Technical Perspectives on Voltage Ride-Through Requirements in IEEE Std 2800-2022: Clarifications and Recommendations for Improvement

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***Abstract*—IEEE Std 2800-2022 establishes performance requirements for inverter-based resources (IBRs) connecting to the transmission system, with Clause 7.2 specifically addressing voltage ride-through capability and associated performance expectations. This paper presents technical perspectives on these requirements, identifying areas where clarification or refinement could enhance the standard's clarity and practical implementation. Through illustrative examples and analysis, the paper offers recommendations for consideration during the revision of the standard, aimed at supporting consistent interpretation and effective integration of IBRs under diverse system conditions**

***Index Terms*—Inverter-Based Resource, Voltage Ride-Through, IEEE Std 2800-2022.**

I. Introduction

As the penetration of inverter-based resources (IBRs) is increasing and their capability continues to evolve, the IEEE Std 2800™-2022 was developed, which addresses minimum technical capability and performance requirements for the IBRs. In this first version of the standard, an attempt has been made to strike a balance between state-of-the-art IBR technology and the needs of the future grid. The IBR performance requirements of the standard include, but are not limited to, reactive capability, active and reactive power control, voltage and frequency ride-through capability and performance, power quality, modeling, and measurement data for performance monitoring and validation. The focus of this paper is to highlight areas of voltage ride-through capability and performance requirements (Clause 7.2) where further clarification or refinement is necessary in the next revision of this standard.

General information applicable to voltage ride-through capability and performance requirements are as follows:

- The reference point of applicability for "capability" requirements is the point of measurement (POM). In simple words, POM is the high-side terminal of the main power transformer.
- The reference point of applicability for "performance" requirements is the point of connection (POC). The POC is the terminal of the IBR unit. IBR unit refers to inverters, wind turbine generators (WTGs) etc. within the IBR plant and may include IBR unit transformer.
- For effectively grounded transmission system, the applicable voltages are phase-to-ground and phase-to-phase voltages. For both low- and high-voltage ride-through, the relevant voltage is defined as the lowest and highest magnitude, respectively, of the fundamental frequency phasor component of the applicable voltages at the POM, relative to the corresponding nominal voltage.

The single-line diagram in Fig. 1 of a typical IBR plant shows the POM and POC. The voltage ride-through requirements for IBR plant with auxiliary equipment limitation (e.g., wind plant) are presented in Table I.

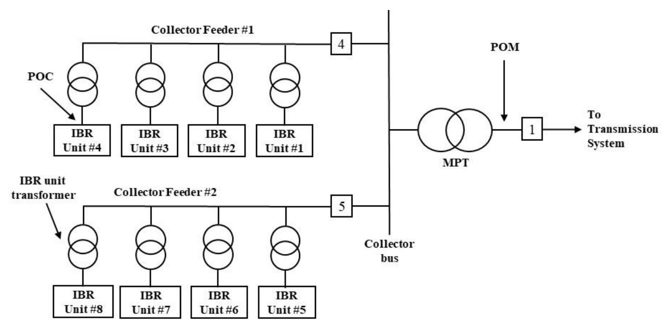

Fig. 1. A typical IBR plant arrangement

TABLE I
Voltage ride-through requirement for IBR plants with Auxiliary Equipment Limitations

Voltage (per unit)	Operation Region	Minimum Ride-Through Time (Sec)
> 1.20	N/A	N/A
> 1.10	Mandatory	1.0
> 1.05	Continuous	1800
≤ 1.05 and ≥ 0.90	Continuous	Continuous
< 0.90	Mandatory	6.00
< 0.70	Mandatory	3.00
< 0.50	Mandatory	1.20
< 0.25	Mandatory	0.32
< 0.10	Permissive	0.32

Except for 500 kV system nominal voltage, the continuous operation region is when the applicable voltage is >= 0.9 per unit and <= 1.05 per unit. The ride-through duration when voltage > 1.05 per unit but <= 1.10 per unit is 1800 second. For 500 kV system nominal voltage, the continuous operation region extends to 1.10 per unit voltage. The time duration specified in Table I is cumulative over one or multiple

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disturbances within a 10-s time period except when applicable voltage is greater than 1.05 per unit and less than or equal to 1.10 per unit, in which case the specified duration is cumulative over one of multiple disturbances within a 3600-s time period.

