# Setting and Verification of Generation Protection to Meet NERC Reliability Standards

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***Abstract*—NERC has recently published several reliability standards PRC-019, PRC-024 and PRC-026. Together with the existing standards PRC-001 and PRC-025, these standards set out the generation and generation interconnection relays reliability requirements for Bulk Electric System (BES). The protection relays are required not only to provide adequate protection to generators, step-up power transformers and unit auxiliary transformers, but also to comply with these standards to avoid tripping off generators during various power system disturbances.**

**This paper first reviews these standards, and studies their impact to the protection functions, such as: To identify the generation and generation interconnection protection relays that are subject to the various NERC standards; How to set and verify the distance/loss-of-field/out-of-step protection elements for stable power swing compliance; How to set and verify the under- and over-frequency voltage protection elements for generator protection and to satisfy the NERC frequency and voltage ride through requirements; How to set and verify the over-excitation and loss-of-field protection elements to coordinate with generator excitation limiters.**

**The paper then analyzes a few cases where the protection relay settings do not meet the reliability standards due to commonly overlooked items, such as the voltage drop, voltage tap position on the step-up transformer and relay over-excitation curve selection.**

***Keywords*—*Bulk Electric System, NERC PRC Compliance, Generation Interconnection Relays, Reliability Standards***

ACRONYM LISTING:

| Acronym | Definition |
|---|---|
| BES | Bulk Electric System |
| NERC | North American Electric Reliability Corporation |
| PRC | (NERC) Protection and Control (Reliability Standards) |
| GSU | Generator Step-up Transformer |
| UAT | Unit Auxiliary Transformer |
| OEL | Over-Excitation Limiter |
| UEL | Under-Excitation Limiter |

## I. INTRODUCTION

Generator protection has been undergoing major changes over the years. Prior to the Northeast black out of 2003, the focus of the generation protection had been on providing adequate protection on the generators, the step-up transformers and the auxiliary equipment. The impact of the protection operation to the power system was considered secondary and there were no clear requirements on how long generators shall remain online under system disturbances.

The investigation of August 14, 2003 Northeast black out shows several violations of NERC operation policies contributed directly to an uncontrolled, cascading outage on the Eastern Interconnection. As a result of this investigation, NERC started the creation of the reliability standards (PRC) and mandatory compliance of these standards within Bulk Electric System (BES) generating units and generating plants. PRC NERC audits are conducted by the eight Regional Entities. The current NERC PRC standards related with generator protection that are in enforcement or to be enforced are listed below in table 1:

Table 1 NERC PRC Reliability Standards on Power System Protection

| Standard | Purpose | Enforcement Date (USA) |
|---|---|---|
| PRC-001 | To ensure system protection is coordinated among operating entities. | 05/29/2015 |
| PRC-019 | To verify coordination of generating unit Facility or synchronous condenser voltage regulating controls, limit functions, equipment capabilities and protection system settings. | 07/01/2016 |
| PRC-024 | Ensure Generator Owners set their generator protective relays such that generating units remain connected during defined frequency and voltage excursions. | 07/01/2016 |
| PRC-025 | To set load-responsive protective relays associated with generation facilities at a level to prevent unnecessary tripping of generators during a system disturbance for conditions that do not pose a risk of damage to the associated equipment. | 10/01/2014 |
| PRC-026 | To ensure that load-responsive protective relays are expected to not trip in response to stable power swings during non-Fault conditions. | 01/01/2018 (R1) 01/01/2020 (the rest) |

## II. OVERVIEW OF GENERATOR PROTECTION SUBJECT TO NERC PRC STANDARDS

Generator protections related to load, voltage and frequency that may trip the generators off-line under system disturbance are addressed in different NERC PRC reliability standards per the table 2 below. Not all protection functions are included in the PRC compliance requirement. Unit protections such as differential protection (87) or protection functions such as reverse power (32) or stator ground protection (64) is not affected by the system disturbance, therefore there is no need to be included in those standards. While some PRC Standards cover all the generators connected to the BES, some other Standards, e.g. PRC-019, require compliance only on single generating unit greater than 20MVA. Each individual PRC standard needs to be checked to verify the necessity of compliance for a given generator protection.

