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A Comparative Assessment of Voltage Ride-Through Testing Profile Definition in PRC-029-1 for Inverter Based Resources

Iman KAFFASHAN
GridStrong Inc.
Canada
iman@gridstrong.ai

Poria ASTERO
GridStrong Inc.
USA
poria@gridstrong.ai

Maryam TORABI
PSC Consulting
Canada
Maryam.torabi@psc consulting.com

Sifat AMIN
PSC Consulting
Canada
Sifat.amin@psc consulting.com

SUMMARY

As inverter-based resources (IBRs) take on a larger share of generation in North America, their voltage ride-through (VRT) capability has a direct bearing on grid reliability. NERC PRC-029-1, a key North American standard for IBR ride-through requirements, specifies voltage-time performance tables intended to ensure that resources remain connected during system disturbances. However, the standard provides the requirement in tabular form and does not define an explicit voltage profile shape for testing. This leaves room for different test implementations. Different interpretations have appeared in regional and industry guidance, including ERCOT NOGRR245 and IEEE 2800-2022, and these interpretations may lead to different compliance outcomes for the same IBR hardware. This paper compares three testing methodologies using a 200 MW utility-scale wind power plant model using electromagnetic transient (EMT) simulation: (a) isolated single-fault tests with full recovery; (b) sequential step-voltage tests without recovery; and (c) sequential tests with at least 10-second recovery periods. The case study shows that the plant passes Methodologies A and C but trips under Methodology B. This indicates that the test methodology itself can affect the compliance result. The paper provides a systematic comparison of the three methods and discusses the technical implications of each approach. The results suggest that PRC-029-1 would benefit from a clearer voltage-profile definition, or from coordinated guidance with IEEE 2800-2022, to improve consistency across regions and testing practices.

KEYWORDS

Compliance testing, grid code, inverter-based resources, phase-locked loop, PRC-029-1, testing methodology, voltage ride-through

1. Introduction

The share of inverter-based resources in North American transmission systems has grown substantially over the past decade. Unlike synchronous generators, grid-following IBRs rely on phase-locked loops (PLLs) for grid synchronization and respond to voltage disturbances through fast-acting current control. NERC's 2023 performance report documented multiple events in which IBR fleets tripped or reduced output during voltage disturbances [1]. Follow-on analysis pointed to equipment capability as only part of the problem; how compliance with ride-through requirements is assessed also plays a role.

NERC PRC-029-1, effective October 1, 2026, is the primary North American standard governing IBR ride-through requirements [2]. It specifies voltage-time performance tables that define the minimum voltage a resource must sustain at each fault duration. FERC approved the standard in July 2025, citing its role in addressing documented fleet performance gaps [3]. The tabular format, however, leaves the shape of the test waveform between discrete table points unspecified. IEEE 2800-2022 narrows but does not close this gap, and regional guidance documents have filled it in different ways [4]-[6].

The voltage tables in PRC-029-1 list discrete voltage-duration points without stating whether they represent a continuous staircase applied in a single test run or separate fault events, each tested with full recovery in between. Table 1 lists the voltage ride-through requirements taken from PRC-029-1 for AC-connected wind IBRs. The standard states that voltage is "restored to normal" following a disturbance but does not define recovery speed, recovery duration, or whether control systems must return to initial conditions before the next event begins. Its 10-second cumulative window can be read either as the total excursion time across independent faults, or as a single sequence of voltage steps that together add up to ten seconds [2], [7].

These interpretations give rise to three distinct testing methodologies, each examined in turn in Sections 3 and 4 using EMT simulation results for the same wind plant. Section 5 then considers what these findings mean for ongoing NERC and IEEE 2800 standardization work.

Table 1 - Voltage Ride-through Requirements for AC-Connected Wind IBR (NERC PRC-029-1, Attachment 1)[2]

Voltage (p.u.)	Operation Region	Min. Ride-Through Time (s)
> 1.20	N/A (May Ride-through zone)	N/A
≥ 1.10	Mandatory Operation Region	1.0
> 1.05	Continuous Operation Region	1800
≤ 1.05 and ≥ 0.90	Continuous Operation Region	Continuous
< 0.90	Mandatory Operation Region	3.00
< 0.70	Mandatory Operation Region	2.50
< 0.50	Mandatory Operation Region	1.20
< 0.25	Mandatory Operation Region	0.16
< 0.10	Permissive Operation Region	0.16

2. Technical Specification and Interpretation Variations

PRC-029-1 requires applicable transmission-connected IBRs to ride through voltage disturbances defined by voltage-time performance tables, with voltage measured at the high side of the main power transformer. All ride-through regions share a single 10-second cumulative window, and the standard references IEEE 2800-2022 performance categories. It applies to new transmission-connected IBRs from its effective date.