The subsequent sections of this paper delve into specific voltage ride-through capability and performance requirements outlined in Clause 7.2 of IEEE Std 2800-2022. The paper highlights areas where ambiguity may arise in applying the standard. By identifying these gaps and proposing potential refinements, the goal is to support a more consistent and technically sound specification of voltage ride-through requirements in future revisions of the standard.

II. Clause 7.2.2.1 – General Requirements and Exceptions

The IEEE 2800 states that the "*IBR plant shall ride through a voltage disturbance event wherein the applicable voltage exceeds or is less than the voltage range representing the continuous operation region, except for voltage magnitude deviations more severe than the voltage thresholds and persisting for greater than the associated durations as specified*". In other words, an IBR plant with auxiliary equipment limitations—such as a wind plant—is required to ride through voltage deviations below the continuous operation region except when the voltage deviation is below 0.9 per unit for > 3 seconds, except when the voltage deviation is below 0.7 per unit for > 2.5 seconds, except when the voltage deviation is below 0.5 per unit for > 1.2 seconds, except when the voltage deviation is below 0.25 per unit for > 0.16 seconds. Based on this understanding, one interpretation of the voltage ride-through requirement is that a wind plant must withstand a single voltage disturbance event where the voltage drops to zero at time t = 0, then gradually recovers as follows:

- Rises to 0.25 pu at t = 0.16 s
- Rises to 0.5 pu at t = 1.2 s
- Rises to 0.7 pu at t = 2.5 s
- Rises to >0.9 pu at t = 3 s

This sequence, illustrated in Fig. 2, suggests that for a single voltage disturbance event as described above, the voltage versus time curve reflecting the voltage ride-through requirements resembles a voltage versus time envelope. However, Annex D in the standard states that voltage ride-through boundary is not intended to define an envelope that can be overlaid on a simulated or recorded (during an event) voltage trajectory to determine conformance.

This distinction is critical when extending the interpretation to IBR unit design and type testing. At the time of writing, IEEE P2800.2—Recommended Practice for Test and Verification Procedures for IBRs Interconnecting with the Bulk Power System—does not propose type tests for individual IBR units and design evaluation tests based on plant-level simulations using a voltage envelope. Instead, verification procedures are focused on individual voltage bands within the voltage ride-through requirements. The concern is that unless the IBR units are type tested for a voltage versus time envelope, relying solely on model based simulations may provide a false sense of security regarding voltage ride-through capability.

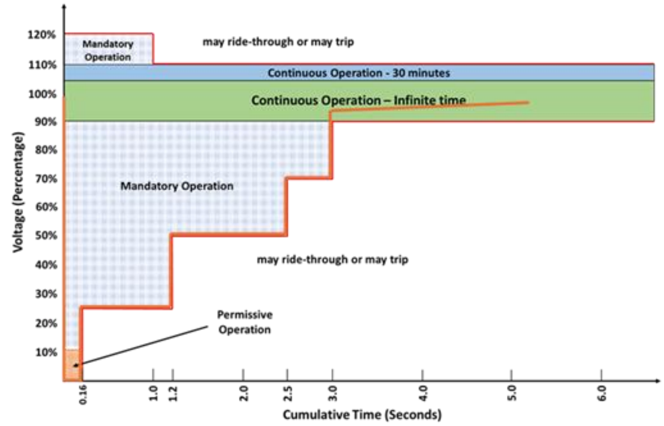

Fig. 2. Voltage disturbance hugging the boundary of voltage versus time curve

Clause 7.2.2.1 includes an exception stating: "*For a voltage disturbance that reduces the applicable voltage at the RPA to less than 50% of the nominal, the IBR plant shall be considered compliant with this standard if the post-disturbance apparent current of the IBR plant is not less than 90% of the pre-disturbance apparent current.*" The intent of the exception is to acknowledge that, over the operational life of an IBR plant and across a wide range of transmission system and plant operating conditions, there may be instances where some IBR units trip during severe voltage disturbance. This recognition is both practical and necessary. However, since apparent current is influenced by reactive current, and reactive current injection or absorption can vary significantly based on system dynamics before and after the disturbance, comparing pre- and post-disturbance apparent current may not be a reliable metric. It may be that the standard alludes to apparent current available and not necessarily measured at the POM. To avoid ambiguity, a more appropriate approach would be to define requirement based on the number of IBR units that remain in service following a severe voltage disturbance. Specifically, the standard should state that the IBR plant is considered compliant if at least 90% of the total IBR units remain in service following the disturbance.

