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Calculating Generator Ride-Through Requirements

An Overview of Translating the NERC Standard PRC-024-3 Voltage Ride-Through Requirements

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Introduction

NERC Standard PRC-024-3 [1] requires Generator Owners to set frequency, voltage, and volts-per-hertz (V/Hz) protection such that the generating resource(s) remains connected to the Bulk Electric System (BES) and injecting current during defined frequency and voltage excursions. For conventional synchronous generation, this includes the protection elements applied to BES generating resource(s), BES generator step-up (GSU) transformer(s), or the high-voltage side of any generator-connected unit auxiliary transformer (UAT) [1] installed on BES generating resource(s). For dispersed power producing resources identified in Inclusion I4 of the BES definition [2], it includes the protection elements applied to the individual dispersed power producing resource(s), elements designed primarily for the delivery of capacity from the individual power producing resources to the point where those resources aggregate to greater than 75 MVA (e.g., collector feeders), or the main power transformer (MPT) of the power producing resources. The protection may be provided by relaying devices or may exist as a protective function within the associated control system(s).

The High Frequency Duration and Low Frequency Duration ride-through curves defined in Attachment 1 of NERC Standard PRC-024-3 represent the minimum time durations allowed for specified frequency excursion thresholds. Similarly, the High Voltage Duration and Low Voltage Duration ride-through curves defined in Attachment 2 of NERC Standard PRC-024-3 represent the minimum time durations allowed for specified voltage excursion thresholds. During these excursions, the applicable protection elements cannot cause the generating resource to trip or cease injecting current. Thus, the zone between these curves is referred to as the “No Trip Zone”.

It is worth noting that the area outside of (i.e., above or below) these curves do not designate any specific requirements for protection that must be applied – in other words, *the area outside the “No Trip Zone” is **not** a “Must Trip Zone.”* It is recommended that protection element settings be determined based on equipment capability in order to ride through disturbances to the greatest extent possible rather than based solely on the “No Trip Zone.” When necessary, the protection may be set within the “No Trip Zone” for certain regulatory or equipment limitations, provided that the limitation is documented and communicated to the Planning Coordinator and Transmission Planner in accordance with Requirement R3 of PRC-024-3.

In an interconnected system, the average frequency measured at any point in the system will produce the same value; thus, all of the applicable frequency protection elements may be assessed against a common ride-through requirement, even when these elements are connected to different buses within the facility.

[1] The transformer may be variably referred to as station power transformer or station service transformer. This is the transformer connected to the generator bus between the low-voltage side of the GSU transformer and the generator terminals.

Voltage, on the other hand, has a degree of de-coupling between buses and therefore is local to each point in the system. The voltage magnitude and angle will differ based on the admittance between buses and the active and reactive power being injected at each bus. For this reason, the applicable voltage and V/Hz protection elements must be assessed against a bus-specific ride-through requirement.

Voltage Protection Requirements

Attachment 2 of PRC-024-3 specifically identifies that the voltage levels comprising the ride-through curves are defined at the high-voltage side of the generator step-up (GSU) transformer(s) or main power transformer(s) (MPTs) with a low-side voltage rating below 100 kV and a high-side rating of 100 kV or above. The NERC Standard PRC-024-3 voltage ride-through curves are shown Figure 1, below. A figure such as this may be used to directly assess the coordination of voltage and V/Hz Protection System elements that are applied to the high-voltage side of the transformer against the requirements of this NERC standard.

