, indicating when further stability studies are needed [2]. These impedance-based metrics represent a key advancement in system strength assessment, as they are specifically designed for the modern grid, and provide insight into the system's small-signal stability.

| SCR | ESCR | IMR |
|---|---|---|
| $SCR = \frac{SC_{MVA,i}}{P_i}$ | $ESCR = \frac{SC_{MVA,i}}{P_i + \sum(\frac{\Delta V_j}{\Delta V_i} \times P_j)}$ | $\frac{\lVert\Delta Z_{AK}(\lambda)\rVert_{max}}{\lVert Z_{AK}(\lambda)\rVert}, \quad for \ \lVert\Delta Z_{AK}(\lambda)\rVert_{max} = \frac{\lvert\sigma\rvert}{\lVert Res_{\lambda}^{*} Y_{kk}^{sys}\rVert}$ |

***Table 1****: System Strength metrics being compared in this study. With $SC_{MVA,i}$ = Short Circuit Current at bus i, $P_i$ = Power rating of IBR under test, $\frac{\Delta V_j}{\Delta V_i}$ = interaction factor, $Z_{AK}(\lambda)$ = original impedance of apparatus connected to bus k, || || = Frobenius norm, $\sigma$ = real part of system eigenvalues, $Res_{\lambda}^{*} Y_{kk}^{sys}$ = conjugate transpose of the residue matrix of the system admittance matrix. [2]*

In this study, the SCR, ESCR, and IMR, are compared against each other in three scenarios leading to small-signal instability to determine which metric can best assess system strength in modern power systems where complex interactions derived from the introduction of IBRs may arise.

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## Methodology

The metrics are evaluated on an IEEE standard 57 bus system where several synchronous machines are replaced by GFMs and GFLs. The three metrics are calculated for key buses using the equations from Table 1, and validation of the metrics is done by running an Electromagnetic Transient (EMT) simulation of the system to test for small-signal instability. The three scenarios evaluated are:

1) **Base scenario**: The base case uses the modified IEEE 57 bus system with several GFM and GFL inverters. It is used as reference and should not lead to instability.
2) **GFL scenario**: some SGs are swapped for GFL inverters of the same rating.
3) **Detuned scenario**: Some of the key GFL inverters are purposely detuned to create undesired interactions.

## Expected Results

Based on the characteristics of each metric and the three scenarios being tested, it is expected that the observed behavior is as follows:

- The SCR should see a steep decrease from scenario 1 to scenario 2, as the GFL inverters are unable to provide the same levels of short circuit current than an SG would. There should be no change from case 2 to 3, as the metric neglects IBR behavior.
- The ESCR should also see a decrease from scenario 1 to 2, but less significantly as it accounts for the contributions from other nearby devices, leading to a more accurate estimate. There should be no change from case 2 to 3.
- The IMR should also decrease from scenario 1 to 2, as well as from 2 to 3, being able to predict possible small-signal instability at key buses, especially coming from poorly tuned converters. The IMR should prove most useful in scenario 3, detecting small-signal instabilities where other metrics cannot.

The SCR is expected to prove outdated and superficial, followed by the ESCR providing a better estimate of system strength, but the IMR should be the most insightful. The results will also serve to parametrize the IMR and create upper and lower bounds for stability regions, since it's a new metric.

### *Outlook*

The new impedance-based metrics like the IMR show promise in assessing not just system strength in the traditional sense but also providing insight into small-signal stability. This could prove useful for medium-to-short-term applications like stability analysis, diagnostics, planning, and real-time operations.

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