Grid Strength Assessment in Weak Distribution Systems: Beyond Short Circuit Ratio

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***Abstract*—Rapid growth of inverter-based distributed energy resources (DERs) in rural Australian feeders has exposed limitations in conventional Short Circuit Ratio (SCR) screening, particularly in long, high-R/X networks where fault-level indices may not reflect transient voltage recovery. This paper proposes and validates a practical distribution-level screening approach that combines a generation-weighted strength index, the Weighted Short Circuit Ratio (WSCR), with a load-flow–based Voltage Stability Index (VSI). Using utility feeder data, WSCR and VSI thresholds are calibrated against electromagnetic transient (EMT) outcomes based on voltage recovery criteria consistent with AS 4777.2:2020. Results show that WSCR provides a stable first-pass filter across increasing DER penetration, while VSI adds locational sensitivity to voltage-limited operating points overlooked by fault-based metrics. Application to a 22-bus test system improves screening accuracy and reduces required EMT studies from eleven to three, corresponding to AUD 160–400 k in avoided analysis for the case study. The framework provides a practical pathway for distribution network service providers (DNSPs) to assess system strength in inverter-dominated feeders and supports compliance with NER S5.1a.9.**

***Index Terms*—grid strength, short circuit ratio, weighted short circuit ratio, voltage stability index, distributed energy resources, EMT validation**

I. Introduction

A. Background and Motivation

Australia's energy transition has driven substantial uptake of inverter-based distributed energy resources (DERs) in rural networks, with photovoltaic (PV) penetration in some feeders now exceeding 200% of minimum demand [1], [2]. These long (40–200 km), high-R/X (0.85–1.15) radial feeders exhibit behaviour markedly different from meshed transmission systems, particularly in their sensitivity to voltage and system strength [3], [4].

Screening has traditionally centred on the Short Circuit Ratio (SCR), i.e., available three-phase short-circuit capacity at a bus relative to the generation tied to that location [5], [6]. Although widely effective for synchronous-machine-dominated systems [7], [8], rural Australian experience shows a recurring paradox: feeders with SCR > 4 have exhibited voltage oscillations under high DER penetration, whereas others with SCR < 3 have operated stably [3]. The mismatch stems from SCR's insensitivity to dispersed infeed, inverter control interactions, and voltage-dependent feeder impedance—factors that dominate in weak, high-R/X networks [9], [10]. These observations reflect a consistent pattern noted in several DNSP operational reviews, where SCR alone fails to rank feeder locations accurately under high inverter penetration.

Alternative indices such as the Weighted Short Circuit Ratio (WSCR) [11], [12] and Voltage Stability Index (VSI) [13]–[15] have been proposed to address these limitations, but robust validation against real distribution feeders and electromagnetic transient (EMT) performance remains limited.

B. Regulatory Context

NER S5.1a.9 places an obligation on distribution network service providers (DNSPs) to ensure adequate system strength at each connection point. In practice, this requirement is commonly operationalised through Effective Short Circuit Ratio (ESCR)–based screening, where ESCR is defined as the ratio of available three-phase short-circuit strength at the connection point to the aggregated inverter-based generation, and ESCR < 3 typically triggers detailed electromagnetic transient (EMT) investigation [1], [3]. However, these thresholds—and the assumptions underpinning them—were developed primarily for meshed transmission networks and do not reflect the operating characteristics of long, resistive 11–33 kV rural distribution feeders with dispersed inverter-based DER [16]. As a result, DNSPs applying transmission-derived heuristics at the distribution level may mischaracterise true stability margins and fail to capture the cumulative and locational impacts of multiple DER installations.

C. Contribution

This paper addresses the gap between SCR screening and EMT behaviour in high-R/X distribution feeders, where QSS methods can misclassify weak nodes and full EMT studies are impractical at scale. The paper makes four contributions.

First, it proposes a QSS–EMT bridging framework linking WSCR and VSI to EMT-validated voltage recovery.