Table 2 Generator Protection and Corresponding PRC Standards

| **Generator Protection Functions** | **PRC-01** | **PRC-019** | **PRC-024** | **PRC-025** | **PRC-026** |
|---|---|---|---|---|---|
| Phase distance | ✓ | | | ✓ | ✓ |
| Phase Overcurrent | ✓ | | | ✓ | ✓ |
| Loss-of-field | | ✓ | | | ✓ |
| Over- and Under-Frequency | | | ✓ | | |
| Over-and Under-Voltage | | | ✓ | | |
| Volts/Hz | | ✓ | ✓ | | |
| Out-of-Step | | | | | ✓ |

## III. ANALYSIS OF THE PROTECTION SETTINGS FOR NERC PRC COMPLIANCE

### *A. Load Responsive Functions*

In order to detect and clear faults on the power system but external to the generator protection zone or generator step-up transformer zone, distance (21) or phase overcurrent (51P/67P) directional toward the transmission system are typically applied and referred to as system backup protection. The settings for these load-responsive relays associated with the generating facilities shall be verified and provided with evidence of the compliance NERC PRC-025-1 and PRC-026-1 to prevent from premature or unnecessary tripping of generators in case of system disturbance and stable power swings. The backup system protection functions shall also coordinate with the transmission line protections per PRC-001, which will not be discusses in this paper.

The PRC-025-1 Generator Relay Loadability Standard has established criteria for setting load-responsive protective relays such that generators may provide reactive power within their dynamic capability during transient time periods to help the system recover from a voltage disturbance.

Relay loadability evaluation criteria in PRC-025-1 lists various options to set the load-responsive relays. When reviewing the PRC-025 compatibility, the first step will be to identify the options that apply for a certain protection function. Examples are given in the standard per Fig. 1. In this paper, we will focus on discussing the generator distance (21) function and step-up transformer HV side OC (51) function highlighted in Fig. 1.

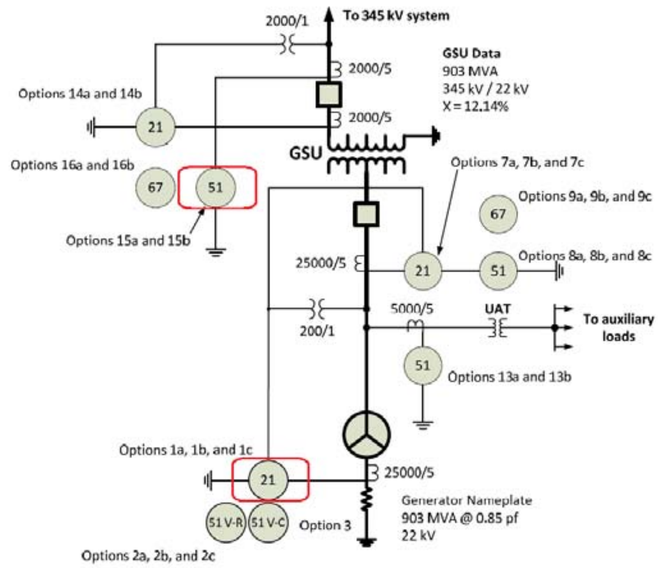



Fig. 1. Generator Load Responsive Protection Functions (Ref. 4)

#### 1) Backup Distance Protection (21)

The distance protection setting criteria per the IEEE Guide for AC Generator Protection (IEEE C37.102) are listed below:

The zone 1 relay element is set to the smaller of the two conditions below:

1. 120% of the unit transformer impedance.

2. Step-up transformer impedance + 80% of the zone 1 reach setting of the shortest transmission line distance relay (neglecting in-feeds)

A time delay of approximately 0.5 second gives the primary protection (generator differential, transformer differential and overall differential) and breaker failure function enough time to operate before the generator backup function.

The zone 2 distance element is typically set at the smallest of the following three criteria:

1. 120% of the longest line with in-feeds

2. 50 to 67% of the generator load impedance (Zload) at the rated power factor angle (RPFA) of the generator. This provides a 150 to 200% margin over generator full load. This is typically the prevailing criteria.

3. 80 to 90% of generator load impedance at the maximum torque angle of the zone 2 impedance relay setting (typically 85 degrees)

Criteria 2 for distance Z2 can be expressed as:

$$Z_2 = \frac{K_1 * Z_{max\_load}}{COS(MTA - RPFA)}$$

$$Z_{max\_load} = \frac{V_{Gnom}^2}{MVA_G} * \frac{CTR}{VTR}$$

Per the PRC-025-1 option 1a, the impedance element shall be set less than the calculated impedance derived from 115% of:

1. Real power output - 100% of the gross MW capability reported to the transmission planer and
2. Reactive power output - 150% of the MW value derived from the generator nameplate MVA rating at rated power factor.

$$Z_{PRC\_025} = \frac{Z_{sec}}{1.15 * COS(MTA - \theta_{transientloadangle})}$$

$$Z_{sec} = \frac{V_{Gen}^2}{S_{Gen}} * \frac{CTR}{VTR}$$

Where $V_{Gen}$=0.95p.u. *$V_{nom}$*$GSU_{ratio}$

$S_{Gen}$=$K_2$* P+j1.5P with $K_2$=Psynch_reported/Psynch_namplate with RPF, if the reported power is not available, it can be assumed that $K_2$=1.

