Technical Rationale

Project 2020-02 Modifications to PRC-024 (Generator Ride-through)

PRC-029-1 – Frequency and Voltage Ride-Through Requirements for Inverter-Based Generating Resources

General Rationale

The drafting team has created a new Reliability Standard (PRC-029-1) to address inverter-based resource (IBR) disturbance ride-through performance criteria. This proposal is a consequence of both the different natures of synchronous and inverter-based generation resources and several recent events exhibiting significant IBR ride-through deficiencies. The proposed PRC-029-1 coincides with certain ride-through requirements of IEEE 2800-2022 but is structured to follow language from FERC Order No. 901, which states that "NERC has the discretion to consider during its standards development process whether and how to reference IEEE standards in the new or modified Reliability Standards."[1]

The lack of standardization of IBR technology (equipment/controller behavior) has created reliability challenges associated with the interconnection of IBR facilities to the power grid. The nature of the fast switching of power electronics of IBR generation and the electronic interface to the transmission system is such that disturbance ride-through behavior is largely determined by manufacturer-specific equipment and controls system designs. These controls may be programmed but also have more restrictive limits on current, both in magnitude and duration. IBR responses to grid disturbances are highly controlled and managed by using fast switching of power electronics devices dependent upon manufacturer specific control system design that can be programmed in many ways and with various and concurrent ride-through performance objectives. Rather than attempting to restrict the myriad of control approaches, protections, and settings, it is more straightforward to require ride-through during defined frequency and voltage excursions.

In contrast to synchronous generation, the need for IBR ride-through requirements has been heightened by recent events during which IBRs have not met PRC-024-3 frequency and voltage ride-through expectations, often due to controls and protection only indirectly associated with the system voltage and frequency excursions. In addition to ride-through, there is the question of what IBRs should be doing as they ride-through. IBR responses to system disturbances can be beneficial or detrimental to both their own ride-through and system reliability, often depending on adjustable control settings. Thus, it is essential to set expectations on performance during ride-through as well as ride-through capability.

IBR do not provide inertia or short circuit contributions, unlike synchronous machines. The drafting team thinks that IBR should compensate for their lack of inertia and short circuit contributions with wider

[1] P 195, FERC Order No. 901; https://elibrary.ferc.gov/eLibrary/filelist?accession_number=20231019-3157&optimized=false; October 17, 2023

tolerances for frequency and voltage excursions. This is the reason for the differences in the frequency and voltage tables and graphs between the two standards.

The proposed PRC-029 must be understood as an event-based standard. though it is also required to provide evidence of the ability to ride-through disturbance events by means of dynamic models and simulation results. Compliance with PRC-029 is determined chiefly though not exclusively from IBR ride-through performance during transmission system events in the field and not from interconnection studies, transmission planning studies, operational planning studies, or from IBR models.. An IBR becomes noncompliant with PRC-029 only when an event in the field occurs that shows that one or more requirements were not satisfied. This intent is clarified by *Operations Assessment* as the Time Horizon designation of requirements R1-R5.

FERC Order No. 901 Directives

PRC-029-1 is proposed in consideration of directives from FERC Order No. 901 that were assigned to the Project 2020-02 drafting team. The following directives were assigned to this drafting team for inclusion in this Standards Project (paragraph numbers of the FERC Order are included for reference):

- Paragraph 190: "Pursuant to section 215(d)(5) of the FPA, we adopt the NOPR proposal and direct NERC to develop new or modified Reliability Standards that require registered IBR generator owners and operators to use appropriate settings (i.e., inverter, plant controller, and protection) to ride through frequency and voltage system disturbances and that permit IBR tripping only to protect the IBR equipment in scenarios similar to when synchronous generation resources use tripping as protection from internal faults."
- Paragraph 190: "The new or modified Reliability Standards must require registered IBRs to continue to inject current and perform frequency support during a Bulk-Power System disturbance."
- Paragraph 190: "Any new or modified Reliability Standard must also require registered IBR generator owners and operators to prohibit momentary cessation in the no-tripmust ride-through zone during disturbances."
- Paragraph 190: "NERC must submit new or modified Reliability Standards that establish IBR performance requirements, including requirements addressing frequency and voltage ride through, post-disturbance ramp rates, phase lock loop synchronization, and other known causes of IBR tripping or momentary cessation."
- Paragraph 193: "Therefore, we direct NERC through its standard development process to determine whether the new or modified Reliability Standards should provide for a limited and documented exemption for certain registered IBRs from voltage ride through performance requirements."
- Paragraph 193: "Further, we direct NERC to ensure that any such exemption would be applicable for only existing equipment that is unable to meet voltage ride-through performance. When such existing equipment is replaced, the exemption would no longer apply, and the new equipment