Second, it introduces a Typical Australian Rural Distribution System (TARDS): an anonymised, industry-derived rural sub-transmission/distribution network intended as a repeatable reference framework for future system strength research.

Third, it derives WSCR and VSI thresholds using AS 4777.2:2020 recovery criteria, calibrated across eight representative EMT operating points.

Fourth, it demonstrates a two-stage WSCR–VSI screen on a 22-bus utility network, improving classification from 59% to 95% while reducing EMT studies from eleven to three.

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II. Framework

A. Analytical Indices

1) Short Circuit Ratio (SCR):

$$\text{SCR}_i = \frac{S''_{k,i}}{P_{\text{gen},i}} \quad (1)$$

Here, $S''_{k,i}$ is the three-phase short-circuit strength at bus i (MVA), calculated using the IEC 60909 method [17]. SCR provides a basic indication of how much fault current capability is available relative to the size of the generator connected at that location.

2) Weighted Short Circuit Ratio (WSCR):

$$\text{WSCR}_i = \text{SCR}_i \times \frac{P_{\text{gen,test}}}{P_{\text{total,network}}} \quad (2)$$

WSCR modifies the conventional SCR by scaling it according to the proportion of the assessed generator's capacity relative to the total installed generation in the network. This weighting introduces sensitivity to how generation is distributed across multiple infeed points [11], [12]. This weighting term ensures that the metric reflects the relative impact of the assessed generator on total DER capacity, rather than the absolute short-circuit capacity alone.

3) Voltage Stability Index (VSI):

$$\text{VSI}_i = 1 - \frac{4\,(P_{\text{load},i}X_{\text{th},i} + Q_{\text{load},i}R_{\text{th},i})}{V_i^2} \quad (3)$$

The VSI quantifies the proximity of bus i to voltage instability by relating the local load to the corresponding Thévenin equivalent seen from that bus [13], [18]. In this work, $P_{\text{load},i}$ and $Q_{\text{load},i}$ denote the active and reactive power demand at bus i, expressed in per unit on a 100 MVA system base. The parameters $R_{\text{th},i}$ and $X_{\text{th},i}$ represent the Thévenin equivalent resistance and reactance (p.u.), and V_i is the steady-state voltage magnitude (p.u.). The formulation reflects the influence of high-R/X feeder characteristics typical of rural distribution systems.

Notation: $P_{\text{gen},i}$ (MW), $P_{\text{gen,test}}$ (MW), $P_{\text{total,network}}$ (MW), $P_{\text{load},i}/Q_{\text{load},i}$ (p.u. on 100 MVA base), $R_{\text{th},i}/X_{\text{th},i}$ (p.u.), V_i (p.u.).

B. Test System: TARDS Network

The studies in this paper are based on the Typical Australian Rural Distribution System (TARDS), derived from an operational sub-transmission planning model used by an Australian distribution network service provider (DNSP). The network represents a weak rural system supplying long radial feeders with limited synchronous fault-level support.

TARDS spans 132/33/22/11 kV and comprises a 132/33 kV zone substation (2×25 MVA), six 33 kV feeders (40–85 km), multiple 33/11 kV transformers (5–10 MVA), and 22 primary buses, with R/X in the 0.85–1.15 range. Two operating scenarios are considered: 30 MW and 100 MW of distributed photovoltaic generation relative to a minimum demand of approximately 50 MW.

The model preserves the original network topology and impedance characteristics, with anonymisation applied to protect confidentiality. No synthetic impedance scaling or notional feeder assumptions were introduced.

C. EMT Validation Protocol

The eight buses were selected to span the full range of SCR, WSCR, and VSI values observed across the network, providing representative coverage of strong, adequate, and marginal operating points. These locations were analysed using PSCAD/EMTDC v5.0.2 [19], [20] to establish the relationship between the analytical indices and transient voltage recovery behaviour.