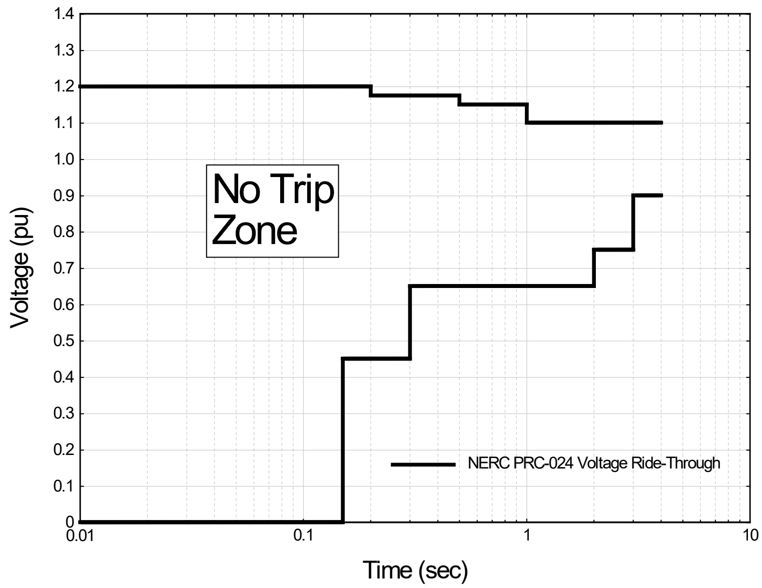

Figure 1: NERC PRC-024-3 Voltage Ride-Through Requirements for Eastern, Western, and ERCOT Interconnections, Defined at the High-Voltage Side of the GSU / MPT

On the other hand, several voltage and/or V/Hz protection elements within the scope of NERC Standard PRC-024-3 are connected to other buses at the facility besides the high-voltage side of the GSU transformer or main power transformer, commonly at the generator terminals or the transformer low-voltage side bus. These elements operate based on the voltage level at that point in the system, which will be different from the transformer high side voltage. Thus, translation of the voltage ride-through time duration curves from the transformer high-voltage side winding to the applicable bus(es) is required to assess the coordination of these voltage and/or V/Hz protection elements. The Evaluating Protection Settings section of PRC-024 Attachment 2 allows for either steady state calculations or dynamic simulations to be used to determine the voltage differences between where the protection is measuring voltage and the high-voltage side of the GSU or MPT, where the voltage ride-through curves are defined.

What is not described in PRC-024 Attachment 2 is the fact that the steady state calculation approach requires a power flow solution to accurately project the ride-through requirements to the buses containing the voltage protection elements. This solution utilizes a fixed known voltage magnitude and assumed voltage angle (but unknown active and reactive power flows) at the transformer high side bus and known active and reactive power (but unknown voltage magnitude and voltage angle) at the generator bus(es). This type of power flow solution generally uses the Newton-Raphson numerical method, and it may be used to translate the PRC-024 voltage ride-through curves from the high-voltage side of the transformer to the associated generator terminal bus or buses. A direct algebraic approach is not feasible, as the power flow solution presents a series of nonlinear equations and therefore cannot be accomplished via non-iterative circuit calculations. [2]

The Newton-Raphson numerical method provides a converging iterative solution that typically requires only a small number of iterations and can be solved for any number of buses in the system being represented. In many cases, the power flow case is as simple as a two-bus system, with one reference bus (with fixed known V and θ) representing the transformer high side and the other as a load bus (with fixed known P and Q) representing the transformer low side and generator terminals. The system becomes more complex with three-winding transformers and multiple levels of step-up transformers to reach the interconnecting voltage. Several commercial power flow software applications are available and used daily in the planning and operation of power systems, which may be used to reflect the voltage ride-through requirements. However, most facilities may be represented by systems of buses that are simple enough to be directly implemented in a computer programming language.

As mentioned in PRC-024 Attachment 2, a dynamic simulation may instead be used, which would provide a detailed time-varying depiction of the estimated response of the generating resources and voltage regulating controls to a voltage excursion caused by conditions external to the facility. Whereas the steady state calculation approach minimizes the level of model data that is required of the facility, the dynamic simulation approach requires both proper steady-state model data to be entered into the simulation software and a validated set of simulation models [3], including limiter models [1]. Based on the model data representing the system, there can be additional complexities such as local mode power oscillations, excitation ceiling limits, or limiter engagement that influence the shape of the voltage ride-through requirements, yielding characteristics that look significantly different from the defined curves (see Figure 2 below).