must comply with the appropriate IBR performance requirements specified in the Reliability Standards (e.g., voltage and frequency ride through, phase lock loop, ramp rates, etc.)."

- Paragraph 193: "Finally, we direct NERC, through its standard development process, to require the limited and documented exemption list (i.e., IBR generator owner and operator exemptions) to be communicated with their respective Bulk-Power System planners and operators (e.g., the IBR generator owner's or operator's planning coordinator, transmission planner, reliability coordinator, transmission operator, and balancing authority)."
- Paragraph 199: "Pursuant to section 215(d)(5) of the FPA, we modify the NOPR proposal. To the extent NERC determines that a limited and documented exemption for those registered IBRs currently in operation and unable to meet voltage ride-through requirements is appropriate due to their inability to modify their coordinated protection and control settings, we direct NERC to develop new or modified Reliability Standards to mitigate the reliability impacts to the Bulk-Power System of such an exemption."
- Paragraph 208: "Pursuant to section 215(d)(5) of the FPA, we adopt the NOPR proposal and direct NERC to develop and submit to the Commission for approval new or modified Reliability Standards that require post-disturbance ramp rates for registered IBRs to be unrestricted and not programmed to artificially interfere with the resource returning to a pre-disturbance output level in a quick and stable manner after a Bulk-Power System."
- Paragraph 209: "The proposed new or modified Reliability Standards must require registered IBRs to ride through momentary loss of synchronism during Bulk-Power System disturbances and require registered IBRs to continue to inject current into the Bulk-Power System at pre-disturbance levels during a disturbance, consistent with the IBR Interconnection Requirements Guideline and Canyon 2 Fire Event Report recommendations."
- Paragraph 209: "Related to ACP/SEIA's comment recommending to revise the directive to require generators to maintain synchronism where possible and continue to inject current to support system stability, we direct NERC, through its standard development process, to consider whether there are conditions that may limit generators to maintain synchronism."
- Paragraph 226: "Further, we believe that there is a need to have all of the directed Reliability Standards effective and enforceable well in advance of 2030 and direct NERC to ensure that the associated implementation plans sequentially stagger the effective and enforceable dates to ensure an orderly industry transition for complying with the IBR directives in this final rule prior to that date." (*pertains multiple projects*)

Rationale for Applicability Section (4.0)

Functional Entities (4.1)

The functional entity responsible for assuring acceptable ride-through performance of IBR is either the Generator Owner (GO) ~~and~~or, in the case of High-voltage Direct Current (VSC-HVDC) transmission facilities that are dedicated connections for IBR inverter-based resources to the BPS, the Transmission Owner (TO).

Facilities (4.2)
Applicability Facilities includes only those IBR that also meet NERC registration criteria. Language used within PRC-029-1 applicability only refers to IBR as a whole plant/facility. Consistent with FERC Order No. 901, IBR performance is based on the overall IBR plant and disturbance monitoring equipment requirements established under the proposed PRC-028-1. Requirements within PRC-029-1 do not apply to individual inverter units or measurements taken at individual inverter unit terminals.

Rationale for Requirement R1

The objective of Requirement R1 is to ensure ~~an~~that all applicable ~~IBR~~IBRs will ride~~-~~ through ~~a~~ grid voltage ~~disturbance~~disturbances consistent with the ~~no-trip~~must ride-through zone and ~~Operation Regions~~operation regions specified in Attachment 1. ~~IBR~~IBRs must be able to demonstrate ride-through performance, that they remain electrically connected, i.e., shall not trip, and continue to exchange current, i.e., shall not enter momentary cessation.