2.1 Aspects Requiring Interpretation

PRC-029-1 voltage tables list discrete points without indicating how voltage transitions between them. A table may specify 0.10 p.u. for 0.16 seconds and 0.50 p.u. for 1.2 seconds, but it does not clarify whether these points define a staircase applied in a single test, whether voltage should return to nominal between them, or what recovery duration is assumed [8].

Table 2 - Three Testing Methodologies in Current Use

Aspect	Methodology A (Isolated)	Methodology B (Sequential, No Recovery)	Methodology C (Sequential, 10-sec Recovery)
Recovery Between Events	Full recovery to 1.0 p.u. with several-second hold	Direct transitions between voltage levels	Full recovery to 1.0 p.u. with 10-second hold
Test Duration	Multiple separate tests	Single continuous test	Single test with recovery periods
Control Reset Between Steps	Full reset	Minimal or none	Full reset
Related Guidance/Practice	Legacy practice; implied in IEEE 2800	Stress-test interpretation for manufacturer use	ERCOT NOGRR245

The standard specifies that voltage is "restored to normal" but does not explicitly define recovery speed or duration, nor whether protection logic and control systems are assumed to reset during recovery. As noted above, the 10-second cumulative window can be read either as ten independent events within a time window or as a single set of sequential steps.

Table 2 ssummarizes the three methodologies considered in this paper. Regional guidance treats the ambiguity differently: ERCOT NOGRR245 explicitly requires sequential testing with 10-second recovery periods for new IBRs, while IEEE 2800-2022 leans toward independent disturbance testing without specifying a fixed recovery duration. PRC-029-1 itself permits either reading through its tabular format and cumulative-time language [1], [4].

3. Methodologies: Technical Characteristics and Comparison

3.1 Methodology A: Isolated Single-Fault Testing

Under Methodology A, each fault event is tested independently with full recovery to pre-disturbance conditions between tests. The voltage-time table is treated as a set of discrete specifications, with each point representing a possible grid event. Because control loops, protection counters, and reactive current limiters start from a stable initial state for each test, grid-following inverters have time to settle between events, limiting PLL phase-angle accumulation [9], [10]. Individual faults on a transmission system typically propagate and clear in this same isolated manner, which is the main strength of the approach; its drawback is that a separate test run is needed for each voltage level.

3.2 Methodology B: Sequential Step-Voltage (Without Recovery)

Methodology B applies all voltage steps consecutively in a single run, transitioning directly from one level to the next without returning to nominal voltage. The practical effect is that PLL synchronization is challenged at every transition without a settling period, as analyzed in [10]. Typical transmission fault clearing does not look like this: voltage generally recovers after a protected fault before another severe voltage event occurs. Of the three approaches, Methodology B places the highest cumulative stress on inverter controls [11].

3.3 Methodology C: Sequential Steps with 10-Second Recovery (ERCOT Model)

Methodology C follows the procedure defined in ERCOT NOGRR245. Each voltage step is applied for the required duration, after which voltage returns to 1.0 p.u. and is held for at least 10 seconds before the next step begins. The recovery hold gives PLL synchronization time to stabilize, lets voltage and frequency protection counters reset, and releases the reactive current limiters. From the IBR's perspective, each step is effectively independent, so the response resembles Methodology A while still covering the full voltage-time table in a single test session. CIGRE C4 guidance on IBR verification testing treats this recovery-bracketed sequential structure as consistent with reproducible compliance assessment [13]. Table 3 compares the three methodologies side by side.

