NERC
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RELIABILITY CORPORATION

ERO Enterprise Endorsed

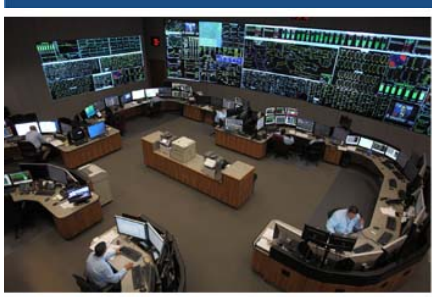
Generator Voltage Protective Relay Settings

Implementation Guidance
PRC-024-2 Requirement R2

January 19, 2018

Submitting Pre-Qualified Organization: NERC Planning Committee (PC)

RELIABILITY | ACCOUNTABILITY

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Overview

Background

Implementation Guidance provides a means for registered entities to develop examples or approaches to illustrate how registered entities could comply with a standard that are vetted by industry and endorsed by the Electric Reliability Organization (ERO) Enterprise. The examples provided in this Implementation Guidance are not exclusive, as there are likely other methods for implementing a standard. The ERO Enterprise's endorsement of an example means the ERO Enterprise Compliance Monitoring and Enforcement Program (CMEP) staff will give these examples deference when conducting compliance monitoring activities. Registered entities can rely upon the example and be reasonably assured that compliance requirements will be met with the understanding that compliance determinations depend on facts, circumstances, and system configurations. [1]

- Guidance documents cannot change the scope or purpose of the requirements of a standard.
- The contents of this guidance document are not the only way to comply with a standard.
- Compliance expectations should be made as clear as possible through the standards development process which should minimize the need for guidance after final ballot approval of a standard.
- Forms of guidance should not conflict.
- Guidance should be developed collaboratively and posted on the NERC website for transparency.

Purpose

This guidance document provides examples of how NERC Registered Entities can project their generator voltage protective relay settings to a corresponding POI voltage, or conversely, project the POI voltages to the corresponding relay voltage. They can then directly compare the relay voltage settings to the PRC-024-2 voltage ride through curve since both values are on the same basis. The technical basis for the variables/assumptions used in these example calculations are included in Appendix 1 of this guide.

Scope

This guidance document applies to Generator Owners (GO) who are demonstrating compliance with PRC 024-2 Requirement R2.

> **R2.** Each Generator Owner that has generator voltage protective relaying activated to trip its applicable generating unit(s) shall set its protective relaying such that the generator voltage protective relaying does not trip the applicable generating unit(s) as a result of a voltage excursion (at the point of interconnection3) caused by an event on the transmission system external to the generating plant that remains within the "no trip zone" of PRC-024 Attachment 2. If the Transmission Planner allows less stringent voltage relay settings than those required to meet PRC-024 Attachment 2, then the Generator Owner shall set its protective relaying within the voltage recovery characteristics of a location-specific Transmission Planner's study. Requirement R2 is subject to the following exceptions:
>
> - Generating unit(s) may trip in accordance with a Special Protection System (SPS) or Remedial Action Scheme (RAS).
> - Generating unit(s) may trip if clearing a system fault necessitates disconnecting (a) generating unit(s).

[1] Source : http://www.nerc.com/pa/comp/Resources/ResourcesDL/Compliance_Guidance_Policy_FINAL_Board_Accepted_Nov_5_2015.pdf

- Generating unit(s) may trip by action of protective functions (such as out-of-step functions or loss-of-field functions) that operate due to an impending or actual loss of synchronism or, for asynchronous generating units, due to instability in power conversion control equipment.
- Generating unit(s) may trip within a portion of the “no trip zone” of PRC-024 Attachment 2 for documented and communicated regulatory or equipment limitations in accordance with Requirement R3.

This guidance document does not demonstrate any calculations for auxiliary equipment voltages.

The examples provided in this document are applicable to facilities where the GSU impedance is the only significant impedance between the point of interconnection (POI) and the relay voltage sensing location and the resource is capable of +/- 0.95 power factor at the POI. For facilities that do not produce a significant amount of reactive power[2], the voltage drop through the GSU transformer is not significant. Therefore, the generator bus voltage can be estimated by reflecting the high-side (POI) voltage to the generator-side solely based on the GSU transformers turns ratio.

[2] See PRC-025-1 Options 4, 5, 10, 12 of the Application Guidelines.

Example Calculations

The following are examples of calculations that could be documented and used to support compliance with the standard. The one-line diagram for the example calculation is shown in Figure 1 and the system parameters are shown below in Table 1.

The quantities used in the following example calculations are example quantities. The basis for these example quantities is included in Appendix 1 of this document. It is reminded that different quantities, that may be determined to be more probable for the specific unit under test, may be substituted for the example quantities in these calculations. These example calculations are intended to provide methodologies to determine the corresponding voltage as seen by the generator voltage protective relay for a given POI voltage. Or conversely, a corresponding POI voltage for a given generator voltage protective relay voltage. Registered Entities may substitute the quantities that they determine to be the most probable for their specific unit, utilizing these methodologies, to compare relay setting voltages to POI voltages.

Relay trip point comparisons

Since the PRC-024-2 Voltage Ride-Through Time Duration Curve ends at four seconds, the accompanying examples display the relay trip characteristic plotted along with the PRC-024 Voltage Ride-Through Time Duration Curve out to four seconds.

In the examples, when comparing generator voltage protection trip settings against the PRC-024-2 Voltage Ride-Through Time Duration Curve, it is important to keep in mind that the curve is defining a no trip area within the curve. PRC-024-2 R2 specifies: "voltage protective relays shall be set to not trip the applicable generating unit for voltage excursions that remain within the no trip zone of Attachment 2". Requirement 2 does not specify any voltage values that the protective relays must trip for, it only specifies values and time that the voltage protective relays must ***not*** trip for. Therefore, in the accompanying examples, if the voltage protective relay trip point is outside the specified "no trip zone" for voltage, there is no cause for concern. It is not required to trip outside of the no trip area. In the PRC-024-2 tables, the term 'instantaneous trip' is used.[3] This term is intended to indicate instantaneous tripping is allowed, if required to protect equipment for abnormal voltages. If the equipment is capable of operating at these abnormal voltages, for greater than the prescribed times, then tripping is not required. Again, if the relay does not trip instantaneously at that value, but at a value outside the curve, there is no cause for concern with respect to the standard.

High Voltage Ride Through Duration		Low Voltage Ride Through Duration	
Voltage (pu)	Time (sec)	Voltage (pu)	Time (sec)
≥1.200	Instantaneous trip	<0.45	0.15
≥1.175	0.20	<0.65	0.30
≥1.15	0.50	<0.75	2.00
≥1.10	1.00	<0.90	3.00

This guidance document demonstrates multiple aspects of determining the generator terminal and GSU high-side simultaneous voltages. Three methods are provided for voltage calculations. The first method demonstrates how to project the relay voltage characteristic to the high-side of the GSU (the typical POI) for a given generator voltage relay setting. This will allow the relay setting to be directly compared to the voltage ride-through time duration curves in

[3] The term instantaneous trip assumes that the tripping element has appropriate filtering and/or security counts to not respond to high-frequency or sub-cycle transients.

Attachment 2 of PRC-024-2. The second and third methods demonstrate how to project the voltage ride-through time duration curve to the secondary of the instrument transformer that supply the generator voltage relay. This will allow the voltage ride-through time duration curves in Attachment 2 of PRC-024-2 to be compared to the relay setting. Method two is based on the PRC-025-1 Option 1b iterative calculation. Method three is a simplified single-iteration approach.

Load Flow Assumption for Low-Voltage Condition

The power factor assumption for the low-voltage condition used in these examples is 0.95 lagging[4] (supplying VArs into the system) as suggested by the standard. This will be the most likely steady-state condition during a low-voltage event, in that the generator will be trying to support the voltage at the POI. While the calculations in this document use these assumptions, other assumptions could be used. A more severe scenario may be a leading power factor condition (absorbing VArs from the system) as the unit would be under excited (lower voltage behind the generator impedance). This would be the more conservative assumption during a low-voltage event for verifying relay setting compliance.

Load Flow Assumption for High-Voltage Condition

The power factor assumption for the high-voltage condition used in these examples is 0.95 lagging[6](supplying VArs into the system) as suggested by the standard. Using lagging power factor would be the more conservative assumption during a high-voltage event for verifying relay setting compliance.

Table 1: System Parameters	
Input Descriptions	**Input Values**
Generator nameplate (MVA @ rated p.f.)	MVA_{GEN_BASE} = 176 MVA
	$p.f._{GEN}$ = 0.85
Generator nominal voltage (line to line)	kV_{GEN_BASE} = 16 kV
Generator step-up (GSU) transformer rating	MVA_{GSU_BASE} = 170 MVA
GSU transformer reactance (170 MVA base)	Z_{GSU} = 10.12%
GSU transformer high-side Nameplate Voltage	kV_{GSU_HS} = 138 kV
GSU transformer low-side Nameplate Voltage	kV_{GSU_LS} = 15 kV
GSU transformer high-side no-load tap Voltage	kV_{GSU_TAP} = 134.5 kV
Nominal System Voltage (line to line)	kV_{SYS_BASE} = 138 kV
Generator VT Ratio	VTR_{GEN} = 140:1
Load power factor	$p.f._{LOAD}$ = 0.95
System MVA base	MVA_{SYS_BASE} = 100 MVA

In the example calculations, the following relays and settings were used:

- One level of undervoltage (27) used for tripping. Pickup set to 102.9 V with a 60 cycle (1 second) delay.
- One level of overvoltage (59) used for tripping. Pickup set to 125.7 V with a 1800 cycles (30 second) delay.