The drafting team determined that the definition of "~~no-trip~~must ride-through zones" and "~~Operation Regions~~operation regions" should be consistent with those terms as used within IEEE 2800-2022. Additionally, the team determined that the voltage thresholds of each ~~Operation Region are~~operation region should be based on measurements taken on the high-side of the main power transformer in PRC-029-1, also consistent with IEEE 2800-2022.

Exceptions to Attachment 1 performance criteria are allowable when 1) an IBR needs to trip to clear a fault within its zone of protection, and 2) a documented equipment limitation prevents an IBR from riding through the disturbance ~~in accordance with~~as permitted under Requirement ~~R6~~R4.

When a grid disturbance occurs, such as a close-in fault or a relatively large switching event, the grid voltage may experience a rapid phase angle shift. In such cases, the phase displacement Δθ can be large enough to pose challenges for the PLL to track the terminal voltage, cause control instability within the inverter, such as the inner current control loop or the DC link control loop, and even lead to tripping of the inverter due to the malfunction of the controls.

Since phase angle jumps are common occurrences on the BPS, this standard requires the IBR to be designed and operated to ride-through a minimum phase angle jump of 25 electrical degrees. This is a typical value and aligns with the requirement in IEEE 2800 2022.

Some IBR equipment has PLL loss of synchronism protection, referring to a protective function that operates when the angle displacement Δθ exceeds a threshold for a predetermined period of time (on the order of a couple of milliseconds). Historically, this protection has been used by some inverter manufacturers, especially for inverters in distribution systems. For the IBR connected to the BPS, this protection function should be disabled. If it is enabled, the phase angle jump protection setting should be configured such that the IBR shall only trip to prevent equipment damage.

Rationale for Requirement R2

In addition to having minimum voltage ride-through capability specified in Requirement R1, ~~an~~all applicable ~~IBR is~~IBRs are also required to adhere to certain voltage ride-through performance criteria during ~~a~~ system ~~disturbance~~disturbances. Acceptable performance criteria ~~is dependent~~depend on the ~~Operation Region~~operation region that an IBR is presently in~~,~~ or ~~it's change~~when in transition from one ~~Operation Region~~operation region to another ~~Operation Region~~operation region. Requirement R2 includes specific performance criteria and is needed to assure consistent IBR performance ~~during~~within and each ~~Operation Region~~operation region in Attachment 1 and when in transition between regions.

Rationale for Requirement R2.1

This subpart of Requirement 2 ensures, when the voltage at the high-side of the main power transformer (MPT) recovers to the Continuous Operation Region from either the Mandatory Operation Region or the Permissive Operation Region, an IBR is expected to deliver the pre-disturbance level of active power or available active power, whichever is less. This requires an IBR to exit the "High Voltage Ride Through (HVRT)" or "Low Voltage Ridge Through (LVRT)" modes properly such that it does not cause reduction in the active power when the system already recovers the voltage within the Continuous Operation Region.

When the voltage at the high-side of the MPT is greater than 0.9 per-unit and less than 0.95 per-unit, IBRs are expected to exit the LVRT mode and come back to "normal operating mode". If an IBR has a default total current limit of 1.0 per-unit, the apparent power production of an IBR will be limited to be below 1.0 per-unit (e.g., the per-unit value of IBR terminal voltage). In such case, IBR needs to configure a preference setting, either to maintain pre-disturbance active power or maximize the reactive power in order to further help with voltage recovery, according to requirements specified by the Transmission Planner, Planning Coordinator, Reliability Coordinator, or Transmission Operator.

Rationale for Requirement R2.2

This subpart of Requirement 2 ensures when the voltage at the high-side of the MPT is within the Mandatory Operation Region, IBRs are expected to enter the HVRT and LVRT mode such that it will inject or absorb reactive current proportional to the level of terminal voltage deviations it measures. IBR shall follow Transmission Planner, Planning Coordinator, Reliability Coordinator, or Transmission Operator specified certain magnitude of reactive power response to voltage changes, if available.

By default, reactive current prioritization shall be configured unless Transmission Planner, Planning Coordinator, Reliability Coordinator, or Transmission Operator requires active power priority.