Table 3 - Methodology Comparison

Criteria	Methodology A (Isolated)	Methodology B (Sequential, No Recovery)	Methodology C (Sequential, 10-sec Recovery)
Represents Typical Grid Faults	Yes	No	Yes
Control Reset Between Steps	Full	Minimal	Full
Test Execution Efficiency	Lower (multiple runs)	Higher (single run)	Medium (single run, longer duration)

Produces Cumulative Control Stress	No	Yes	No

4. Case Study: 200 MW Wind Power Plant Testing

The case study uses a 200 MW wind power plant modelled in EMT software and connected to a 345 kV system. The plant consists of two aggregated wind turbine generator equivalents with rated outputs of 120 MW and 80 MW. Both units use grid-following converter controls with PLL synchronization, and the simulation time-step is 10 µs. Pre-disturbance conditions are 1.02 p.u. voltage at the point of measurement (POM), $jX_L = 0$ (so POI and POM are electrically the same), 200 MW active power output, and approximately 0 MVAR reactive power output. All disturbances are balanced three-phase voltage dips applied at the POM. The plant configuration is shown in Figure 1.

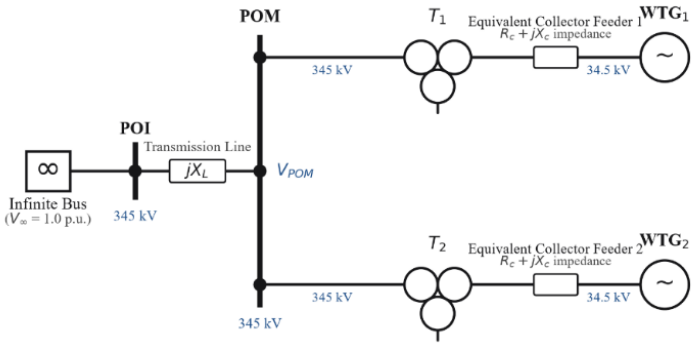


***Figure 1** – Single-Line Diagram for the Wind Farm Power Plant Under Study*

4.1 Test Scenario 1: Isolated Single-Fault Testing (Methodology A)

The plant response under Methodology A is shown in Figure 2. The voltage dip levels and fault durations applied under Methodology A are taken from the PRC-029-1 performance table for wind IBRs, shown in Table 1. Four isolated voltage dip tests are considered: 0.0 p.u. for 0.16 s, 0.25 p.u. for 1.2 s, 0.5 p.u. for 2.5 s, and 0.7 p.u. for 3.0 s. These cases are shown in Figure 2(a), Figure 2(b), Figure 2(c), and Figure 2(d), respectively. For example, during the isolated 0.5 p.u. voltage sag, active power injection falls to approximately 100 MW as the current limiter activates, while reactive power rises to around 90 MVAR in support of voltage. The PLL maintains stable synchronisation throughout, with smooth phase tracking and no frequency counter accumulation, and all protection thresholds remain within limits with neither unit tripping.

The plant rides through all voltage-duration points when each event is tested with full recovery between steps, and both aggregated units remain connected throughout all four test scenarios.