[4] See Appendix 1 for rationale for using 0.95 lagging

- One level of definite time Volts/Hertz (V/Hz) (24) used for tripping. Pickup set to 118% of generator nominal with a time delay of 120 cycles (2 seconds).
- One level of inverse time V/Hz (24) used for tripping. Pickup set at 110% of generator nominal with a delay of 45 seconds at 118% of generator nominal.
- The operate time of the inverse time V/Hz (24) can be determined at any multiple of pickup using the following formula:

$$t = \frac{3.27}{\left(\frac{V_{\text{Applied}}}{V_{\text{Pickup}}} - 1\right)^{1}}$$

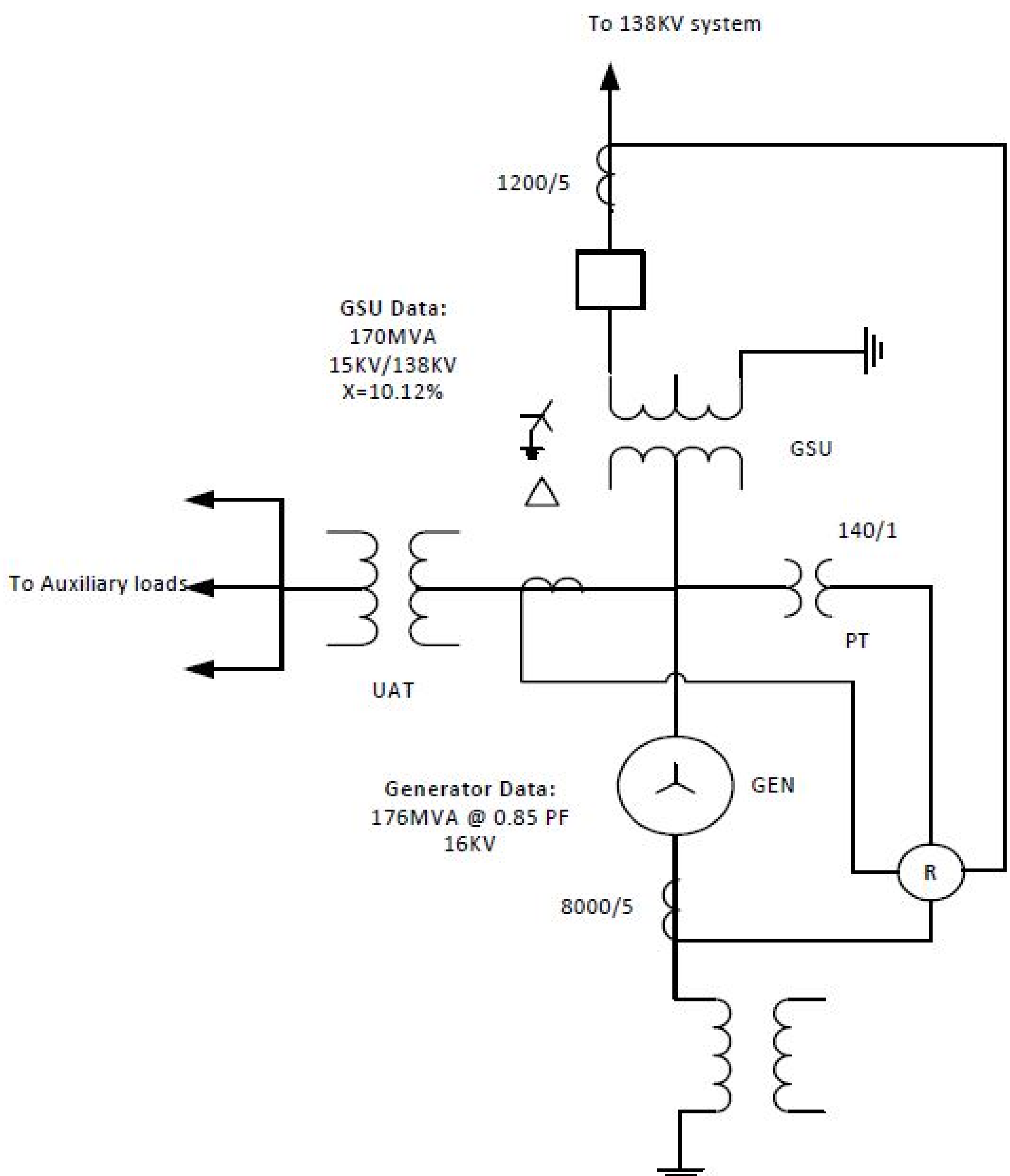

Figure 1

Example Calculations: Project the Relay Characteristic to PRC-024 Graph Method

The required voltage ride-through limits, as shown in Attachment 2 of PRC-024, are given in per unit voltage at the point of interconnection (POI) on the high-side of the GSU. The voltage transformer (VT) providing the signal to the voltage relay is located at the generator terminals. In order to validate compliance with PRC-024, the required relay element pickup voltage has to be reflected to the POI and account for the voltage drop across the GSU at the assumed loading level. The actual tapped ratio and per unit voltage base ratio must be accounted for in projecting the generator relay set points to the POI. The calculations are done in per unit on the generator base, then converted to the power system base using the ratio of the power system base to the generator base.

Calculate the generator real power output (MW_{GEN}):

Eq. (1) $MW_{GEN} = MVA_{GEN\_BASE} * p.f._{GEN}$

$MW_{GEN} = 176 \text{ MVA} * 0.85$[5]

$MW_{GEN} = 149.6 \text{ MW}$

Calculate the GSU transformer impedance on the generator base (Z_{GSU_GBASE}):

Eq. (2) $$\mathbf{Z_{GSU\_GBASE} = Z_{GSU}} * \left(\frac{\mathbf{MVA_{GEN\_BASE}}}{\mathbf{MVA_{GSU\_BASE}}}\right) * \left(\frac{\mathbf{kV_{GSU\_LS}}}{\mathbf{kV_{GEN\_BASE}}}\right)^{\mathbf{2}}$$

$$Z_{GSU\_GBASE} = 10.12\% * \left(\frac{\mathbf{176\ MVA}}{\mathbf{170\ MVA}}\right) * \left(\frac{\mathbf{15\ kV}}{\mathbf{16\ kV}}\right)^{\mathbf{2}}$$

$Z_{GSU\_GBASE} = 9.21\%$ on the generator base

Calculate the nominal generator VT secondary voltage (V_{SEC}):

Eq. (3) $$VSEC = \frac{kV_{GEN\_BASE}}{VTR_{GEN}}$$

$$VSEC = \frac{16\ kV}{140}$$

$VSEC = 114.29 \text{ V}$

Calculate the ratio of generator base voltage to POI base voltage ($Ratio_{GEN-POI}$) using the actual high-side voltage tap selected on the GSU (kV_{GSU_TAP}) to project the V_{GEN} to the POI, neglecting the load flow voltage drop on the GSU:

Eq. (4) $$\mathbf{Ratio_{SYS\_GEN}} = \frac{\mathbf{kV_{SYS\_BASE}}}{\mathbf{kV_{GEN\_BASE}}}$$

$$Ratio_{SYS\_GEN} = \frac{\mathbf{138\ kV}}{\mathbf{16\ kV}}$$

$Ratio_{SYS\_GEN} = 8.625$

Eq. (5) $$\mathbf{GSU_{RATIO}} = \frac{\mathbf{kV_{GSU\_TAP}}}{\mathbf{kV_{GSU\_LS}}}$$

$$GSU_{RATIO} = \frac{\mathbf{134.5\ kV}}{\mathbf{15\ kV}}$$

$GSU_{RATIO} = 8.967$

Eq. (6) $$\mathbf{Ratio_{GEN\_POI}} = \frac{\mathbf{Ratio_{GSU}}}{\mathbf{Ratio_{SYS\_GEN}}}$$

$$Ratio_{GEN\_POI} = \frac{\mathbf{8.967}}{\mathbf{8.625}}$$

$Ratio_{GEN\_POI} = 1.040$

[5] See Appendix 1, page 38, for detailed explanation of Eq. (1)

Verify the generator to power system base conversion and convert the generator base voltage at the low-side of the GSU in per unit to the voltage at the system (POI) at the actual voltage tap selected on the GSU (neglecting load flow voltage drop):

Eq. (7) $\mathbf{kV_{GEN\_pu}} = \frac{\mathbf{kV_{GEN\_BASE} * GSU_{RATIO}}}{\mathbf{kV_{SYS\_BASE}}}$

$kV_{GEN\_pu} = \frac{\mathbf{16\ kV * 8.967}}{\mathbf{138\ kV}}$

kV_{GEN_pu} = 1.040 on the generator base

Load Flow Assumptions for Steady-state Voltage Drop Calculations

As per the Voltage Ride-Through guidance provided in PRC-024, the voltage protective relay settings were evaluated using the following loading conditions:

1. The generator is operating at full nameplate real-power output.
2. The load power factor (pf_{LOAD}) is 0.95, as measured at the generator terminals:
   - 0.95 lagging (supplying VArs into the system) for evaluation of the undervoltage elements as prescribed in PRC-024 as most likely loading condition when the system voltage is low.
   - 0.95 lagging (supplying VArs into the system) for evaluation of the overvoltage elements as the condition that would be the worst case for coordination between the overvoltage protective elements and the Voltage Ride-Through Time Duration Curve in Attachment 2 of PRC-024

Calculate the generator apparent power at 0.95 load power factor (MVA_{LOAD}) using the value of MW_{GEN} from Eq. 1:

Eq. (8) $\mathbf{MVA_{LOAD}} = \frac{MW_{GEN}}{p.f._{LOAD}}$

$MVA_{LOAD} = \frac{\mathbf{149.6\ MW}}{\mathbf{0.95}}$

MVA_{LOAD} = 157.5 MVA

Convert MVA_{LOAD} from Eq. 8 to per unit on the generator base (MVA_{LOAD_pu}):

Eq. (9) MVALOAD_pu = $\frac{MVA_{LOAD}}{MVA_{GEN\_BASE}}$

$MVA_{LOAD\_pu} = \frac{\mathbf{157.5\ MVA}}{\mathbf{176\ MVA}}$

MVA_{LOAD_pu} = 0.895 p.u. on the generator base

Undervoltage Element

One level of undervoltage is set to trip with a pickup of 102.9 V (V_{27}) and a time delay of 1 second.
Calculate the undervoltage pickup (V_{27_pu}) in per unit of secondary volts:

Eq. (10) $V_{27\_pu} = \frac{\mathbf{V_{27}}}{\mathbf{V_{sec}}}$

$V_{27\_pu} = \frac{\mathbf{102.9\ V}}{\mathbf{114.29\ V}}$

V_{27_pu} = 0.9 p.u. on the generator V.T. voltage base

Calculate the generator load current (I_{LOAD_27}) at the rated generator MW output with 0.95 lagging power factor for the generator terminal voltage at the relay undervoltage set point:

Eq. (11) $\mathbf{I_{LOAD\_27}} = \frac{\mathbf{MVA_{LOAD\_pu}}}{\mathbf{V_{27\_pu}}} \angle \mathbf{cos^{-1}(pf_{LOAD})}$

$I_{LOAD\_27} = \frac{\mathbf{0.895}}{\mathbf{0.9}} \angle \mathbf{cos^{-1}(0.95)}$

$I_{LOAD\_27} = 0.994\angle\text{-}18.2°$ p.u. on the generator base

Calculate the per unit voltage drop across the GSU (V_{DROP_27}) at the rated generator MW output with a 0.95 lagging power factor:

Eq. (12) $V_{DROP\_27} = I_{LOAD\_27} * \mathbf{j\ Z_{GSU\_GBASE}}$

$V_{DROP\_27} = (\mathbf{0.994\angle-18.2°}) * (\mathbf{0.0921\angle 90°})$

$V_{DROP\_27} = \mathbf{0.092\angle 71.81°}$ p.u. on the generator base

Calculate the per unit voltage at the POI (V_{POI_27}) for the rated generator MW output with 0.95 lagging power factor:

Eq. (13) $\mathbf{V_{POI\_27} = V_{27\_pu} - V_{DROP\_27}}$

$V_{POI\_27} = \mathbf{0.9\angle 0°} - \mathbf{0.092\angle 71.81°}$

$V_{POI\_27} = \mathbf{0.876\angle-5.69°}$ p.u. on the generator base

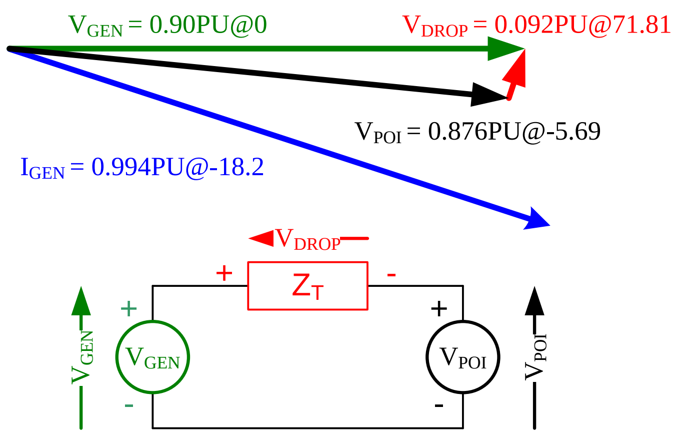

Figure 2

Project the voltage element setting ($V_{POI\_27\_SET}$) from the generator terminals to the POI, accounting for the voltage drop across the GSU:

Eq. (14) $V_{POI\_27\_SET} = |V_{POI\_27}| * Ratio_{GEN\_POI}$

$V_{POI\_27\_SET} = 0.876 * 1.040$

$V_{POI\_27\_SET} = 0.911$ p.u. on the system base

Plotting these results on the chart from Attachment 2 in Figure 3, it can be seen that this setting lies within the ‘No Trip’ zone and would not be compliant with PRC-024-2.

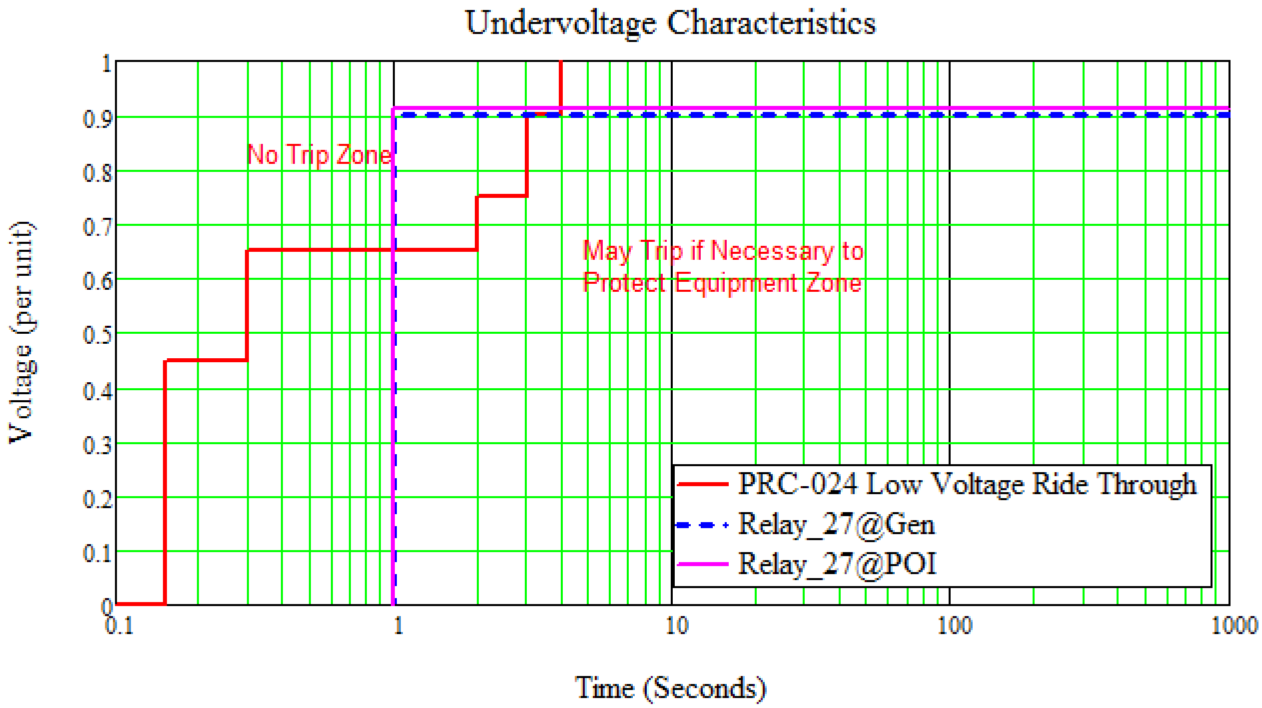

Figure 3

Overvoltage Settings

One level of overvoltage is set to trip with a pickup of 125.7 V (V_{59}) and a time delay of 30 seconds. Calculate the overvoltage pickup in per unit (V_{59_pu}):

Eq. (15) $V_{59\_pu} = \dfrac{\mathbf{V_{59}}}{\mathbf{V_{sec}}}$

$V_{59\_pu} = \dfrac{\mathbf{125.7\ V}}{\mathbf{114.29\ V}}$

V_{59_pu} = 1.1 p.u. on the generator V.T. base

Calculate the load current at rated MW output with 0.95 lagging power factor (I_{LOAD_59}) for generator terminal voltage at the relay overvoltage set point:

Eq. (16) $I_{LOAD\_\mathbf{59}} = \dfrac{\mathbf{MVA_{LOAD\_pu}}}{\mathbf{V_{59\_pu}}} \angle \mathbf{cos^{-1}}(\mathbf{pf_{LOAD}})$

$I_{LOAD\_59} = \dfrac{\mathbf{0.895}}{\mathbf{1.1}} \angle \mathbf{cos^{-1}}(\mathbf{0.95})$

$I_{LOAD\_59} = 0.813\angle -18.2°$ p.u. on the generator base

Calculate the per unit voltage drop across the GSU at the rated generator MW output at a 0.95 lagging power factor (V_{DROP_59}):

Eq. (17) $V_{DROP\_\mathbf{59}} = \mathbf{I_{LOAD\_59}} * \ \mathbf{j\ Z_{GSU\_GBASE}}$

$V_{DROP\_59} = (\mathbf{0.813}\angle - \mathbf{18.2}°) * \ (\mathbf{0.0921}\angle \mathbf{90}°)$

$V_{DROP\_59} = \mathbf{0.075}\angle \mathbf{71.81}°$ p.u. on the generator base

Calculate the per unit voltage at the POI at rated MW output with 0.95 lagging power factor (V_{POI_59}):

Eq. (18) $V_{POI\_\mathbf{59}} = \mathbf{V_{59\_pu}} - \mathbf{V_{DROP\_59}}$

$V_{POI\_59} = \mathbf{1.1}\angle \mathbf{0}° - \ \mathbf{0.075}\angle \mathbf{71.81}°$

$V_{POI\_59} = \mathbf{1.079}\angle - \mathbf{3.78}°$ p.u. on the generator base

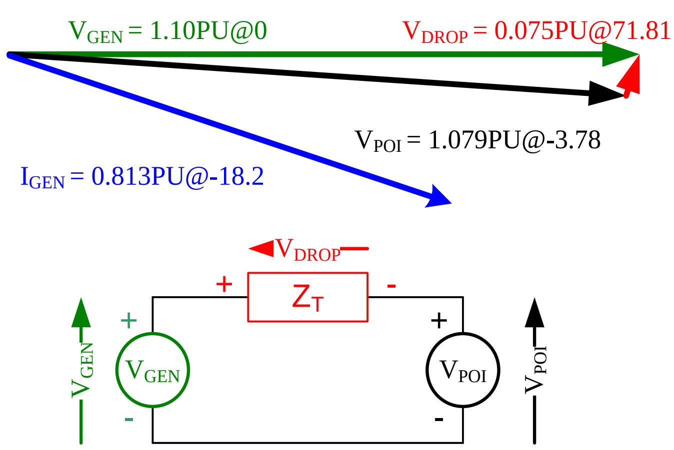

Figure 4

Project the voltage element setting ($V_{POI\_59\_SET}$) from the generator terminals to the POI, accounting for the voltage drop across the GSU:

Eq. (19) $V_{POI\_59\_SET} = |V_{POI\_59}| * Ratio_{POI\_GEN}$

$V_{POI\_59\_SET} = 1.079 * 1.040$

$V_{POI\_59\_SET} = 1.122$ p.u. on the system base

Plotting these results on the chart from Attachment 2 in Figure 5, it can be seen that this setting lies outside the 'No Trip' zone and would be compliant with PRC-024-2.