Rationale for Requirement R2.3

This subpart of Requirement 2 ensures when the voltage at the high-side of the MPT is within the permissive operation region, IBRs are allowed to enter the current block mode to avoid tripping off from the grid. The drafting team takes into consideration the physical operational capability of the power electronics devices under such low voltage condition. However, the IBR facility shall restart current exchange in less than or equal to five cycles of positive sequence voltage retraining to a continuous operation region or mandatory operation region.

Rationale for Requirement R2.4

This subpart of Requirement 2 ensures when a fault is cleared on the transmission system, the voltage regulators of connected IBRs must adjust the reactive current injection to restore the transmission system voltage to the pre-disturbance voltage as defined by the automatic voltage regulator (AVR) setpoint. The drafting team acknowledges that tuning of the AVR requires a balance between multiple competing physical factors, e.g., rise time, overshoot, and transient stability. However, it is anticipated that IBR controls will be tuned to allow for a stable post-disturbance voltage recovery without causing excessive overshoot or undershoot of the setpoint. When such overshoots do occur, they must not exceed the magnitude and duration of the applicable table given in Attachment 1. Furthermore, this standard anticipates that control system tuning to prevent such over/under voltages will focus on the speed at which the controller responds to setpoint changes rather than on the magnitude of the reactive current response. For example, reductions in k-factor to prevent over/under voltages should only be considered as a last resort.

Rationale for Requirement R2.~~4~~5

This subpart of Requirement 2 ensures that IBR returns to effective pre-disturbance operation unless otherwise specified or needed by the Transmission Planner, Planning Coordinator, Reliability Coordinator, or Transmission Operator.

~~*Rationale for Requirement R2.5*~~

~~This subpart of Requirement 2 ensures that voltage protection settings of IBR are based on maximum equipment capabilities rather than settings based directly on, or just outside, of the no-trip zone.~~

Must Ride-through

Rationale for Requirement R3

The objective of Requirement R3 is to provide transient overvoltage ride-through for IBR during the non-fault switching event. Voltage transients are commonly occurring on the BPS due to switching actions, fault clearing, lightning, etc. IBR shall ride-through the transient overvoltage condition specified in **Attachment 2** during the non-fault switching events in the transmission systems. During this transient overvoltage event, IBRs should continue to inject current, but it does not have to respond to transient overvoltage, i.e., enter reactive priority mode and/or change magnitude of current output.

If necessary, IBRs may operate in current blocking mode, when instantaneous voltage exceeds 1.2 p.u., to help ensure stable response that does not lead to tripping and to eliminate the IBR as a possible cause for the overvoltage. If IBRs operate in the current blocking mode, it shall restart current exchange in less than or equal to five cycles following instantaneous voltage falling below, and remaining below, 1.2 p.u. This is different than momentary cessation, which involves a resource returning over a longer time frame with a specified delay and ramp rate.

The drafting team notes that IBR should not be set to trip on an instantaneous, unfiltered voltage measurements, except due to known equipment limitations.

Rationale for Requirement R4

The objective of Requirement R4 is to ensure that IBR remainsIBRs remain electrically connected, synchronized, and exchanging current-, that is, continuing to operate during a frequency excursion event.

Grid frequency reflects the balance of system generation and load. A system event that causes a generation/load imbalance will cause system frequency to deviate from nominal. The system may experience an over-frequency event (in the case of more generation than load) or an under-frequency event (in the case of less generation than load). Inertia resists the deviation from nominal frequency, giving the operators additional time to rebalance generation and load. System inertia depends on the amount of rotating mass connected to the system (such as the synchronous generators or motors). The larger the system inertia, the slower the system frequency will deviate from the nominal value and the lower the grid Rate Of Change Of Frequency (ROCOF), giving more time to try to rebalance generation and load. Also, higher system inertia may minimize the risk of Cascading generation loss caused by the operation of generator frequency protection.