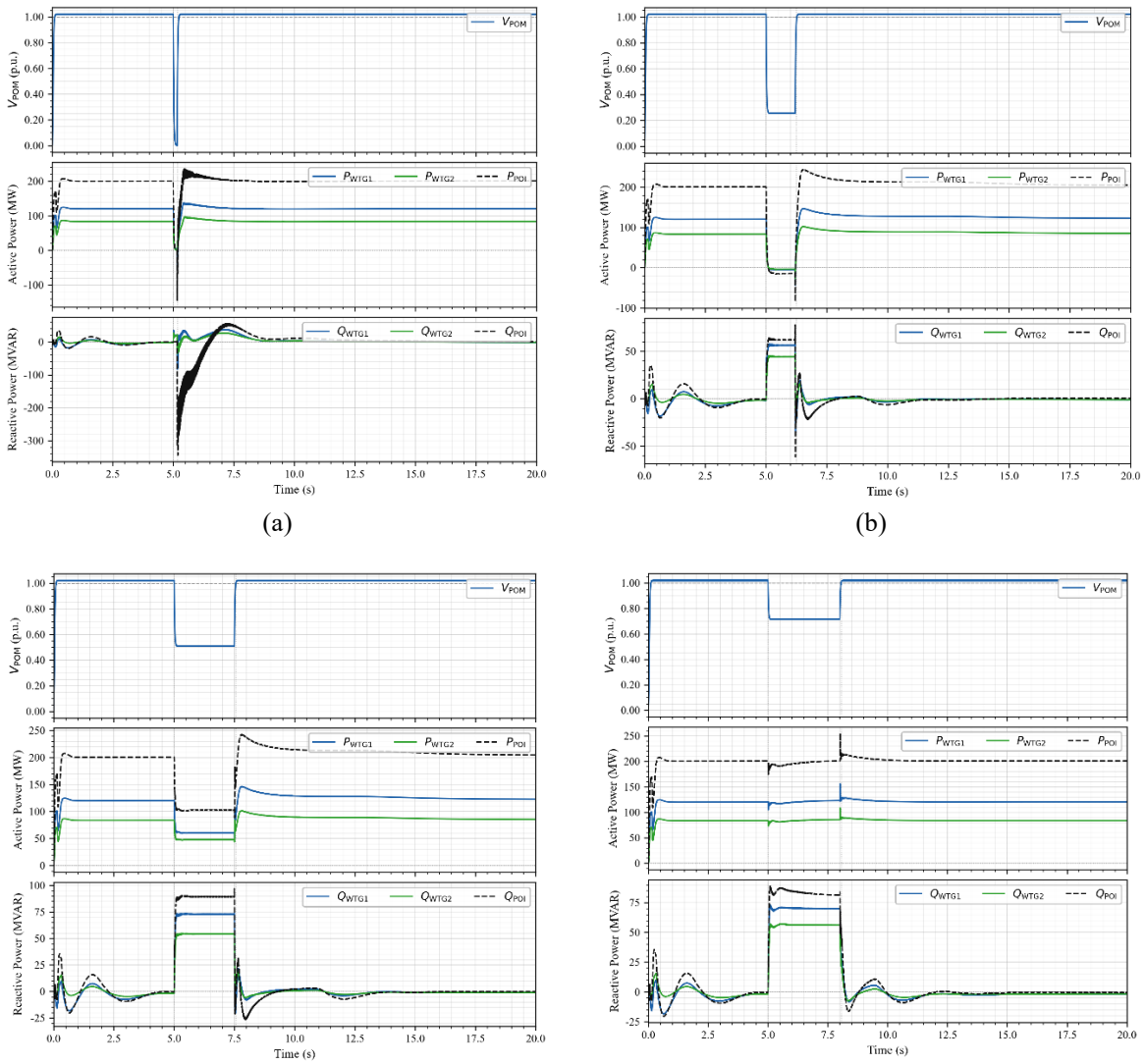


***Figure 2** – Methodology A: Plant Response Waveforms for: (a) Voltage dip to 0.0 p.u. for 0.16 sec, (b) Voltage dip to 0.25 p.u. for 1.2 sec, (c) Voltage dip to 0.5 p.u. for 2.5 sec, (d)Voltage dip to 0.7 p.u. for 3.0 sec*

4.2 Test Scenario 2: Sequential Step-Voltage Without Recovery (Methodology B)

As in Methodology A, the voltage dip levels and fault durations are taken from the PRC-029-1 performance table for wind IBRs. However, under Methodology B, the voltage steps are applied consecutively without intermediate recovery. The resulting plant response is shown in Figure 3. At each step transition, the PLL experiences a phase-angle jump without a settling window, consistent with the behaviour described in [9]. By approximately 7.5 s, when voltage transitions from 0.5 p.u. to 0.7 p.u., the protection threshold for WTG 1 (120 MW) trips the unit. The reactive current limiter, which approached saturation during the 0.5 p.u. step, provides reduced margin for subsequent steps, accelerating the threshold exceedance. WTG 2 continues but enters unstable operation shortly after. This cumulative control stress mechanism is documented in PNNL's IBR performance analysis [12]. This outcome differs from

Methodology A, where the same plant remains stable. This may be a genuine ride-through limitation under this stress condition, which PRC-029-1 does not state the plant must withstand.