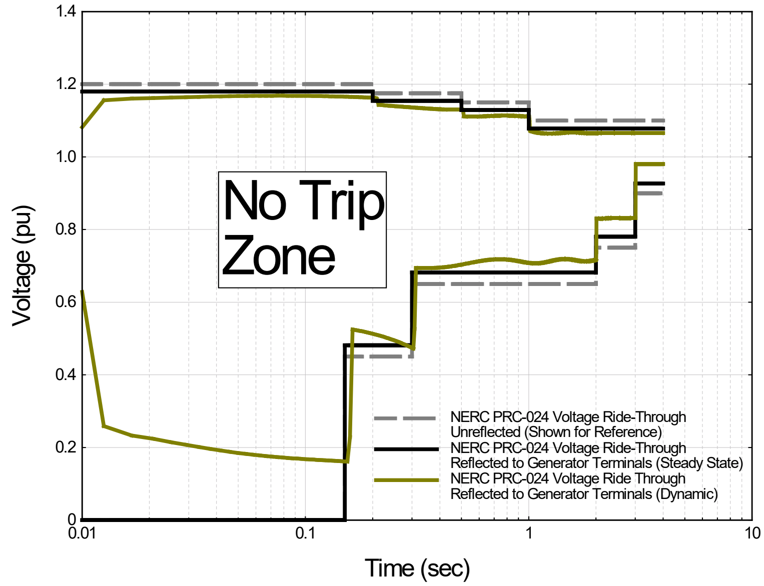

Figure 2: NERC PRC-024-3 Voltage Ride-Through Requirements for Eastern, Western, and ERCOT Interconnections, Reflected to Synchronous Generating Unit Terminals – Example

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[2] The NERC PRC-024-2 implementation guide [5] offers example algebraic circuit equations to translate a given generator voltage level to the high side of the transformer for direct comparison against the ride-through requirements or to translate the ride-through to the generator terminals using an assumed power factor at the high side and a resulting correction factor. The former option is inconsistent with the specifications of Attachment 2, which requires a voltage excursion of known magnitude at the high side of the transformer; while the latter results in a much lower level of accuracy than the Newton-Raphson method. Neither approach is valid for facilities with a more complex arrangement, such as with three-winding transformers, etc.

In either approach, the reactive power output of the generating resource(s) should always be such that it opposes the change in voltage at the high side of the transformer (i.e., supplying reactive power during under-voltage conditions and absorbing reactive power during over-voltage conditions) due to the automatic voltage regulating control systems. This is especially observable in the case of assessing the requirements associated with the High Voltage Duration ride-through curve via dynamic simulation, as shown in Figure 3 below.

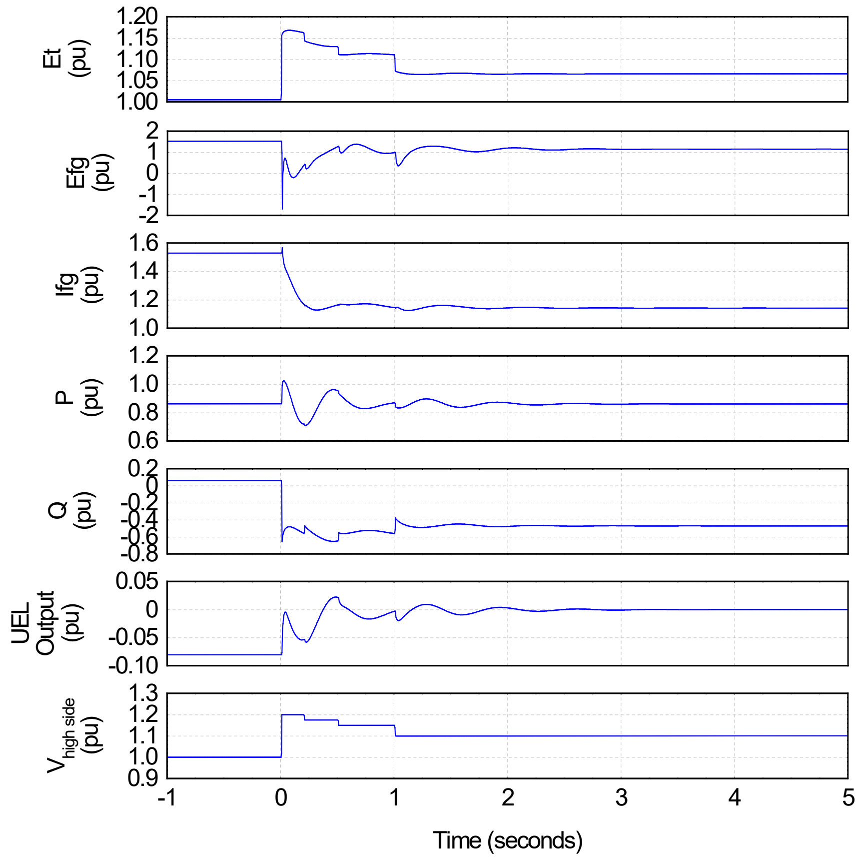

Figure 3: Dynamic Simulation Results of the NERC PRC-024-3 High Voltage Ride-Through Requirements for Eastern, Western, and ERCOT Interconnections – Example