1) **Inverter model:** A generic grid-following PV inverter model compliant with AS 4777.2:2020 requirements [21].
2) **Fault scenario:** A solid three-phase (ABC–G) fault with a fault resistance of 0.01 Ω is applied at the point of common coupling (PCC) of the DER connected to the assessed bus at $t = 1.0$ s.
3) **Protection clearing:** The fault is cleared at $t = 1.1$ s (100 ms), consistent with typical rural distribution feeder protection clearing times.
4) **Performance criterion:** A bus is classified as *PASS* if the post-fault voltage satisfies $V_{1\text{s}} \geq 0.9$ p.u. and the voltage recovery time $t_{\text{rec}} < 1.0$ s; otherwise it is deemed *FAIL*. Here, $V_{1\text{s}}$ denotes the voltage magnitude one second after fault initiation.

The screening thresholds proposed in this paper were obtained by iteratively tuning WSCR and VSI bounds to maximise consistency with these EMT outcomes, following calibration approaches used in prior dynamic stability studies [10], [22].

III. Results and Analysis

A. International Screening Practices

Table I summarises major international grid strength screening practices, highlighting the transmission-oriented origins of most commonly applied metrics and motivating the need for a distribution-level adaptation. In North America, NERC and WECC rely on SCR-based criteria—including the Composite System SCR (CSCR)—for transmission-level screening [5], [6]. AEMO applies the Equivalent SCR (ESCR), with ESCR < 3 typically triggering electromagnetic transient (EMT) analysis [3]. ERCOT has examined WSCR values below 2 as indicative of increased risk in wind-dominated corridors [11]. Several European operators have adopted performance-based approaches without fixed numerical thresholds [23]. While these practices provide useful reference points, they offer limited sensitivity to the spatial diversity and high-R/X characteristics of multi-infeed rural distribution feeders.

B. Metric Stability Across DER Penetration

As generation in the TARDS network increased from 30 MW to 100 MW, the three indices exhibited markedly different behaviour:

- **SCR:** Node N107 declined from 8.92 to 2.68 (approximately 70%), with similar reductions observed across the network.

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TABLE I
INTERNATIONAL GRID STRENGTH ASSESSMENT PRACTICES

Region	Metric	Threshold	Limitation
NERC [5]	SCR	> 3 strong; < 2 weak	Assumes single-infeed behaviour
ERCOT [11]	WSCR	< 2 risk	Limited operational validation
AEMO [1], [3]	ESCR + EMT	ESCR $< 3 \Rightarrow$ EMT	Transmission-centric; limited distribution relevance
WECC [6]	CSCR	> 2.5	Tailored to HVDC; not suited to feeders
EU [23]	Dynamic	None	Performance-based; varies by jurisdiction

TABLE II
EMT VALIDATION RESULTS (8 REPRESENTATIVE BUSES)

Bus	SCR	WSCR	VSI	t_{rec} (s)	Result
B1	8.92	6.69	0.982	0.52	PASS
B2	4.55	2.31	0.956	0.68	PASS
B3	3.21	1.15	0.923	0.81	PASS
B4	2.80	0.85	0.911	0.95	PASS
B5	2.15	0.62	0.895	1.08	FAIL
B6	1.45	0.51	0.872	1.35	FAIL
B7	0.89	0.48	0.851	1.58	FAIL
B8	0.64	0.52	0.918	0.92	PASS

- **WSCR:** Node N107 remained essentially unchanged at 6.69 (0% variation), with system-wide changes below 5%.
- **VSI:** Remained within approximately ± 0.02 p.u., identifying marginal buses such as N106 (VSI = 0.911) despite its SCR = 4.0.

WSCR's stability arises from the proportional nature of its formulation in (2), which scales with total installed generation. In contrast, VSI responds directly to changes in reactive power margin and feeder impedance, providing early indication of voltage sensitivity that traditional short-circuit–based metrics may overlook.