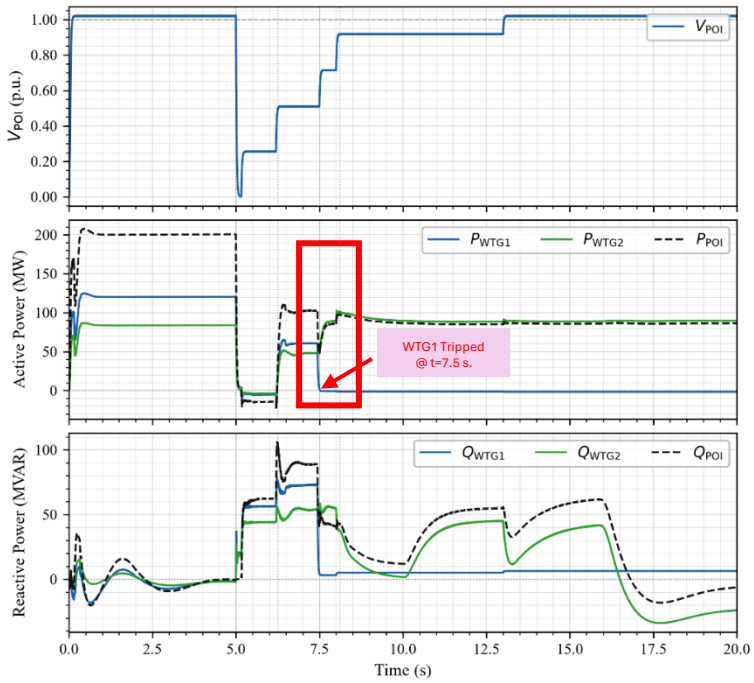


***Figure 3** – Methodology B: Plant Response Waveforms for sequential Voltage Dips without Recovery*

4.3 Test Scenario 3: Sequential Steps with 10-Second Recovery (Methodology C)

The plant response under Methodology C is shown in Figure 4. During each 10-second recovery period, active power ramps back to 200 MW, reactive power returns to baseline, and frequency deviation settles below 0.01 Hz. Voltage and frequency protection counters reset fully before the next step begins, and PLL phase errors resolve during the hold, giving stable synchronization for each subsequent event. Reactive current reserve is likewise restored, so margin is available for the next step. No tripping is observed, and both aggregated units remain connected throughout the full test.

4.4 Comparative Results

Compliance outcomes across all three methodologies are summarized in Table 4. The plant passes under Methodologies A and C and fails under Methodology B. The same plant model satisfies the voltage-time requirements when recovery is provided between voltage steps, so the difference comes down to whether the test sequence allows control states to reset between events.

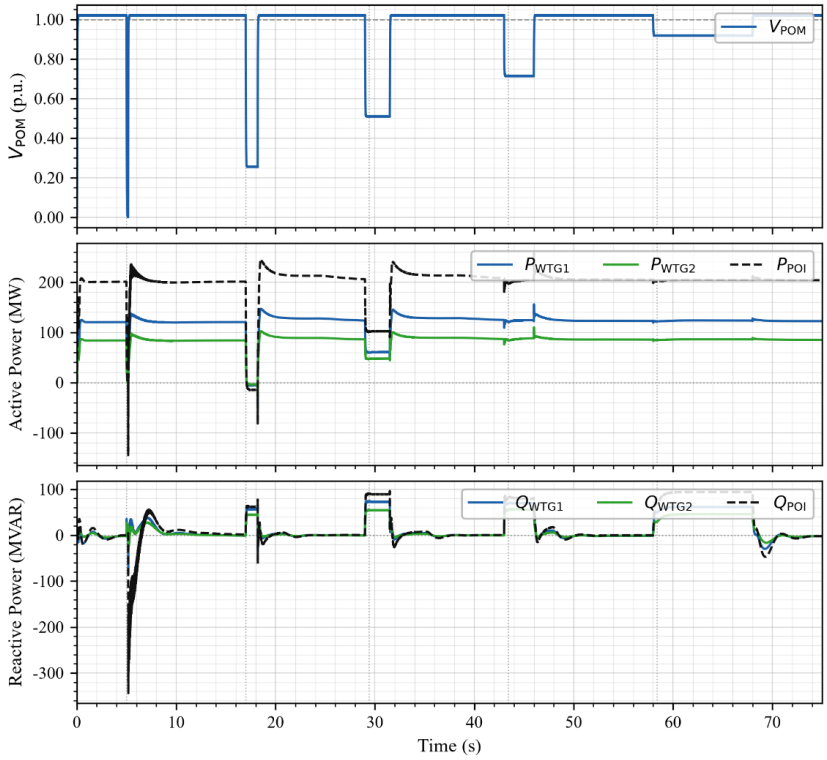


***Figure 4** – Methodology C: Plant Response Waveforms for sequential Voltage Dips with at least 10-second Recovery Period at 1.0 p.u.*

Table 4 - Compliance Outcomes by Methodology

Methodology	Unit 1 Status	Unit 2 Status	Trip Observed
A: Isolated Faults	Stable	Stable	No
B: Sequential, No Recovery	Trips at 7.5s	Unstable	Yes
C: Sequential, 10-sec Recovery	Stable	Stable	No

These results show that the selected methodology can change the compliance outcome for the same plant model and settings. Under Methodology B, the trip reflects cumulative control stress from consecutive steps without recovery. This may be a genuine ride-through limitation, though PRC-029-1 does not state whether the standard requires the plant to withstand this condition. Figure 5 compares the overlaid voltage profiles for all three methods. In this figure, Methodology A is represented only by the 0.5 p.u. voltage dip because each voltage dip is tested separately under the same timing conditions.