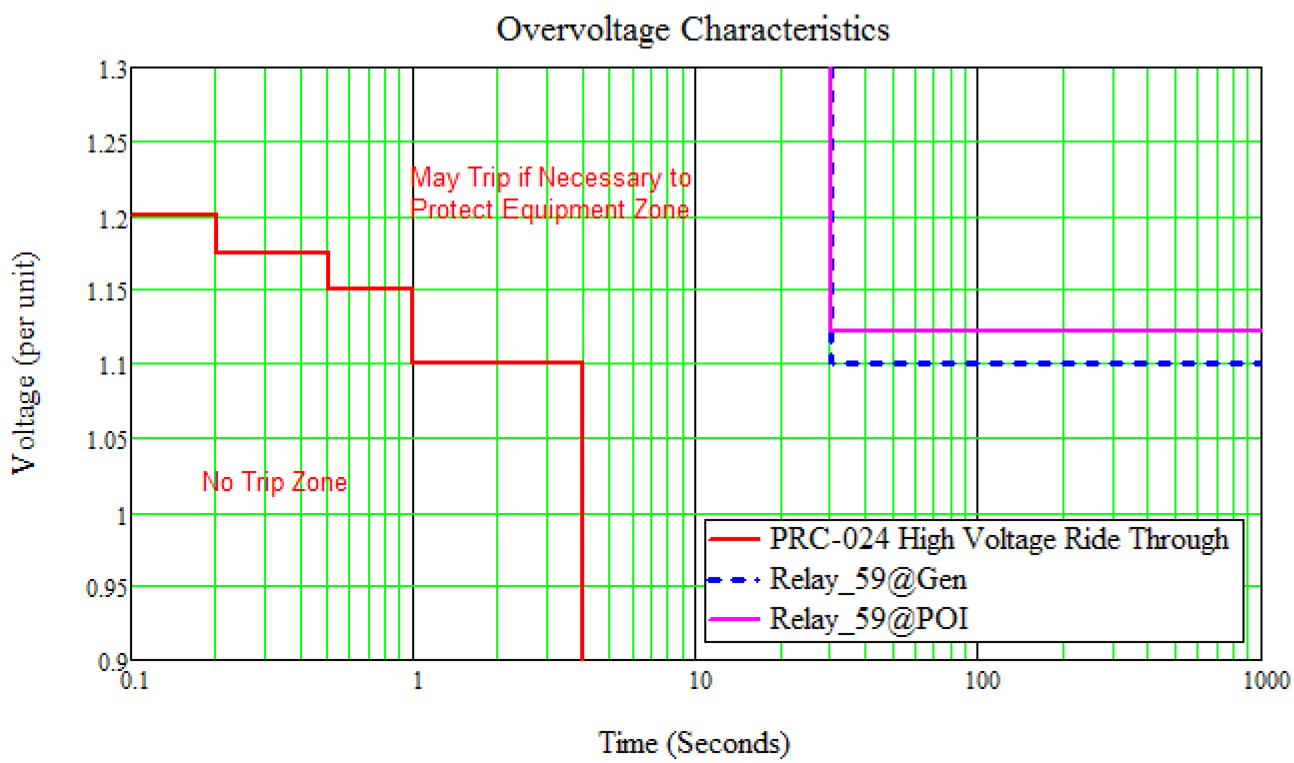

Figure 5

Volts/Hertz Setting

Assuming one level of definite-time volts per hertz (V/Hz) element set to trip the generator if the V/Hz ratio exceeds 118% for 2 seconds. Using the following Equation:

Eq. (20) $I_{LOAD\_24D} = \frac{MVA_{LOAD\_pu}}{V_{24\_pu}} \angle \cos^{-1}(pf_{LOAD})$

$I_{LOAD\_24D} = \frac{0.895}{1.18} \angle \cos^{-1}(0.95)$

$I_{LOAD\_24D} = 0.758\angle - 18.2°$ p.u on the generator base

Calculate the voltage drop across the GSU:

Eq. (21) $V_{DROP\_24D} = \mathbf{I_{LOAD\_24D}} * \ \mathbf{j\,Z_{GSU\_GBASE}}$

$V_{DROP\_24D} = (\mathbf{0.758\angle -18.2}°) * \ (\mathbf{0.0921\angle 90}°)$

$V_{DROP\_24D} = \mathbf{0.0698\angle 71.81}°$ p.u. on the generator base

Calculate the generator voltage at the POI for the assumed load flow:

Eq. (22) $V_{POI\_24D} = \mathbf{V_{24\_pu}} - \mathbf{V_{DROP\_24D}}$

$V_{POI\_24D} = \mathbf{1.18\angle 0}° - \ \mathbf{0.0698\angle 71.81}°$

$V_{POI\_24D} = \mathbf{1.16\angle -3.28}°$ p.u. on the generator base

Project the voltage element from the generator terminals to the POI, including the voltage drop on the GSU:

Eq. (23) $V_{POI\_24D\_SET} = |V_{POI\_24D}| * \text{Ratio}_{GEN\_POI}$

$V_{POI\_24D\_SET} = 1.16 * 1.040$

$V_{POI\_24D\_SET} = 1.206$ p.u. on the system base

One level of inverse-time V/Hz element is set to trip for V/Hz ratio greater than 110% with a time-dial setting for 45 seconds at 118% (TD = 3.27). Since the inverse-time curve requires multiple calculations, depending on the desired resolution of the curve to be produced, the calculations for the point on the curve that intersects with the definite time element (118%) will be shown and a table of results used to develop the rest of the curve in this example will be given.

Calculate the load current at the rated MW output at 0.95 lagging power factor for the example point on the curve:

Eq. (24) $I_{LOAD\_24IT} = \frac{\text{MVA}_{\text{LOAD\_pu}}}{V_{24IT}} \angle \cos^{-1}(\text{pf}_{\text{LOAD}})$

$I_{LOAD\_24IT} = \frac{0.895}{1.18} \angle \cos^{-1}(0.95)$

$I_{LOAD\_24IT} = 0.758\angle -18.2°$ p.u. on the generator base

Calculate the per unit voltage drop from the generator terminals to the POI at assumed load flow:

Eq. (25) $V_{DROP\_24IT} = \mathbf{I_{LOAD\_24IT}} * \ \mathbf{j\,Z_{GSU\_GBASE}}$

$V_{DROP\_24IT} = (\mathbf{0.758\angle -18.2}°) * \ (\mathbf{0.0921\angle 90}°)$

$V_{DROP\_24IT} = \mathbf{0.0698\angle 71.81}°$ p.u. on the generator base

Calculate the per unit voltage at the POI at assumed load flow:

Eq. (26) $V_{POI\_24IT} = \mathbf{V_{24IT}} - \mathbf{V_{DROP\_24IT}}$

$V_{POI\_24IT} = \mathbf{1.18\angle 0}° - \ \mathbf{0.0698\angle 71.81}°$

$V_{POI\_24IT} = \mathbf{1.16\angle -3.28}°$ p.u. on the generator base

Project the inverse-time V/Hz element from the generator terminals to the POI accounting for the voltage drop across the GSU:

Eq. (27) $V_{POI\_24IT\_SET} = |V_{POI\_24IT}| * Ratio_{GEN\_POI}$

$V_{POI\_24IT\_SET} = 1.16 * 1.040$

$V_{POI\_24IT\_SET} = 1.206$ p.u. on the system base

Table 2 contains the results of Eq. 24-27 for the range of values for V_{24IT} from 110% to 118% V/Hz ratios. Figure 6 shows the results of the calculated voltage plot of the definite and inverse-time curves for the V/Hz settings on the graph from Attachment 2.

Table 2						
V_{24IT}	M_{24IT}	T_{24IT}	I_{LOAD_24IT}	V_{DROP_24IT}	V_{POI_24IT}	$V_{POI\_24IT\_SET}$
1.101	1.001	3600.0	$0.813\angle-18.2°$	$0.0748\angle71.81°$	1.080	1.123
1.105	1.005	720.0	$0.810\angle-18.2°$	$0.0746\angle71.81°$	1.084	1.127
1.11	1.009	360.0	$0.806\angle-18.2°$	$0.0742\angle71.81°$	1.089	1.132
1.12	1.018	180.0	$0.799\angle-18.2°$	$0.0736\angle71.81°$	1.099	1.143
1.13	1.027	120.0	$0.792\angle-18.2°$	$0.0729\angle71.81°$	1.109	1.153
1.14	1.036	90.0	$0.785\angle-18.2°$	$0.0723\angle71.81°$	1.120	1.164
1.15	1.045	72.0	$0.778\angle-18.2°$	$0.0716\angle71.81°$	1.130	1.174
1.16	1.055	60.0	$0.771\angle-18.2°$	$0.0710\angle71.81°$	1.140	1.185
1.17	1.064	51.4	$0.765\angle-18.2°$	$0.0704\angle71.81°$	1.150	1.196
1.18	1.073	45.0	$0.758\angle-18.2°$	$0.0698\angle71.81°$	1.160	1.206

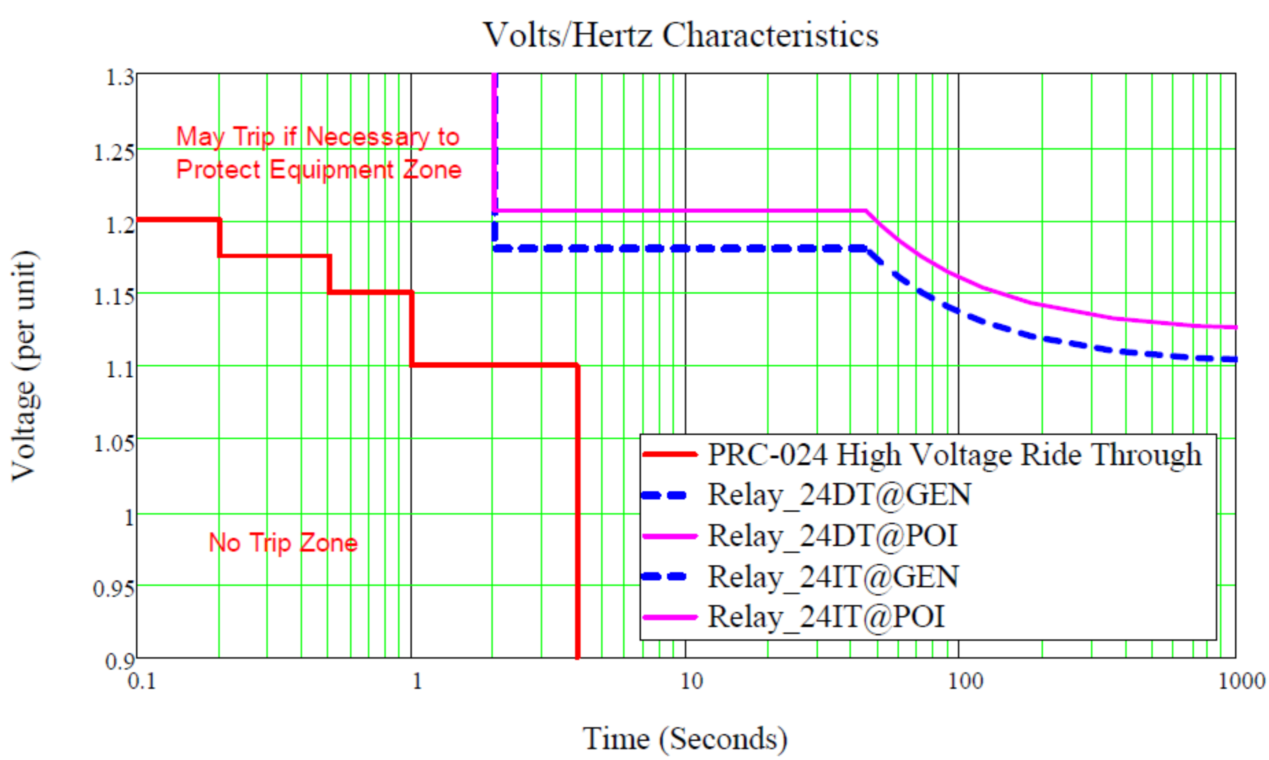

Figure 6

As an alternative to graphing the results to verify compliance, the results can be presented in a tabular form as shown below in Table 3:

Table 3: Tabular Form							
Undervoltage (27) Settings to be evaluated:							
		27 Setting Pickup:	102.90	Vsec			
		27 Time Delay:	1	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**27 Pick Up PU_{POI}**	**Op Time (sec)**	**Result**	**Notes**
0.900	3.00	14.25	140	0.911	1.00	DOES NOT COMPLY	Relay operate time is LESS than the required delay
0.750	2.00	11.99	140	0.911	1.00	DOES NOT COMPLY	Relay operate time is LESS than the required delay
0.650	0.30	10.47	140	0.911	1.00	COMPLY	Relay operate time is greater than the required delay
0.450	0.15	7.23	140	0.911	1.00	COMPLY	Relay operate time is greater than the required delay
Overvoltage (59) Settings to be evaluated:							
		59 Setting Pickup:	125.70	Vsec			
		59 Setting Time Delay:	30	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**59 Pick Up PU_{POI}**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	17.28	140	1.122	NoOp	COMPLY	Applied voltage is below pickup of 59 element - No Operation
1.150	0.50	18.04	140	1.122	30.00	COMPLY	Relay operate time is greater than the required delay
1.175	0.20	18.42	140	1.122	30.00	COMPLY	Relay operate time is greater than the required delay
1.200	0.00	18.81	140	1.122	30.00	COMPLY	Relay operate time is greater than the required delay
Overvoltage (24DT) Settings to be evaluated:							
		24DT Setting Pickup:	134.86	Vsec	118% of generator nominal = 1.18 * 16000V / 140 = 134.86Vsec		
		24DT Setting Time Delay:	2	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**24D Pick Up PU_{POI}**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	17.28	140	1.206	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.150	0.50	18.04	140	1.206	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.175	0.20	18.42	140	1.206	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.200	0.00	18.81	140	1.206	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
Overvoltage (24IT) Settings to be evaluated:							

		24IT Setting Pickup:	125.71	Vsec	110% of generator nominal = 1.10 * 16000V / 140 = 125.71Vsec		
		24IT Setting Time Delay:	2	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**24I Pick Up PU_{POI}**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	17.28	140	1.100	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.150	0.50	18.04	140	1.150	133.3	COMPLY	Relay operate time is greater than the required delay
1.175	0.20	18.42	140	1.175	70.6	COMPLY	Relay operate time is greater than the required delay
1.200	0.00	18.81	140	1.200	48.6	COMPLY	Relay operate time is greater than the required delay

Example Calculations: PRC-025 Iterative Method

This is an iterative method that has its basis in PRC-025-1, Option 1b. It begins with the per unit voltage at the POI and reflects it to the generator terminals. The voltage calculated at the generator terminals is used to evaluate operation of the generator protective voltage relays.

Calculate Real Power output (MW_{GEN}):

Eq. (28) $MW_{GEN} = MVA_{GEN\_BASE} * p.f._{GEN}$

$MW_{GEN} = 176 \text{ MVA} * 0.85$

$MW_{GEN} = 149.6 \text{ MVA}$

Calculate Reactive Power Output ($MVAr_{GEN}$):

Eq. (29) $MVAr_{GEN} = MW_{GEN} * \tan(\cos^{-1}(p.f._{LOAD}))$

$MVAr_{GEN} = 149.6 \text{ MW} * \tan(18.2°)$

$MVAr_{GEN} = 49.17 \text{ MVAr}$

Convert the generator power output during system disturbance into per unit on the system base (MVA_{GEN_pu}):

Eq. (30) $MVA_{GEN\_pu} = \frac{\mathbf{MW_{GEN}}}{\mathbf{MVA_{SYS\_BASE}}} + j\frac{\mathbf{MVAr_{GEN}}}{\mathbf{MVA_{SYS\_BASE}}}$

$MVA_{GEN\_pu} = \frac{\mathbf{149.6\ MW}}{\mathbf{100\ MVA}} + j\frac{\mathbf{49.17\ MVAr}}{\mathbf{100\ MVA}}$

$MVA_{GEN\_pu} = 1.496 \text{ p.u.} + j\, 0.4917 \text{ p.u. on the system base}$

Convert the GSU reactance into per unit on the system base (Z_{GSU_pu}):

Eq. (31) $Z_{GSU\_pu} = Z_{GSU} * \left(\frac{\mathbf{MVA_{SYS\_BASE}}}{\mathbf{MVA_{GSU\_BASE}}}\right) * \left(\frac{\mathbf{kV_{GSU\_HS}}}{\mathbf{kV_{GEN\_BASE}}}\right)^{\mathbf{2}}$

Z_{GSU_pu} = 10.12% * $\left(\frac{\mathbf{100\ MVA}}{\mathbf{170\ MVA}}\right)$ * $\left(\frac{\mathbf{138\ kV}}{\mathbf{138\ kV}}\right)^{\mathbf{2}}$

Z_{GSU_pu} = 0.0595 $\mathbf{\Omega_{pu}}$ on the system base

Calculate kV_{LOW_BASE} to account for the difference between kV_{SYS_BASE} and kV_{GSU_TAP}:

Eq. (32) $kV_{LOW\_BASE} = kV_{SYS\_BASE} * \left(\frac{\mathbf{kV_{GEN\_BASE}}}{\mathbf{kV_{GSU\_TAP}}}\right)$

kV_{LOW_BASE} = 138 kV * $\left(\frac{\mathbf{15\ kV}}{\mathbf{134.5\ kV}}\right)$

kV_{LOW_BASE} = 15.39 kV

<u>**Calculations for Undervoltage Values**</u>

Using the formulas below, calculate the generator voltage (kVLOW_pu) for each high-side voltage (kVPOI pu) from the Voltage Ride-through Time Duration Curve in Attachment 2.

Set the initial value of kV_{LOW_pu} to 0.9 p.u. and repeat calculations until kV_{LOW_pu} converges with a difference of less than 1% between iterations:

Eq. (33) $\boldsymbol{\theta_{LV}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{MW_{GEN}} * |\mathbf{Z_{GSU\_pu}}|}{|\mathbf{kV_{LOW\ pu}}| * |\mathbf{kV_{POI\ pu}}|}\right]$

Eq. (34) $|kV_{LOW\ pu}| = \frac{|\mathbf{kV_{POI\ pu}}| * \mathbf{cos}(\boldsymbol{\theta}_{\mathbf{LV_x}}) \pm \sqrt{|\mathbf{kV_{POI\ pu}}|^2 * \mathbf{cos^2}(\boldsymbol{\Theta}_{\mathbf{LV\_x}}) + 4 * \mathbf{MVAr_{GEN\ pu}} * \mathbf{Z_{GSU\_pu}}}}{\mathbf{2}}$

Eq. (35) $\%\Delta_{x\text{-}y} = \frac{kV_{LOW\_pu\_x} - kV_{LOW\_pu\_y}}{V_{LOW\_pu\_y}}$

Using Eq. 33-35 with $kV_{LOW\ pu\_1}$ = 0.9, calculate iteratively until %Δ < 1.0%:

Eq. (36) $\boldsymbol{\theta_{LV\_1}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{MW_{GEN}} * |\mathbf{Z_{GSU\_pu}}|}{|\mathbf{kV_{low\ pu\_1}}| * |\mathbf{kV_{POI\ pu}}|}\right]$

$\boldsymbol{\theta_{LV\_1}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{1.496 * 0.0595}}{\mathbf{0.9 * 0.9}}\right]$

$\boldsymbol{\theta_{LV\_1}}$ = 6.312°

Eq. (37) $|kV_{LOW\ pu\_2}| = \frac{|\mathbf{kV_{POI\ pu}}| * \mathbf{cos}(\boldsymbol{\theta}_{\mathbf{LV_1}}) \pm \sqrt{|\mathbf{kV_{POI\ pu}}|^2 * \mathbf{cos^2}(\boldsymbol{\Theta}_{\mathbf{LV\_1}}) + 4 * \mathbf{MVAr_{GEN\ pu}} * \mathbf{Z_{GSU\_pu}}}}{\mathbf{2}}$

$|kV_{LOW\ pu\_2}| = \frac{\mathbf{0.9 * cos(6.312)} \pm \sqrt{\mathbf{(0.9)^2 * cos^2(6.312) + 4 * 0.4917 * 0.0595}}}{\mathbf{2}}$

$|kV_{LOW\ pu\_2}|$ = 0.926 V_{pu}

The result of the quadratic equation yields a positive and negative result with the negative value being ignored. Check value of kV_{LOW_pu} for convergence:

Eq. (38) $\%\Delta_{1\text{-}2} = \frac{kV_{LOW\ pu\ 1} - kV_{LOW\ pu\ 2}}{V_{Low\ pu\ 2}}$

$\%\Delta_{1\text{-}2} = \frac{0.926 - 0.9}{0..9}$

$\%\Delta_{1\text{-}2} = 2.9\%$

Since $\%\Delta$ is greater than 1%, substitute 0.926 kV_{pu} for $kV_{LOW\ pu\_3}$ in the next iteration:

Eq. (39) $\boldsymbol{\theta_{LV\_2}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{MW_{GEN} * |Z_{GSU\_pu}|}}{\mathbf{|kV_{low\ pu\_2}| * |kV_{POI\ pu}|}}\right]$

$\boldsymbol{\theta_{LV\_2}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{1.496 * 0.0595}}{\mathbf{0.926 * 0.9}}\right]$

$\boldsymbol{\theta_{LV\_2}} = 6.13°$

Eq. (40) $|kV_{LOW\ pu\_3}| = \frac{\mathbf{|kV_{POI\ pu}| * cos(\theta_{\mathit{LV\_2}}) \pm \sqrt{|kV_{POI\ pu}|^2 * cos^2(\Theta_{LV\_2}) + 4 * MVAr_{GEN\ pu} * Z_{GSU\_pu}}}}{\mathbf{2}}$

$|kV_{LOW\ pu\_3}| = \frac{\mathbf{0.9 * cos(6.133) \pm \sqrt{(0.9)^2 * cos^2(6.133) + 4 * 0.4917 * 0.0595}}}{\mathbf{2}}$