Figure 1 illustrates these trends. SCR decreases sharply with increasing DER penetration because the underlying short-circuit base remains fixed while generation grows. This behaviour explains why SCR frequently misclassifies strength in multi-infeed feeders. By comparison, WSCR varies little across the same operating range, and VSI exhibits limited change yet reliably marks buses approaching marginal stability (VSI $\lesssim 0.92$). Error bars reflect the spread across different bus locations, highlighting VSI's locational sensitivity and WSCR's robustness to penetration shifts.

C. EMT Validation and Threshold Determination

To develop practical screening thresholds, EMT simulations were carried out on eight representative TARDS buses. Table II compares their steady-state indices with dynamic performance following a 100 ms three-phase fault. The voltage recovery time t_{rec} was adopted as the primary indicator of stability, consistent with AS 4777.2:2020 requirements.

These eight locations collectively span the full range of observed strength conditions in the feeder, ensuring that the derived thresholds generalise across weak, intermediate, and strong nodes.

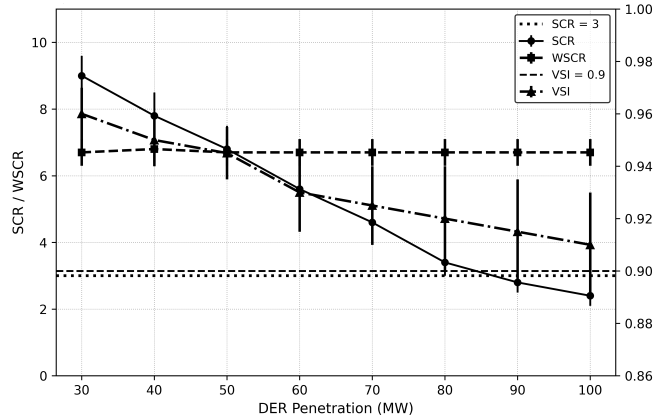

Fig. 1. Metric behaviour as DER penetration increases from 30 MW to 100 MW. SCR declines sharply (60–70%), whereas WSCR remains stable ($< 5\%$ variation). VSI highlights buses approaching marginal stability (VSI < 0.92). Error bars indicate spatial variability. The horizontal dotted line denotes SCR = 3, and the horizontal dashed line denotes VSI = 0.9.

TABLE III
PROPOSED SCREENING THRESHOLDS

Condition	WSCR	VSI
Strong	> 1.5	> 0.95
Adequate	0.8–1.5	0.90–0.95
Review required	< 0.8	< 0.90

The EMT outcomes reveal a clear separation between stable and unstable operating points when assessed using VSI and WSCR. All buses with VSI ≥ 0.92 recovered satisfactorily, while those with VSI ≤ 0.87 failed. Borderline cases around 0.89 produced mixed results, indicating a practical tolerance of approximately ± 0.02 p.u. and supporting a working threshold of VSI ≥ 0.90.

For WSCR, values above approximately 1.5 consistently corresponded to stable behaviour, whereas values below 0.6 aligned with a high risk of instability. The intermediate range (0.6–1.0) required confirmation via VSI, motivating the combined rule WSCR > 0.8 with supplementary VSI assessment.

The results also reaffirm the limitations of conventional SCR. Bus B8, with SCR = 0.64—normally classified as "very weak"—passed dynamically due to its relatively high VSI of 0.918. Conversely, Bus B5 (SCR = 2.15) failed because its VSI was only 0.895. These observations illustrate how SCR alone can misclassify strength in inverter-dominated feeders.

Figure 2 illustrates representative EMT voltage recovery traces. Bus B4 (VSI = 0.911) satisfies the AS 4777.2:2020 recovery criterion, whereas Bus B5 (VSI = 0.895) does not. The proposed VSI threshold of 0.90 is therefore consistent with observed EMT recovery behaviour.