As shown in Table I, the region where voltage at the point of measurement (POM) falls below 10% is designated as the permissive operation region. Within this region, the IBR is permitted to inject or block current. The permissive operation region was introduced due to limited understanding of the risks and benefits associated with current injection or blocking under such low-voltage conditions. Since the publication of the standard, there has been little to no literature offering guidance on how this capability should be utilized. Moreover, transmission entities have increasingly required IBRs to continue injecting current within the permissive operation region. To address this gap, the next revision of the standard should consider providing clearer guidance and revising the requirement as necessary.

III. Clause 7.2.2.2 – Voltage Disturbances within Continuous Operation Region

Clause 7.2.2.2 specifies that for voltage disturbances within the continuous operation region, the IBR plant "*shall continue*

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to deliver the pre-disturbance level of active power or available active power, whichever is less." It also allows for "*temporary deviations of active power output as agreed upon between the IBR owner and the transmission system operator.*"

If the IBR plant is operating at its continuous (rated) active power prior to the disturbance, it should be capable of maintaining that active power level and supplying reactive power up to its defined capability—provided the frequency remains near nominal.

However, under stressed conditions—such as when frequency is at the lower limit of the continuous range (e.g., 58.8 Hz) and voltage is also depressed (e.g., 0.95 p.u.)—the plant may not be able to sustain both the pre-disturbance active power, and the minimum required reactive power simultaneously. In such cases, if operating in voltage control mode, the IBR plant would prioritize reactive power delivery over active power to support voltage.

Furthermore, Clause 7.2.2.2 states: "*If the IBR plant cannot deliver both active and reactive power due to its current limit (or apparent power limit), when the applicable voltage is below 95%, then preference shall be given to active power or reactive power according to requirements specified by the TS operator.*" This wording implies that when the applicable voltage is above 95%, the IBR plant is expected to deliver both rated active and reactive power. However, as previously noted, the IBR plant's ability to do so also depends on system frequency, which should be acknowledged in this clause.

When IBR plant's power plant controller (PPC) operates in voltage control mode (as defined in Clause 5.2.2 of IEEE Std 2800-2022), it adjusts reactive power to maintain voltage at the POM. Since power is proportional to voltage, if the POM voltage near the lower end of the continuous operation region, the PPC will typically request maximum active and reactive power from IBR units. At that point, IBR unit's internal controls determine priority, as the ultimate constraint is IBR unit's current limit. Given active and reactive power references from the PPC, the IBR unit's current required to meet these references is a function of the IBR unit's terminal voltage. Fig. 3 illustrates a case where IBR units prioritize reactive power during a low-voltage condition while operating at their current limit, with the PPC still in voltage control mode. Before the disturbance, the plant delivers 95 MW (its rated active power). At t = 10 s, the voltage drops to 92% of nominal. In response, the plant increases reactive power output to its limit of 32 MVAr (≈33% of 95 MW), but due to current limit, active power is reduced to 86.6 MW. The increase in reactive power helps POM voltage to recover to 93.7%. However, because of low voltage and current limits, the plant cannot supply rated active and reactive power simultaneously.

Most IBR units do not necessarily offer a configurable option where one could choose between active and reactive power priority when POM voltage (and equivalent POC voltage) is within the continuous operation region. Even if IBR units are configured to prioritize active power when POM voltage is between 90% and 95%, this mode carries risk. Depending on tap position of various transformers within the plant, the POC voltage may remain close to POM voltage, when active power is prioritized. Most IBR units enter voltage ride-through mode below 90% terminal voltage, so operating near 90% POM voltage could result in undesirable behavior.