Unlike the conditions listed in previous versions of the PRC-024 standard [4] and the methodology listed in the NERC implementation guide [5], lagging power factor operation is not an acceptable assumption when considering high voltage conditions. Instead, the closed-loop AVR controls will act to reduce excitation and/or the reactive power output of the generating resource(s) in an attempt to restore voltages to their pre-disturbance level (i.e., the regulated voltage setpoint). Using any other assumptions for the generator reactive power output in these calculations ignores the laws of physics and the characteristics of closed-loop feedback control systems. The assumption of lagging power factor operation corresponds to an assumption that the generator(s) and AVR controls are the driving forces behind the over-voltage conditions at the transformer high side rather than the condition being caused by an event on the Transmission System external to the generating facility.

When assessing the requirements associated with the Low Voltage Duration ride-through curve, additional considerations and assumptions must be used at times. In the case of the zero-voltage condition, active power flow is necessarily zero at the high side of the transformer. Other low voltage levels may also require reduced levels of active power generation in order to yield a converging steady state power flow solution. When using a dynamic simulation approach, particularly for conventional synchronous generating units, applying the defined voltage profile at the transformer high side bus often results in the unit(s) accelerating to the point that the generator loses synchronism with the rest of the power system. In such cases, it may be necessary to perform simulations of each prescribed voltage level separately and combine the results of the simulations to yield a resulting ride-through characteristic. Additional guidance from NERC may be necessary in the cases where the 9-cycle bolted fault simulation proves to be longer than the critical clearing time for some generating units, especially if a dynamic performance-based solution becomes the only option for demonstrating compliance with this requirement in future revisions of this NERC standard.

It should be noted that both the steady state and dynamic approaches yield solutions that shrink the "No Trip Zone" are from the original (non-reflected) characteristic, as seen in Figure 2 previously. The extent to which this area is reduced will depend on the transformer impedance, reactive power capability of the equipment, and/or the tuning of the voltage regulating controls. The dynamic solution will often yield an even smaller "No Trip Zone" than the steady state calculation due to the temporary emergency duty reactive power levels that are available prior to limiter action.

Conclusions

Voltage and V/Hz protection elements must be assessed against a voltage ride-through requirement that is specific to the bus at which the elements are located. NERC Standard PRC-024-3 allows for either steady state calculations or dynamic simulations to be used to assess these protection elements against the voltage ride-through requirements defined at the high-voltage side of the GSU transformer or main power transformer to demonstrate compliance with Requirement R2. The steady-state assessment requires an iterative numerical method to solve for the given known quantities (voltage and angle at the transformer high side bus, active and reactive power injected at the generator bus or buses), while the dynamic assessment requires a validated set of dynamic simulation models and power system model data to yield results that are representative of the installed equipment at the facility.

The steady-state solution requires less equipment model data to compute, but it can lead to more stringent ride-through requirements than the dynamic simulation since the generating resources are commonly capable of temporary emergency duty reactive power levels. Additional guidance may be necessary from NERC when the dynamic simulation-based solution produces results that demonstrate system instability, particularly for synchronous generating units. For both approaches, the conditions and assumptions determining the most probable active and reactive power loading conditions for the unit(s) under study must be consistent with the laws of physics that govern active and reactive power flow on the power system and the characteristics associated with closed-loop voltage regulating controls, as described in this paper.

References

[1] "Frequency and Voltage Protection Settings for Generating Resources," NERC Standard PRC-024-3.

[2] North American Electric Reliability Corporation, Bulk Electric System Definition Reference Document, Version 3, Aug-2018.

[3] "Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions," NERC Standard MOD-026-1.

[4] "Generator Frequency and Voltage Protective Relay Settings," NERC Standard PRC-024-2.

[5] North American Electric Reliability Corporation (NERC), "Generator Voltage Protective Relay Settings - Implementation Guidance PRC-024-2 Requirement R2, 19-Jan-2018".