$|kV_{LOW\ pu\_3}| = 0.926\ V_{pu}$

Eq. (41) $\boldsymbol{\theta_{LV\_3}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{MW_{GEN} * |Z_{GSU\_pu}|}}{\mathbf{|kV_{low\ pu\_3}| * |kV_{POI\ pu}|}}\right]$

$\boldsymbol{\theta_{LV\_3}} = \mathbf{sin^{-1}}\left[\frac{\mathbf{1.496 * 0.0595}}{\mathbf{0.926 * 0.9}}\right]$

$\boldsymbol{\theta_{LV\_3}} = 6.131°$

Check value of kV_{LOW_pu} for convergence:

Eq. (42) $\%\Delta_{2\text{-}3} = \frac{V_{low\ pu\ 2} - V_{low\ pu\ 3}}{V_{low\ pu\ 3}}$

$\%\Delta_{2\text{-}3} = \frac{0.926 - 0.926}{0.926}$

$\%\Delta_{2\text{-}3} = 0\%$

%Δ is less than 1% so iteration is complete. Convert $kV_{LOW\ pu}$ to generator voltage base:

Eq. (43) $kV_{GEN\_0.9pu} = kV_{LOW\ pu\_3} * kV_{LOW\_BASE}$

$kV_{GEN\_0.9pu} = 0.926 \text{ p.u.} * 15.39 \text{ kV}$

$kV_{GEN\_0.9pu} = 14.25 \text{ kV}$

Table 4 contains the results for the calculations for each undervoltage step in Attachment 2:

Table 4								
kV_{LOW_1}	θ_{LV_1}	kV_{LOW_2}	$\%\Delta_{1-2}$	θ_{LV_2}	kV_{LOW_3}	$\%\Delta_{2-3}$	θ_{LV_3}	kV_{GEN}
0.90	6.132°	0.926	2.9%	6.133°	0.926	0%	6.131°	14.25 kV
0.75	9.109°	0.778	3.7%	8.777°	0.779	0.08%	8.77°	11.99 kV
0.65	12.168°	0.679	4.4%	11.649°	0.680	0.17%	11.629°	10.47 kV
0.45	26.09°	0.467	3.7%	25.082°	0.470	0.6%	24.91°	7.23 kV

Calculations for Overvoltage Values

Repeat the calculations for each step of the overvoltage curve using Eq 33-35. Table 5 contains the results for the calculations for each overvoltage step in Attachment 2:

Table 5								
kV_{LOW_1}	θ_{LV_1}	kV_{LOW_2}	$\%\Delta_{1-2}$	θ_{LV_2}	kV_{LOW_3}	$\%\Delta_{2-3}$	θ_{LV_3}	kV_{GEN}
1.10	4.221°	1.123	2.1%	4.134°	1.123	0.01%	4.133°	17.28 kV
1.15	3.861°	1.172	1.9%	3.787°	1.172	0.00%	3.787°	18.04 kV
1.175	3.698°	1.197	1.9%	3.63°	1.197	0.00%	3.63°	18.42 kV
1.20	3.546°	1.222	1.8%	3.483°	1.222	0.00%	3.483°	18.81 kV

Evaluate relay operations based on applied voltage from the generator VTs. The results of the evaluation are shown in Table 6 below:

Table 6							
Undervoltage (27) Settings to be evaluated:							
		27 Setting Pickup:	102.90	Vsec			
		27 Time Delay:	1	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
0.900	3.00	14.25	140	101.79	1.00	DOES NOT COMPLY	Relay operate time is LESS than the required delay
0.750	2.00	11.99	140	85.64	1.00	DOES NOT COMPLY	Relay operate time is LESS than the required delay
0.650	0.30	10.47	140	74.79	1.00	COMPLY	Relay operate time is greater than the required delay
0.450	0.15	7.23	140	51.64	1.00	COMPLY	Relay operate time is greater than the required delay
Overvoltage (59) Settings to be evaluated:							
		59 Setting Pickup:	125.70	Vsec			
		59 Setting Time Delay:	30	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	17.28	140	123.43	NoOp	COMPLY	Applied voltage is below pickup of 59 element - No Operation
1.150	0.50	18.04	140	128.86	30.00	COMPLY	Relay operate time is greater than the required delay
1.175	0.20	18.42	140	131.57	30.00	COMPLY	Relay operate time is greater than the required delay
1.200	0.00	18.81	140	134.36	30.00	COMPLY	Relay operate time is greater than the required delay

Overvoltage (24DT) Settings to be evaluated:							
		24DT Setting Pickup:	134.86	Vsec	118% of generator nominal = 1.18 * 16000V / 140 = 134.86Vsec		
		24DT Setting Time Delay:	2	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	17.28	140	123.43	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.150	0.50	18.04	140	128.86	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.175	0.20	18.42	140	131.57	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.200	0.00	18.81	140	134.36	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation

Overvoltage (24IT) Settings to be evaluated:							
		24IT Setting Pickup:	125.71	Vsec	110% of generator nominal = 1.10 * 16000V / 140 = 125.71Vsec		
		24IT Setting Time Delay:	2	sec			
VPOI	**Delay required (sec)**	**Vgen (kV)**	**PT ratio / 1**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	17.28	140	123.43	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.150	0.50	18.04	140	128.86	130.8	COMPLY	Relay operate time is greater than the required delay
1.175	0.20	18.42	140	131.57	70.19	COMPLY	Relay operate time is greater than the required delay
1.200	0.00	18.81	140	134.36	47.56	COMPLY	Relay operate time is greater than the required delay

Example Calculations: Simple Iteration Method

This method starts by assuming a 0.95 lagging power factor at the POI. It then calculates the angular difference between the generator voltage and the POI voltage to account for the I^2X losses of the GSU. The load-flow current angle at the POI is then adjusted by this voltage-drop angle to give the 0.95 power factor load flow out of the generator recommended in the standard. This simple iteration provides results with adequate accuracy. The calculations are done in per-unit on the power system base, then converted to the generator base using the ratio of the generator base to the power system base. The ratio of the GSU is considered using its actual no-load tap setting. One set of calculations is required for each of the eight voltage levels that define the voltage curve in Attachment 2 of PRC-024. The generator relay set-point values are compared to the newly-constructed graph in relay secondary volts of Attachment 2 of PRC-024 to determine if the generator voltage relay settings are compliant.

Calculate the generator real power output at rated MVA (MW_{GEN}):

Eq. (44) $MW_{GEN} = MVA_{GEN\_BASE} * p.f._{GEN}$

$MW_{GEN} = 176 \text{ MVA} * 0.85$

$MW_{GEN} = 149.6 \text{ MW}$

Convert the GSU transformer impedance from the GSU base to the power system base ($Z_{GSU\_SYS\_BASE}$):

Eq. (45) $Z_{GSU\_SYS\_BASE} = Z_{GSU} * \left[\frac{\mathbf{MVA_{SYS\_BASE}}}{\mathbf{MVA_{GSU\_BASE}}}\right] * \left[\frac{\mathbf{kV_{GSU\_HS}}}{\mathbf{kV_{SYS\_BASE}}}\right]^{\mathbf{2}}$

$Z_{GSU\_SYS\_BASE} = 10.12\% * \left[\frac{\mathbf{100\ MVA}}{\mathbf{170\ MVA}}\right] * \left[\frac{\mathbf{138\ kV}}{\mathbf{138\ kV}}\right]^{\mathbf{2}}$

$Z_{GSU\_SYS\_BASE} = 5.95\%$ on the system base

Calculate the ratio of POI base voltage to generator base voltage ($Ratio_{POI\text{-}GEN}$) using the actual high-side voltage tap selected on the GSU (kV_{GSU_TAP}) to project the V_{POI} to the generator terminals, neglecting the load flow voltage drop on the GSU:

Eq. (46) $Ratio_{SYS\_GEN} = \frac{\mathbf{kV_{SYS\_BASE}}}{\mathbf{kV_{GEN\_BASE}}}$

$Ratio_{SYS\_GEN} = \frac{\mathbf{138\ kV}}{\mathbf{16\ kV}}$

$Ratio_{SYS\_GEN} = 8.625$

Eq. (47) $GSU_{RATIO} = \frac{\mathbf{kV_{GSU\_TAP}}}{\mathbf{kV_{GSU\_LS}}}$

$GSU_{RATIO} = \frac{\mathbf{134.5\ kV}}{\mathbf{15\ kV}}$

$GSU_{RATIO} = 8.967$

Eq. (48) $Ratio_{POI\text{-}GEN} = \frac{\mathbf{Ratio_{SYS\_GEN}}}{\mathbf{GSU_{RATIO}}}$

$Ratio_{POI\text{-}GEN} = \frac{\mathbf{8.625}}{\mathbf{8.967}}$

$Ratio_{POI\text{-}GEN} = 0.962$

Verify the power system to generator base conversion and convert the system base voltage (POI) at the low-side of the GSU in per unit to the voltage at the generator at the actual voltage tap selected on the GSU (neglecting load flow voltage drop):

Eq. (49) $kV_{GEN\_PU} = \frac{\left(\frac{\mathbf{kV_{SYS\_BASE}}}{\mathbf{GSU_{RATIO}}}\right)}{\mathbf{kV_{GEN\_BASE}}}$

$$kV_{GEN\_PU} = \frac{\left(\frac{138\ kV}{8.967}\right)}{16\ kV}$$

$kV_{GEN\_PU} = 0.962$ p.u. 1 p.u. at the POI equals 0.962 p.u. at the generator terminals

Load Flow Assumptions for Steady-state Voltage Drop Calculations

As per the Voltage Ride-Through guidance provided in PRC-024, the voltage protective relay settings are evaluated using the following load conditions:

1. The generator is operating at full nameplate real-power output.
2. The load power factor ($p.f._{LOAD}$) is 0.95, as measured at the generator terminals:
   - 0.95 lagging (supplying VArs into the system) for evaluation of the undervoltage elements, as prescribed in PRC-024, as most likely loading condition when the system voltage is low.
   - 0.95 lagging (supplying VArs into the system) for evaluation of the overvoltage elements as the condition that would be the worst case for coordination between the overvoltage protective elements and the Voltage Ride-Through Time Duration Curve in Attachment 2 of PRC-024

Calculate the generator apparent power at 0.95 load power factor (MVA_{LOAD}) using the value of MW_{GEN} from Eq. 44:

Eq. (50) $MVA_{POI\_1} = \frac{MW_{GEN}}{p.f._{LOAD}}$

$$MVA_{POI\_1} = \frac{149.6\ MW}{0.95}$$

$MVA_{POI\_1} = 157.5$ MVA

Convert to a per unit value on the system base:

Eq. (51) $\mathbf{MVA_{POI\_1\_pu}} = \frac{MVA_{POI\_1.0}}{MVA._{SYS\_BASE}}$

$$MVA_{POI\_1\_pu} = \frac{157.5\ MVA}{100\ MVA}$$

$MVA_{POI\_1\_pu} = 1.575$ p.u. on the system base

1.2 p.u. voltage

$V_{POI\_1.2\_pu} = \mathbf{1.2\angle 0°}$ p.u.