A reduction in system inertia is an inevitable consequence of a power system transiting toward more IBR and less synchronous generators. As discussed in the previous paragraph, less system inertia means the frequency will deviate from the nominal value more quickly during a generation/load imbalance event and will expose the system to a higher ROCOF. A wider frequency ride-through capability for IBR may be required to avoid the risk of widespread tripping. To reduce the risk of widespread IBR tripping during frequency disturbances, and more generally to ensure the reliability of future grids with high IBR penetration, the drafting team proposes a 6-second frequency ride-through capability requirement for frequencies in the ranges of 61.8Hz to 64Hz or 57.0Hz to 56.0Hz range. The proposed 6-second time frame of the frequency ride-through capability requirement is beyond the IEEE 2800 standard frequency ride-through requirement and beyond frequency ride-through requirements for synchronous machines under proposed PRC-024-4.

IBR lacksIBRs lack the inertia and short circuit contributions of synchronous machines. To compensate for the lack of inertia and short circuit contributions, they should have wider tolerances for frequency and voltage excursions to meet the needs of future power systemsystems with a higher percentage of IBR. Synchronous resources are more sensitive to frequency deviations than IBR resources. All IBR resources (except for type 3 wind turbines) interface to the grid through fast switching of power electronics devices. These power electronic devices are much less sensitive to the transmission system frequency excursion than non-hydraulic turbine synchronous resources (steam turbines and combustion turbines). In the case of the non-hydraulic turbine synchronous resources, the turbine is usually considered to be more restrictive than the generator in limiting IBR frequency ride-through because of possible mechanical resonances in the many stages of turbine blades. Off-nominal frequencies may bring blade vibrational frequencies closer to a mechanical resonate frequency and cause damage due to the vibration stresses. However, inverter-interfaced-IBR does not share this vibrational failure mode. Therefore, IBR should be capable of riding through the increased proposed 6-second frequency ride-through requirement without risk of equipment damage or need for frequency protection to operate.

Requirement R4R3 does not prescribe specific frequency protection settings for IBR equipment. IBR frequency protection settings should only be set to protect the IBR from damage caused by operation at off-nominal frequency. An IBR owner must ensure that the IBR frequency protection does not prevent an IBR from meeting the R4R3 ride-through requirement.

This standard requires that IBR remainsIBRs remain electrically connected and continuescontinue to exchange current during a frequency excursion event in which the frequency remains within the no-tripmust ride-through zone\ according to Attachment 3 and while the absolute ROCOF magnitude is less than or equal to 5 Hz/second. Some IBR controllers and their ability to remain electrically connected and continue to exchange current towith the grid are sensitive to ROCOF during a frequency excursion event. If needed to maintain the stability of the IBR or prevent equipment damage, the R4R3 requirement allows the IBR to trip for an absolute ROCOF exceeding 5Hz/sec within the no-tripmust ride-through zone as shown in Attachment 32. Failure to ride-through due to ROCOF exceeding 5Hz/sec shall only be allowed during a generator/load imbalance event that causes the frequency to deviate from nominal.

The ROCOF protection should not operate at the onset of a fault, during a fault, or at fault clearance, i.e., it should be disabled for faults. The IBR shall ride-through any system disturbance while the voltage at the high side of the main power transformer remains within the no-tripmust ride-through zones as specified in Attachment 1. Furthermore, to reduce the risk of IBR tripping on ROCOF protection, ROCOF shall be calculated as the average rate of change for multiple calculated system frequencies for some time greater than or equal to 0.1 seconds.

Rationale for Requirement R5R4

The objective of Requirement R5 is to ensure IBR remains electrically connected and exchanging current during instantaneous positive sequence voltage phase angle changes initiated by certain non-fault switching events.

Unlike synchronous generators, for which the synchronization mechanism to the grid is naturally preserved by the inertia, the grid following voltage source inverters (VSI) used for the majority of existing IBR facilities are equipped with the Phase-lock loop (PLL) device for synchronization purposes. A typical synchronous reference frame PLL schematic is given in Fig. 1, where the three-phase voltages in the abc reference frame (v_a, v_b, and v_c) are transformed to the dq frame (v_d' and v_q') by the Park's transformation and the phase angle θ is controlled by a feedback loop that regulates the q component to zero.