Additionally, there is no need to explicitly state that "*changes of active power are permitted in response to control commands in accordance with 4.6 or in response to other control settings*" in Clause 7.2.2.2 for the following reasons:

- Clause 4.6 does not define specific control capability requirements. It simply states that the IBR plant *"shall be capable of responding to external control inputs,"* with the specific inputs determined by mutual agreement between the IBR plant owner and the transmission system operator.
- The control inputs referenced in Clause 4.6 are manual inputs and are intended to override automatic control functions. As such, any changes in active power resulting from these inputs are already implicitly covered and do not require separate mention.

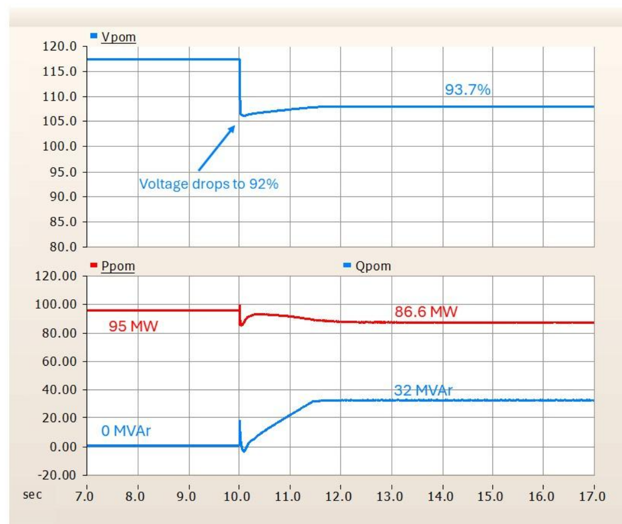

Fig. 3. IBR plant response when operating in voltage control mode

IV. Clause 7.2.2.3 – Low- and High-Voltage Ride-Through within the Mandatory Operation Region

A. *Clause 7.2.2.3.4 Current injection during ride-through mode*

Clause 7.2.2.3.4 outlines the characteristics of current injection requirements during voltage ride-through conditions. These requirements are applicable at the point of connection (POC), i.e., the terminals of the IBR unit. IEEE Std 2800-2022 specifies that "*for unbalanced faults, in addition to increased positive-sequence reactive current, the IBR unit shall inject negative-sequence current.*" The current characteristics is defined in terms of incremental positive-sequence reactive current (ΔIR-1) and incremental negative-sequence reactive current (ΔIR-2). The term "incremental" refers to difference between during fault and pre-fault currents. Recognizing current limit of IBR units, the standard further states that "*if the IBR unit's total current limit is reached, either ΔIR-1 or ΔIR-2, or both may be reduced with a preference of equal reduction in both currents.*" Furthermore, "the *ΔIR-1* shall not be reduced below *ΔIR-2*."

The current wording of the requirement allows flexibility in control design and performance during fault conditions. However, this flexibility also introduces ambiguity in interpretation, which can result in inconsistent implementation. Specifically, the requirement permits the incremental positive-sequence reactive current (ΔIR-1) to exceed the incremental negative-sequence reactive current (ΔIR-2). Consider a line-to-line (B-C) fault on IBR unit terminals, where the positive-sequence and negative-sequence voltages become equal. Assuming a pre-fault operating terminal voltage of 1.0 per unit and ignoring current injection from IBR unit, change in positive-sequence voltage (ΔV1) and negative-sequence voltage (ΔV2) are also equal. Under this condition, setting current injection from IBR unit to ΔIR-1 equal to ΔIR-2, results in zero reactive current injection in an unfaulted phase. This behavior is illustrated in Fig. 4, where ΔIR-1 (~55%) is nearly equal to ΔIR-2 (~52.5%). Given that IBR unit reaches its current limit, the active current injection is reduced to zero. Fig. 5 shows a case where ΔIR-1 > ΔIR-2, leading to increased reactive current injection in the unfaulted phase and a corresponding voltage rise of approximately 10%. Conversely, Fig. 6 demonstrates a scenario where ΔIR-1 < ΔIR-2 resulting in a voltage drop of about 10% in the unfaulted phase.