Iteration 1:

Calculate the load flow current in per unit assuming rated MW output at 0.95 lagging power factor:

Eq. (52) $I_{LOAD\_1.2\text{-}1} = \frac{MVA_{POI\_1\_pu}}{V_{POI\_1.2\_pu}} \angle \cos^{-1}(pf_{LOAD})$

$I_{LOAD\_1.2\text{-}1} = \frac{\mathbf{1.575}}{\mathbf{1.2}}\angle\mathbf{cos^{-1}(0.95)}$

$I_{LOAD\_1.2\text{-}1} = \mathbf{1.312\angle - 18.2}°$ p.u. on the generator base

Calculate the per unit voltage drop from the POI to the generator terminals at the assumed load flow:

Eq. (53) $V_{DROP\_1.2\text{-}1} = I_{LOAD\_1.2\text{-}1} * \mathbf{j\,Z_{GSU\_SYS\_BASE}}$

$V_{DROP\_1.2\text{-}1} = (\mathbf{1.312\angle - 18.2}°) * (\mathbf{0.0595\angle 90}°)$

$V_{DROP\_1.2\text{-}1} = \mathbf{0.078\angle 71.8}°$ p.u. on the generator base

Calculate the per unit voltage drop at the generator terminals at the assumed load flow:

Eq. (54) $V_{GEN\_1.2\text{-}1} = V_{POI\_1.2\_pu} + V_{DROP\_1.2\text{-}1}$

$V_{GEN\_1.2\text{-}1} = (\mathbf{1.2\angle 0}°) + (\mathbf{0.078\angle 71.8}°)$

$V_{GEN\_1.2\text{-}1} = \mathbf{1.227\angle 3.47}°$ p.u. on the generator base

Calculate the power factor at the generator for 0.95 at the POI:

Eq. (55) $p.f._{1.2\text{-}1} = \cos(\angle V_{GEN\_1.2\text{-}1} - \angle I_{LOAD\_1.2\text{-}1})$

$p.f._{1.2\text{-}1} = \cos(\mathbf{3.47}° + \mathbf{18.2}°)$

$p.f._{1.2\text{-}1} = 0.929$

The calculated values and their vector relationships are shown in Figure 7 below.

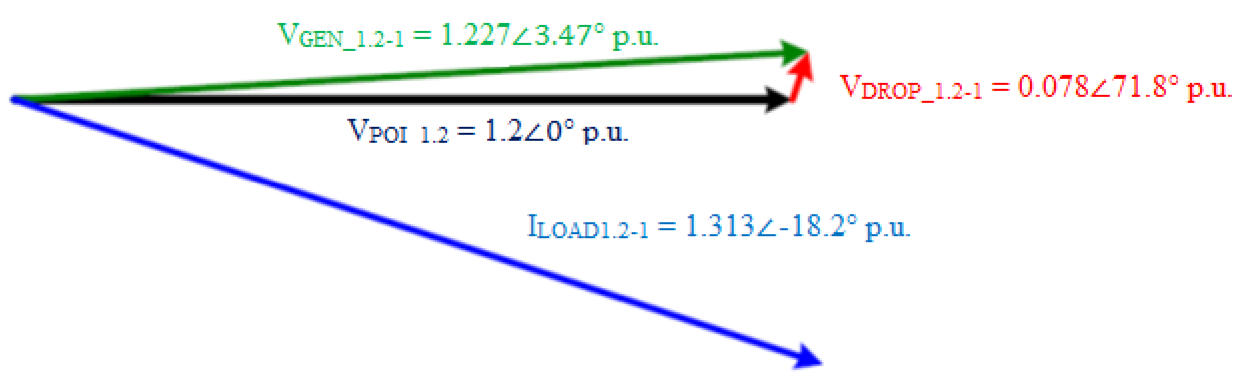

Figure 7

Rotate the load-flow current by the difference of power factor angle between the POI and the generator calculated in the first iteration to obtain the desired generator power factor angle for the next iteration.

<u>Iteration 2</u>:

Eq. (56) $MVA_{1.2\text{-}2} = \frac{\mathbf{MW_{GEN}}}{\mathbf{p.f._{1.2-1}}}$

$MVA_{1.2\text{-}2} = \frac{\mathbf{149.6\ MW}}{\mathbf{0.929}}$

$MVA_{1.2\text{-}2}$ = 161.0 MVA

Eq. (57) $\mathbf{MVA_{1.2\text{-}2\_pu}} = \frac{\mathbf{MVA_{1.2-2}}}{\mathbf{MVA_{SYS\_BASE}}}$

$MVA_{1.2\text{-}2\_pu} = \frac{\mathbf{161.0\ MVA}}{\mathbf{100\ MVA}}$

$MVA_{1.2\text{-}2\_pu}$ = 1.61 p.u. on the system base

Calculate the load flow current in per unit assuming rated MW output at the power factor calculated in the first iteration:

Eq. (58) $\mathbf{I_{LOAD\_1.2\text{-}2}} = \frac{\mathbf{MVA_{1.2-2\_pu}}}{\mathbf{V_{POI\_1.2\_pu}}} \angle\left[\mathbf{cos^{-1}(pf_{LOAD})} + \angle\mathbf{V_{GEN_{1.2-1}}}\right]$

$I_{LOAD\_1.2\text{-}2} = \frac{\mathbf{1.61}}{\mathbf{1.2}} \angle[\mathbf{cos^{-1}(0.95) + 3.47°}]$

$I_{LOAD\_1.2\text{-}2} = \mathbf{1.341\angle - 14.73°}$ p.u. on the generator base

Calculate the per unit voltage drop from the POI to the generator terminals at the assumed load flow:

Eq. (59) $V_{DROP\_1.2\text{-}2} = I_{LOAD\_1.2\text{-}2} * \mathbf{j\ Z_{GSU\_SYS\_BASE}}$

$V_{DROP\_1.2\text{-}2} = (\mathbf{1.342\angle - 14.73°}) * (\mathbf{0.0595\angle 90°})$

$V_{DROP\_1.2\text{-}2} = \mathbf{0.08\angle 75.27°}$ p.u. on the generator base

Calculate the per unit voltage drop at the generator terminals at the assumed load flow:

Eq. (60) $V_{GEN\_1.2\text{-}2} = V_{POI\_1.2\_pu} + V_{DROP\_1.2\text{-}2}$

$V_{GEN\_1.2\text{-}2} = (\mathbf{1.2\angle 0°}) + (\mathbf{0.08\angle 75.27°})$

$V_{GEN\_1.2\text{-}2} = \mathbf{1.223\angle 3.62°}$ p.u. on the generator base

Calculate the power factor at the generator to confirm the simple iteration gives 0.95 at the generator:

Eq. (61) $p.f._{1.2\text{-}2} = \cos(\angle V_{GEN\_1.2\text{-}2} - \angle I_{LOAD\_1.2\text{-}2})$

$p.f._{1.2\text{-}2} = \cos(\mathbf{3.62° + 14.73°})$

$p.f._{1.2\text{-}2} = 0.949$

The calculated values and their vector relationships for the second iteration are shown in Figure 8 below.

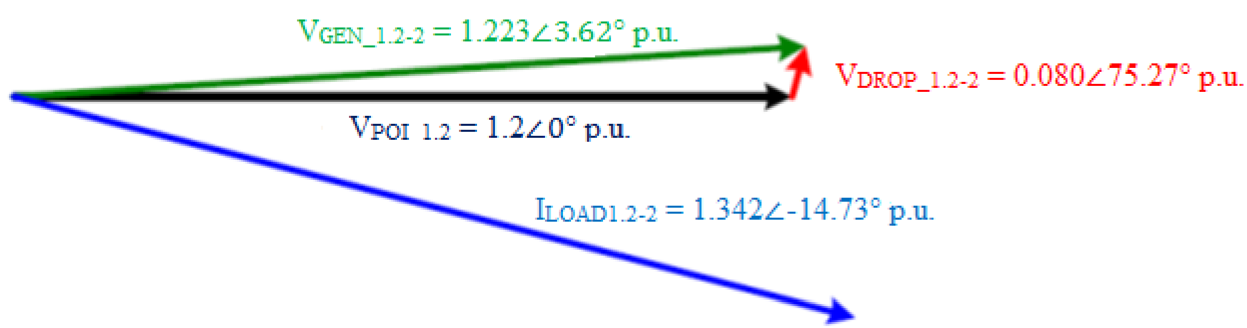

Figure 8

Convert the voltage ride-through value to the generator VT secondary voltage seen by the relay:

Eq. (62) $\mathbf{V_{GEN\_1.2\_SEC}} = \dfrac{\mathbf{V_{GEN\_1.2.2} * RATIO_{POI\_GEN} * kV_{GEN\_BASE}}}{\mathbf{VTR_{GEN}}}$

$V_{GEN\_1.2\_SEC} = \dfrac{\mathbf{1.223 * 0.962 * 16\ kV}}{\mathbf{140}}$

$V_{GEN\_1.2\_SEC} = 134.42$ V

Repeat Equations 52-62 for each voltage level from the graph in Attachment 2. The results for each equation at each voltage are in Table 7:

Table 7							
V_{POI} (p.u.)	Iteration	MVA_{POI_pu} (p.u.)	I_{LOAD} (p.u.)	V_{DROP} (p.u.)	V_{GEN} (p.u.)	p.f.$_2$	V_{GEN_SEC} (V)
1.2	1	1.575	$\mathbf{1.312}\angle$-18.2°	0.078∠71.8°	$\mathbf{1.227}\angle$3.47°	0.929	
1.2	2	1.610	1.341∠-14.73°	0.08$\angle\mathbf{75.27}$°	1.223$\angle\mathbf{3.62}$°	0.949	134.42
1.175	1	1.575	$\mathbf{1.340}\angle$-18.2°	0.08∠71.8°	$\mathbf{1.202}\angle$3.61°	0.928	
1.175	2	1.611	1.371∠-14.58°	0.082$\angle\mathbf{75.42}$°	1.198$\angle\mathbf{3.78}$°	0.949	131.71
1.15	1	1.575	$\mathbf{1.369}\angle$-18.2°	0.082∠71.8°	$\mathbf{1.178}\angle$3.77°	0.927	
1.15	2	1.613	1.403∠-14.43°	0.084$\angle\mathbf{75.57}$°	1.174$\angle\mathbf{3.95}$°	0.949	129.01
1.1	1	1.575	$\mathbf{1.432}\angle$-18.2°	0.085∠71.8°	$\mathbf{1.130}\angle$4.11°	0.925	
1.1	2	1.617	1.470∠-14.08°	0.088$\angle\mathbf{75.92}$°	1.125$\angle\mathbf{4.33}$°	0.949	123.62
0.9	1	1.575	$\mathbf{1.750}\angle$-18.2°	0.104∠71.8°	$\mathbf{0.938}\angle$6.06°	0.912	
0.9	2	1.641	1.823∠-12.14°	0.109$\angle\mathbf{77.86}$°	0.929$\angle\mathbf{6.56}$°	0.947	102.11
0.75	1	1.575	$\mathbf{2.100}\angle$-18.2°	0.125∠71.8°	$\mathbf{0.798}\angle\mathbf{8.56}$°	0.893	
0.75	2	1.675	2.234∠-9.64°	0.133$\angle\mathbf{80.36}$°	0.783$\angle\mathbf{9.63}$°	0.944	86.11
0.65	1	1.575	$\mathbf{2.423}\angle$-18.2°	0.144∠71.8°	$\mathbf{0.708}\angle\mathbf{11}$.15°	0.872	
0.65	2	1.716	2.640∠-7.04°	0.157$\angle\mathbf{82.96}$°	0.687$\angle\mathbf{13.12}$°	0.939	75.55
0.45	1	1.575	$\mathbf{3.499}\angle$-18.2°	0.208∠71.8°	$\mathbf{0.552}\angle$21.02°	0.775	
0.45	2	1.931	4.291∠2.82°	0.255$\angle\mathbf{92.82}$°	0.506$\angle\mathbf{30}$.25°	0.888	55.67

Evaluate relay operations based on applied voltage from the generator VTs (V_{GEN_SEC}) from Table 7. The results of the evaluation are shown in Table 8 below:

Table 8					
Undervoltage (27) Settings to be evaluated:					
		27 Setting Pickup:	102.90	Vsec	
		27 Time Delay:	1	sec	
VPOI	**Delay required (sec)**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
0.900	3.00	102.11	1.00	DOES NOT COMPLY	Relay operate time is LESS than the required delay
0.750	2.00	86.11	1.00	DOES NOT COMPLY	Relay operate time is LESS than the required delay
0.650	0.30	75.55	1.00	COMPLY	Relay operate time is greater than the required delay
0.450	0.15	55.67	1.00	COMPLY	Relay operate time is greater than the required delay
Overvoltage (59) Settings to be evaluated:					
		59 Setting Pickup:	125.70	Vsec	
		59 Setting Time Delay:	30	sec	
VPOI	**Delay required (sec)**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	123.62	NoOp	COMPLY	Applied voltage is below pickup of 59 element - No Operation
1.150	0.50	129.01	30.00	COMPLY	Relay operate time is greater than the required delay
1.175	0.20	131.71	30.00	COMPLY	Relay operate time is greater than the required delay
1.200	0.00	134.42	30.00	COMPLY	Relay operate time is greater than the required delay
Overvoltage (24DT) Settings to be evaluated:					
		24DT Setting Pickup:	134.86	Vsec	118% of generator nominal = 1.18 * 16000V / 140 = 134.86Vsec
		24DT Setting Time Delay:	2	sec	
VPOI	**Delay required (sec)**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	123.62	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.150	0.50	129.01	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.175	0.20	131.71	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.200	0.00	134.42	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
Overvoltage (24IT) Settings to be evaluated:					
		24IT Setting Pickup:	125.71	Vsec	110% of generator nominal = 1.10 * 16000V / 140 = 125.71Vsec
		24IT Setting	2	sec	

		Time Delay:			
VPOI	**Delay required (sec)**	**Vsec applied to relay**	**Op Time (sec)**	**Result**	**Notes**
1.100	1.00	123.62	NoOp	COMPLY	Applied voltage is below pickup of 24DT element - No Operation
1.150	0.50	129.01	124.67	COMPLY	Relay operate time is greater than the required delay
1.175	0.20	131.71	68.57	COMPLY	Relay operate time is greater than the required delay
1.200	0.00	134.42	47.23	COMPLY	Relay operate time is greater than the required delay

Appendix 1 - Basis for Quantities used in calculations

Basis for 1.0 per-unit Voltage and Power Factor used in Example Calculations

In Attachment 2 of PRC-024-2 titled "Voltage Ride-Through Curve Clarifications, Evaluating Protective Relay Settings:" the standard states:

PRC-024-2 Attachment 2

Voltage Ride-Through Curve Clarifications
Curve Details:

1. The per unit voltage base for these curves is the nominal operating voltage specified by the Transmission Planner in the analysis of the reliability of the Interconnected Transmission Systems at the point of interconnection to the Bulk Electric System (BES).
2. The curves depicted were derived based on three-phase transmission system zone 1 faults with Normal Clearing not exceeding 9 cycles. The curves apply to voltage excursions regardless of the type of initiating event.
3. The envelope within the curves represents the cumulative voltage duration at the point of interconnection with the BES. For example, if the voltage first exceeds 1.15 p.u. at 0.3 seconds after a fault, does not exceed 1.2 per unit voltage, and returns below 1.15 p.u. at 0.4 seconds, then the cumulative time the voltage is above 1.15 p.u. voltage is 0.1 seconds and is within the no-trip zone of the curve.
4. The curves depicted assume system frequency is 60 Hertz (Hz). When evaluating Volts/Hertz protection, you may adjust the magnitude of the high-voltage curve in proportion to deviations of frequency below 60 Hz.
5. Voltages in the curve assume minimum fundamental frequency phase-to-ground or phase to-phase voltage for the low-voltage duration curve and the greater of maximum RMS or crest phase-to-phase voltage for the high-voltage duration curve.

Evaluating Protective Relay Settings:

1. Use either the following assumptions or loading conditions that are believed to be the most probable for the unit under study to evaluate voltage protection relay setting calculations on the static case for steady-state initial conditions:
   a. All of the units connected to the same transformer are online and operating.
   b. All of the units are at full nameplate real-power output.
   c. Power factor is 0.95 lagging (i.e. supplying reactive power to the system) as measured at the generator terminals.
   d. The automatic voltage regulator is in automatic voltage control mode.
2. Evaluate voltage protection relay settings assuming that additional installed generating plant reactive support equipment (such as static VAr compensators, synchronous condensers, or capacitors) is available and operating normally.
3. Evaluate voltage protection relay settings accounting for the actual tap settings of transformers between the generator terminals and the POI.

Attachment 2 in PRC-024-2 provides guidance to the generator asset owner (GO) on how to verify compliance. Item 1 of the Curve Details of Attachment 2 says, "The per unit voltage base for these curves is the nominal operating voltage specified by the Transmission Planner in the analysis of the reliability of the Interconnected Transmission Systems at the point of interconnection to the Bulk Electric System (BES)." Planners must plan the system such that it operates within the equipment capabilities of BES assets. They generally limit their acceptable operating states to some range of the system nominal voltage. The voltage used in the analysis is meant to designate the nominal voltage base used in the planner's system model. The GO must confirm the system nominal voltage for the POI bus that is used in the planner's model of the bulk electric system. This will normally be the standard nominal voltage of the system and will not vary from bus to bus for a given voltage level of the BES. Because the no-trip zone limits are steady-state representations of the severity of the voltage transient versus the time to recover during a transient event, it is acceptable to use the system model nominal in defining these limits. If the planners determine that operating voltages must deviate significantly from nominal, they generally recommend changes in the recommended setting of the no-load tap changer (NLTC) on the generator step-up transformer to ensure that the generation assets can operate within their nominal operating ranges. Thus, if a NLTC is adjusted, verification of compliance of voltage sensitive relays with PRC-024 limits should be repeated.

Item 1 of the Evaluating Protective Relay Settings section of Attachment 2 says, "Use either the following assumptions or loading conditions that are believed to be the most probable for the unit under study . . ." The standard then goes on to suggest assuming that generator is at full nameplate real-power output and at 0.95 lagging power factor and that the AVR is in automatic voltage control mode. In order to understand the intent of this guidance, we have to go back to understanding that we are using a steady-state analysis to provide ride-through capability for a transient event.

Let us first look at the undervoltage limits. A transient undervoltage condition is likely to occur due to a short circuit in the vicinity of a generating unit. A severe short circuit should be cleared relatively quickly and the unit should be able to recover. If the unit is initially running at leading power factor (under excited and absorbing VArs from the system), the internal voltage behind the generator impedance will be low and the generator's ability to ride-through the transient low voltage event is reduced. Thus, for evaluating undervoltage element coordination with the ride-through curve, this will likely be the worst-case scenario. Assuming that leading power factor will reduce the generator voltage in steady-state conditions and reduce coordination margins with undervoltage tripping elements relative to assuming lagging power factor in the calculations. In steady-state conditions, one would not expect the unit to be absorbing VArs during an undervoltage condition. However, the four-second time window of the ride-through curves is intended to represent a transient disturbance. The standard allows us to assume lagging power factor for this condition so that is what is used in the examples. If the GO would like to find the worst case for coordination, they are allowed to use an assumption of leading power factor in the calculations.

Examining the overvoltage limits, for a transient condition, a fast-acting exciter will likely have boosted the excitation during a slow-clearing short circuit to help the unit remain stable. Thus, once the short circuit is cleared, the generator terminal voltage will be elevated until the AVR has had time to reduce the excitation to steady-state levels. For this case, the unit during the four-second transient time window will be running at lagging power factor (over excited and supplying VArs into the system). Thus, we use the assumption recommended in the standard of lagging power factor in the example for evaluating overvoltage elements.

In Eq 1, the nameplate data of the generator is used to determine the rated MW of the unit. The nameplate specifies that the unit is rated at 176 MVA and 0.85 power factor. MVA at 0.85 power factor yields a value of 149.6 MW. Typical generating units are then designed with a turbine that will produce that rated power in MW. Therefore, in these examples, 149.6 MW is used as the rated power output of the example generator. The example calculations then use that rated power level with the unit operating at 0.95 power factor for the voltage drop calculations.

These are the basis of the quantities that are used in these example calculations. It is reminded that, as the PRC-024 Standard states, other quantities that are determined to be more probable for your specific unit may be substituted for the quantities used in these calculations.