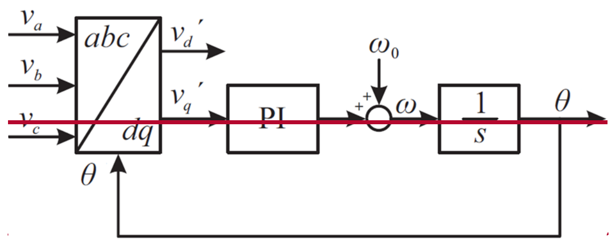

Figure 1: Schematic Diagram of a Synchronous Reference Frame PLL

When the inverter operates in the steady state, it is locked to the grid voltage via the PLL, assuming the PI controller is well tuned. In this case the phase displacement between the grid voltage and that measured by the PLL, Δθ is zero, as shown in Fig. 2.

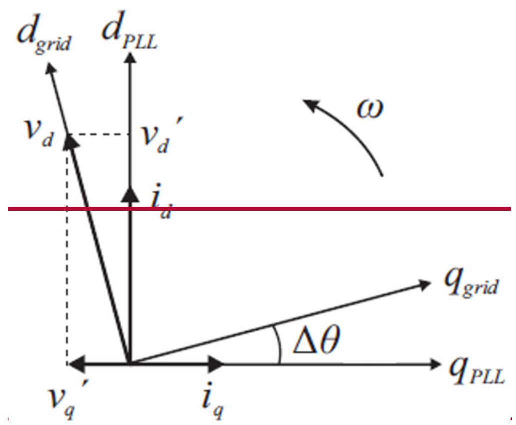

Figure 2: Phasor Diagram of Grid Voltage and Current

When a grid disturbance occurs, such as a close-in fault or a relatively large switching event, the grid voltage may experience a rapid phase angle shift. In such cases, the phase displacement Δθ can be large enough to pose challenges for the PLL to track the terminal voltage, cause control instability within the inverter, such as the inner current control loop or the DC link control loop, and even lead to tripping of the inverter due to the malfunction of the controls.

Since phase angle jumps are common occurrences on the BPS, this standard requires the IBR to be designed and operated to ride-through a minimum phase angle jump of 25 electrical degrees. This is a typical value and aligns with the requirement in IEEE 2800-2022. Furthermore, for a phase angle jump of 25 degrees or more, the IBR shall only trip to prevent equipment damage.

Some IBR equipment has PLL loss of synchronism protection, referring to a protective function that operates when the angle displacement Δθ exceeds a threshold for a predetermined period of time (on the order of a couple of milliseconds). Historically, this protection has been used by some inverter manufacturers, especially for inverters in distribution systems. For the IBR connected to the BPS, this protection function should be disabled. If it is enabled, the phase angle jump protection setting shall be configured such that the IBR shall only trip to prevent equipment damage.

Rationale for Requirement R6

The objective of Requirement R5R4 is to ensure legacy IBR may needare able to obtain an exemption to the voltage ride-through requirements if hardware replacements or other costly upgrades would be necessary to comply with Requirements R1 or Requirement R2. This provision allows such exemptions as long as such limitations are documented and communicated to the Planning Coordinator, Transmission Planner, and Reliability Coordinator of the respective footprints in which the IBR project is located. The Planning Coordinator, Transmission Planner, and Reliability Coordinator will then need to take the voltage ride-through limitations into account in planning and operations.

Limitations must not be construed as complete exemptions from the applicable **Attachment 1** table but must be specific as to which voltage band(s) and associated duration(s) cannot be satisfied or specific as to the number of cumulative voltage deviations within a ten-second time period that the equipment can ride-through if less than four. Limitation descriptions should identify the specific equipment and explain the characteristic(s) of that equipment that prevent ride-through. If any equipment limitation is removed or otherwise corrected, it is likewise necessary to communicate to the Planning Coordinator, Transmission Planner, and Reliability Coordinator of this.

FERC Order No. 901 states that this provision would be limited to exempting “certain registered IBRs from voltage ride-through performance requirements.” This is the reason that no similar provisions are included for exemptions for frequency, or rate-of-change-of-frequency (ROCOF) ,phase angle change ride-through requirements per R3.