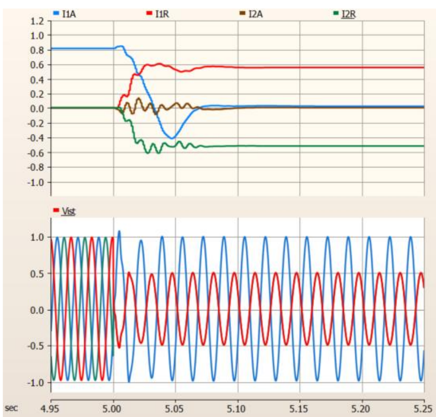

Fig. 4. IBR unit fault response for terminal L-L fault with ΔIR-1 ≈ ΔIR-2

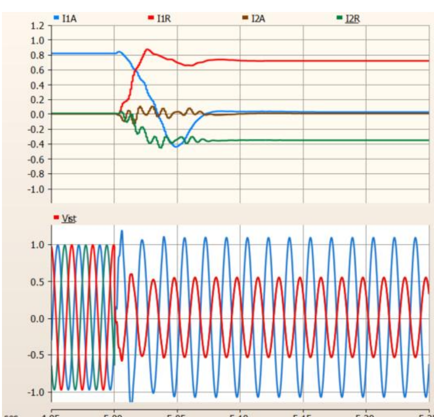

Fig. 5. IBR unit fault response for terminal L-L fault with ΔIR-1 > ΔIR-2

Considering grid needs, the requirement should be that the ratio of change in positive-sequence voltage to change in positive-sequence reactive current should be equal to the ratio of change in negative-sequence voltage to change in negative-sequence reactive current. This proportionality must be maintained while respecting the total current capability of the IBR unit. A requirement written in this manner would also yield acceptable performance for all types of unbalanced faults. The current limit logic presented in [3] could serve as a reference illustrating required IBR unit fault response during unbalanced faults.

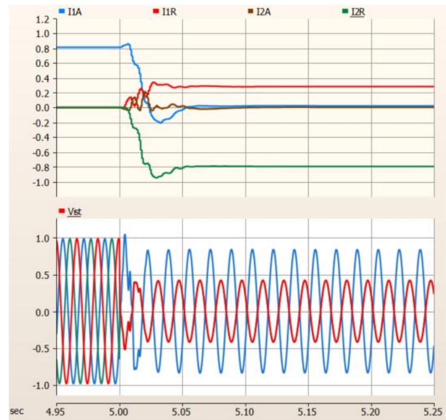

Fig. 6. IBR unit fault response for terminal L-L fault with ΔIR-1 < ΔIR-2

B. Clause 7.2.2.3.5 – Performance specifications

Clause 7.2.2.3.5 outlines performance specifications for IBR unit terminal current during both balanced and unbalanced faults, when voltage falls outside the continuous operation region, as interpreted at the IBR unit terminals. The step response time, settling time, and settling band are specified in Table 13 of IEEE Std 2800-2022. There is an opportunity to clarify the following points in a future revision:

- Scope of performance specifications: It is unclear whether the specified performance metrics apply to the total terminal current or to each individual component—namely, the positive- and negative-sequence active and reactive currents. Clarifying this distinction would improve consistency in interpretation and implementation.
- Time for Voltage Measurement: During the development of performance specifications in Table 12, it was understood that the time required to detect a voltage change at the IBR unit terminals is included within the step response time specified in Table 13 of IEEE Std 2800-2022. The example included in Annex E to illustrate performance requirements also include voltage measurement time in step response time. However, the standard defines step response time as "*the time between the step change in a system quantity measured at a defined location and when the output of the system reaches 90% of required output change, before any overshoot.*" The definition could be interpreted as time starting after the voltage change has been measured. If interpreted this way, the standard does not explicitly specify time permitted for voltage measurement, which could result in inconsistent application of the performance requirement. Clarifying this point in the next revision would ensure consistent understanding and application of the performance requirements.
- Non-uniform settling band: The non-uniform settling band,

defined as -2.5%/+10% of IBR unit maximum current, may be problematic and could result in inconsistent interpretations or implementations. A settling band should typically be symmetric around the target value.

Furthermore, Clause 7.2.2.6 states: "*Upon applicable voltage returning to the continuous operation region (as interpreted at the IBR unit terminals), IBR units shall have the capability to cease injection of incremental positive-sequence reactive current (ΔIR-1) and incremental negative-sequence reactive current (ΔIR-2), in accordance with the performance requirements specified in Clause 7.2.2.3.5.*" It is important to note that the IBR unit's post-disturbance reactive current injection is highly dependent on system dynamics, especially during real-world operating conditions and perhaps during a type testing. These dynamics can significantly influence the post-fault reactive current behavior, and therefore, the ability to cease incremental reactive current injection may vary depending on the specific system response. This requirement in the standard should be relaxed to account for this.