Table III consolidates the proposed screening bands. Together with the two-stage WSCR–VSI process, these thresholds allow DNSPs to evaluate connection points efficiently while remaining aligned with AS 4777.2:2020 expectations.

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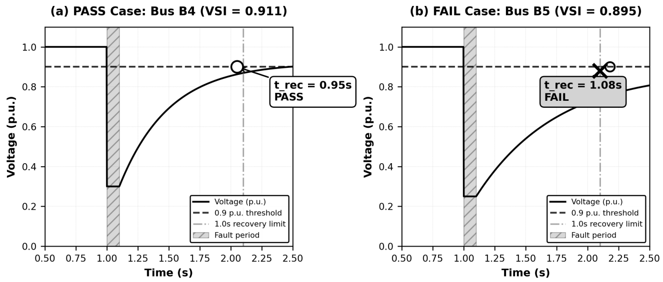

Fig. 2. Representative EMT voltage recovery traces. (a) Bus B4 (VSI = 0.911) recovers to 0.92 p.u. within 0.95 s. (b) Bus B5 (VSI = 0.895) fails to reach 0.9 p.u. by 1.0 s, with t_{rec} = 1.08 s. Both cases are subjected to a 100 ms ABC–G fault.

TABLE IV
REPRESENTATIVE NODE METRICS ACROSS TEST SYSTEMS

Node	P_{gen} (MW)	SCR	WSCR	VSI	Note
N1	25.0	10.0	2.05	0.956	Strong
N2	20.0	4.00	0.82	0.911	Marginal
N3	15.0	4.33	0.65	0.904	V-limited
N4	14.0	6.43	2.24	0.984	Stable
N5	25.0	4.80	3.12	0.978	Robust
N6	20.0	9.00	1.60	0.952	Adequate

D. Representative Node Metrics

Here, "N"-prefixed nodes refer to the broader QSS dataset, while "B"-prefixed buses refer to the EMT-validated subset. Applying the proposed thresholds to representative nodes across the test systems provides further confirmation of their robustness. Table IV summarises the results, demonstrating the relative stability of WSCR and the sensitivity of VSI to localised voltage performance.

Nodes with VSI < 0.92 typically correspond to long, resistive feeder paths or limited local voltage support, reinforcing their identification as marginal. WSCR remains comparatively stable and captures electrical distance effects well. For example, N2 has an SCR of 4.0 but a marginal VSI of 0.911, while N3 shows voltage limitation (VSI = 0.904) despite a similar SCR. Together, WSCR and VSI provide complementary insights into distribution-level strength.

E. Case Study: 22-Bus TARDS Application

The proposed WSCR–VSI process was applied to the full 22-bus TARDS network to demonstrate practical screening performance.

In **Stage 1**, buses were filtered using WSCR > 0.8. Seven buses fell below the threshold, while fifteen satisfied it and progressed directly.

In **Stage 2**, the seven flagged buses were reassessed using VSI ≥ 0.9. Four passed this criterion and were deemed acceptable with monitoring, while three remained marginal and required EMT study. This highlights WSCR as an effective first-pass filter and VSI as a precise indicator of local voltage strength.

Compared with an *SCR-only* screen (SCR < 3), which would have flagged eleven buses, the combined approach offers greater precision. Field evidence from Essential Energy indicates that four of those eleven buses operate stably under existing DER levels, illustrating misclassification when SCR is applied directly in high-R/X feeders. Moreover, SCR alone did not flag Node N106 (SCR = 4.0, VSI = 0.911), a known voltage-limited location.

Overall, the proposed method reduces EMT studies from eleven to three, focusing effort on genuinely marginal buses (14% of the network). At typical EMT study costs of AUD 20–50 k, this corresponds to AUD 160–400 k in avoided expenditure and approximately 4–8 weeks of engineering effort for the case study. At DNSP scale (order of $\sim$100 DER assessments per year), similar screening precision would avoid 30–40 EMT studies annually, translating to AUD 0.6–2.0 million in avoided cost while improving screening consistency.