5. Discussion: Technical and Standardization Considerations

5.1 Profile Definition in Standards

The case study leaves an open question of interpretation: two methodologies pass and one fails for the same plant model and settings, and PRC-029-1's text does not indicate which one reflects

its intent. EPRI's 2025 review concluded that explicitly defining the voltage profile shape is technically feasible and would reduce current interpretation variation [7].

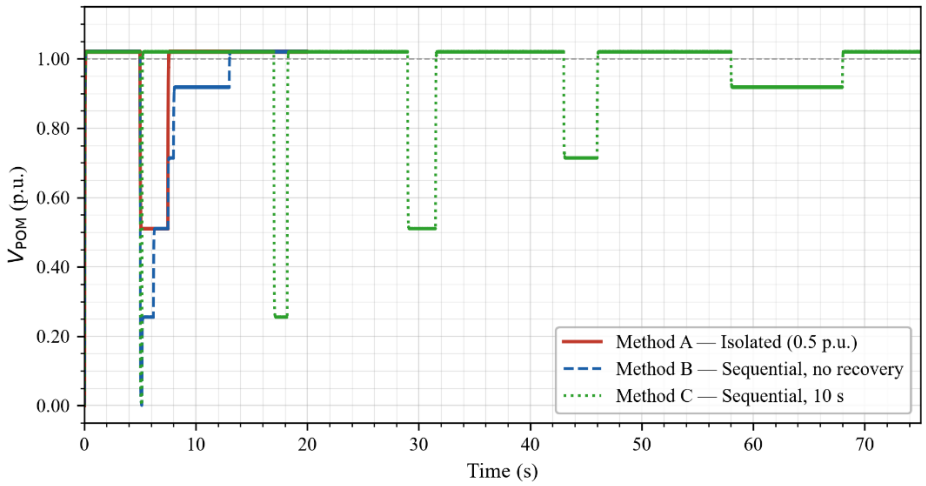


***Figure 5** – Overlay Comparison: Three Testing Methodology Voltage Profiles*

Methodologies A and C both assume that voltage events clear independently before the next one occurs, which lines up with typical transmission fault clearing. Methodology B, in contrast, applies consecutive voltage steps within a compressed timeframe and without intermediate recovery, producing a more severe control-stress condition than a cleared fault followed by recovery, and one that is less representative of typical protected transmission-system behavior This does not establish which stress condition PRC-029-1 requires the plant to withstand.

Historical transmission fault sequences could help determine which methodology best matches the standard's intent. The 10-second recovery period in Methodology C gives time for voltage recovery, protection counter reset, and control-system settling; writing this requirement explicitly into PRC-029-1, or aligning it with IEEE 2800 guidance, would go a long way toward reducing regional variation.

5.2 Measurement Location Interpretation

PRC-029-1 specifies voltage at the high side of the main transformer, but transformer impedance and collector-system losses can create a difference between that measurement point and the wind turbine generator terminals. Standardized guidance on translating high-side voltage requirements to unit-terminal test conditions would remove a secondary source of variation in how the standard is applied across different site configurations.

6. Conclusions

NERC PRC-029-1's voltage-time tables do not specify a voltage profile shape or testing procedure, and this gap allows for more than one reading of the standard. Three methodologies were compared here: isolated single-fault tests (Methodology A), sequential steps without recovery (Methodology B), and sequential steps with 10-second recovery following the ERCOT NOGRR245 approach (Methodology C).

EMT simulation of a 200 MW wind plant found that the same plant model passes under Methodologies A and C and fails under Methodology B, confirming that compliance outcomes can hinge on which test profile is applied rather than solely on the plant's ride-through capability. This does not mean the plant lacks ride-through capability, only that PRC-029-1 does not specify which stress condition it must cover. Writing the voltage profile and recovery requirements into the standard explicitly, rather than leaving them to regional interpretation, would give testing organizations a consistent basis for compliance assessment across regions.

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