V. Clause 7.2.2.4 – Consecutive voltage deviations ride-through capability

The consecutive voltage deviation ride-through capability requirement in IEEE Std 2800-2022 was introduced in response to events where IBRs failed to ride through multiple voltage dips occurring within a short time frame. While the intent is to improve grid reliability, the current wording could be interpreted to require ride-through for an indefinite number of voltage dip scenarios over time, making conformance difficult to demonstrate. Furthermore, IBR units that rely on chopper circuits to absorb excess energy during voltage disturbances may face limitations in riding through consecutive dips due to the thermal constraints of the chopper. The revision of the IEEE Std 2800 should address these challenges.

VI. Clause 7.2.2.6 – Restore output after voltage ride-through

Clause 7.2.2.6 specifies: "*Upon the applicable voltage returning to the continuous operation region, from a mandatory or permissive operation region where the IBR plant performs ride-through in mandatory operation mode, the IBR plant shall have the capability to restore active power output to 100% of the pre-disturbance level at an average rate equal to 100% of the ICR divided by the specified active power recovery time.*" The default recovery time is set to 1 second, configurable within a range of 1.0 to 10.0 seconds.

This requirement effectively mandates that active power recovery following a voltage ride-through event must follow a ramped profile, meaning the plant control system must be explicitly designed to deliver a ramped response. Such a prescriptive approach may constrain control design flexibility, particularly for controls capable of responding more dynamically, or in cases where the transmission system could benefit from a different form of active power recovery.

Fig. 7 illustrates an example of an acceptable ramped active power recovery response, along with a case that would be considered non-compliant under the current standard requirements.

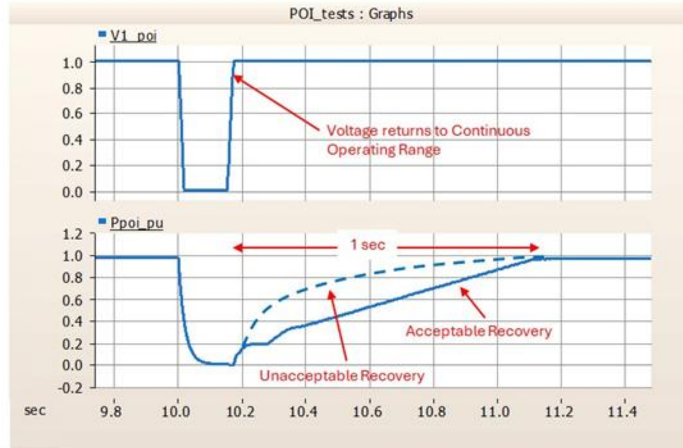

Fig. 7. Example of active power recovery following voltage ride-through operation

VII. Clause 7.2.3 – Transient overvoltage ride-through requirements

The transient overvoltage (TrOV) ride-through requirements in Clause 7.2.3 of IEEE Std 2800-2022 are defined at the POM. However, TrOV-based protection is typically implemented at the IBR unit level, i.e., at the POC, not at the POM. This creates a disconnect between where the requirement is applied and where protection actions are triggered, necessitating a reflection of TrOV conditions from the POM to the POC to assess ride-through capability. Additionally, verifying TrOV ride-through capability through type testing presents challenges, as outlined in the latest draft of IEEE P2800.2. These challenges make conformance with the TrOV ride-through requirement difficult to demonstrate in practice. The next revision of IEEE Std 2800 should consider these issues and make necessary adjustment to TrOV ride-through capability requirements.

VIII. Conclusion/Summary

Clause 7.2 of IEEE Std 2800-2022 outlines voltage ride-through capability and performance requirements for inverter-based resources. While the standard provides a strong foundation—and its intent is clear—it is important to recognize that, as the first of its kind, some requirements may benefit from further clarification to support consistent interpretation and practical implementation. Based on experience with applying the standard, this paper identifies opportunities for refinement in future revisions, ultimately supporting more consistent implementation and reliable integration of IBRs into the transmission system.

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