IV. DISCUSSION

A. Why WSCR Outperforms SCR

In high-R/X feeders, WSCR and VSI track EMT behaviour more reliably than SCR due to three structural advantages. First, the generation-weighting term captures spatial dispersion: a 20 MW plant located remotely from the substation influences local system strength differently from one connected nearby, as reflected in Eq. (2). Second, proportional scaling of the numerator and denominator renders WSCR largely insensitive to aggregate DER growth, shifting emphasis from penetration level to local strength margins. Third, WSCR occupies a compact and interpretable numerical range (typically 0.5–3.0), whereas SCR can vary by more than an order of magnitude across a single feeder.

These characteristics are evident in the EMT results. Bus B8, despite having SCR = 0.64, recovered stably due to a favourable VSI of 0.918 and would have been misclassified as "very weak" under SCR-only screening. Conversely, Bus B5 (SCR = 2.15) failed dynamically with VSI = 0.895, illustrating how apparently adequate SCR values can mask marginal voltage dynamics.

B. VSI's Complementary Role

VSI provides voltage-specific sensitivity that WSCR (and SCR) cannot. Through the Thévenin-equivalent formulation in Eq. (3), VSI responds directly to reactive margin in feeders where $R/X \approx 1$, a defining characteristic of rural distribution networks. Values approaching 0.9 provide early indication of emerging voltage weakness [15], [24].

Low VSI values identify insufficient local voltage support and inform targeted mitigation measures such as capacitor banks, STATCOMs, or volt–var control [9], [10]. Node N106 (SCR = 4.0, VSI = 0.911) illustrates this effect: short-circuit strength appeared adequate, yet the long, resistive feeder path constrained voltage stability [4], [25].

C. Practical Implementation Considerations

WSCR and VSI can be derived directly from standard load-flow and IEC 60909 short-circuit studies [17]. Thévenin impedances required for VSI estimation may be obtained analytically or via small-signal perturbation techniques [18], both supported by common planning tools. WSCR requires only knowledge of total installed generation, readily available from DNSP connection registers.

Indicative thresholds of VSI ≥ 0.9 and WSCR > 0.8 were shown to be effective for the studied network; however, operators may refine these values to reflect local risk tolerance, data quality, and operating practice. The EMT-calibration procedure adopted here is readily transferable to other high-R/X feeders and international contexts [26], [27].

D. Study Limitations

EMT validation was conducted on eight buses spanning the observed metric ranges. Broader validation across additional feeders would strengthen statistical confidence in the proposed thresholds. Outside the EMT-validated subset, the analysis focused on steady-state behaviour [28] and feeder characteristics typical of regional New South Wales; testing across other NEM regions will be required to assess generality [24].

Inverter models were assumed to operate at fixed power factor under nominal conditions, noting that AS 4777.2:2020 permits dynamic behaviour. Network identifiers were anonymised to protect utility data. These limitations reflect the study's role as a QSS–EMT bridging exercise, with expanded EMT validation forming part of the planned companion journal work.

V. Conclusion

This paper presented an EMT-validated framework for distribution-level system strength screening in networks with high inverter-based resource penetration. By combining the Weighted Short Circuit Ratio (WSCR) with the Voltage Stability Index (VSI), the approach provides a practical alternative to conventional SCR-based screening for high-R/X feeders.

EMT validation confirms VSI as a reliable indicator of transient voltage recovery consistent with AS 4777.2:2020, with WSCR providing a stable first-pass strength measure across increasing DER penetration. Application to a 22-bus TARDS network demonstrates that the two-stage WSCR–VSI process substantially reduces unnecessary EMT studies while improving screening precision.

The framework integrates directly with standard planning studies and supports DNSP compliance with NER S5.1a.9 through a transparent, evidence-based screening process. Future work will extend EMT validation across additional feeders, operating conditions, and inverter technologies, forming the basis of the companion journal publication.

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