A comparison $Z_2$ and $Z_{PRC\_025}$ under the following condition shows:

$$\frac{Z_{PRC\_025}}{Z_2} = \frac{V_{Gen}^2}{K_1 * V_{Gnom}^2} * \frac{M_{VAG}}{1.15 * S_{Gen}} * \frac{COS(MTA - RPFA)}{COS(MTA - \theta_{transientloadangle})}$$

When $K_1$=0.5, $K_2$=1 pf=0.95 MTA=85°,

$$\frac{Z_{PRC\_025}}{Z_2} = 0.372$$

From above calculation, it can be observed that the setting of Z2 in the normal practice may not satisfy the NERC PRC-025-1 requirement, and a validation is required.

The generator backup distance setting is shown in Fig. 2 below:

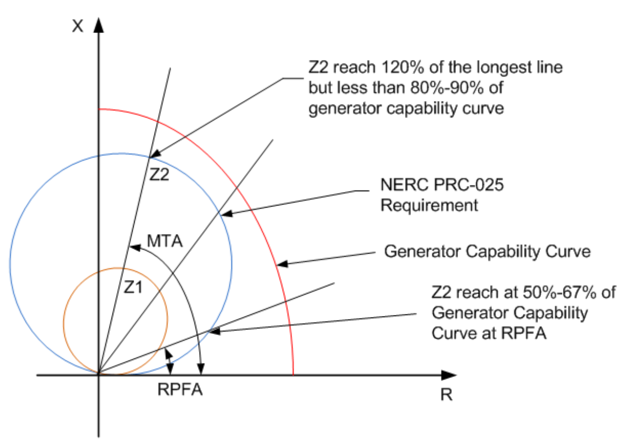



Fig. 2. Generator Backup Distance (21) Protection Settings

The Relay Performance during Stable Power Swings standard (PRC-026-1) has established criteria for evaluating load-responsive protective relay performance during stable power swings as described in attachment A of the PRC-026-1 standard. The standard applies to protective functions which could trip instantaneously or with a time delay of less than 15 cycles on load current. Therefore, it is obvious that the distance Z1 (21-1) owned by generation owner if set to trip below 15 cycles shall comply the NERC PRC-026-1. However, per the IEEE setting guide line for Z1, if it is set to trip at 30 cycles (0.5 s), then there is no further obligation to the owner in this standard for this load responsive protective relay.

If the Z1 is set to trip within 15 cycles, then PRC-026-1 will apply. The calculation of power swing impedance is required to make sure the Z1 characteristic is not in the region where a stable power swing would occur.

The power swing impedance at the relay location ($Z_R$) can be calculated using the formula shown below:

$$Z_R = \frac{(1-m) * E_s\angle\delta + m * E_R}{E_S\angle\delta - E_R)} * Z_{sys}$$

$$m = \frac{X_d'}{Z_{sys}}$$

Where:

$X_d$' is the generator saturated transient reactance.
$Z_{sys}$ is the total equivalent system impedance.
$E_S$ is the sending-end voltage.
$E_R$ is the receiving-end voltage.

Fig. 3 below shows an example PRC-026-1 generator distance compliance check. It can be observed that Zone 1 and Zone 2 are both confined within the unstable power swing region. The PRC-026 attachment B, Criterion A, therefore, can be met.

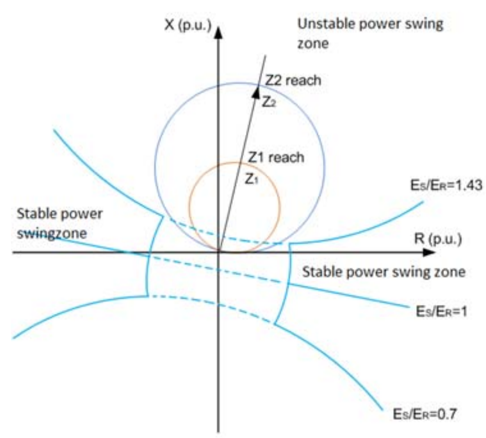



Fig. 3. Generator Backup Distance (21) and Power Swing Compliance Check

2) Over-Current Protection (50/51)

The pickup setting of overcurrent function shall comply with both the PRC-025-1 and PRC-026-1.

While PRC-025-1 put emphasis on the generator capability of providing reactive power under voltage disturbance. For example, option 15a in this standard, specifies that when the line terminal voltage drops to 0.85 pu, the overcurrent element shall be set greater than 115% of the calculated current derived from 100% reported real power P and reactive power of 120% P.

$$I_{limit} = 1.15 * \frac{S_G}{\sqrt{3} * 0.85Vn}$$

Where:
$S_G$=P+j1.2P, P is the reported active power.
$V_n$ is the generator rated line-to-line voltage

PRC-026-1attachment B, criterion B evaluates overcurrent for tripping with a time delay of less than 15cycles. The phase overcurrent pickup must be set to above the maximum allowable current, which can be calculated as below:

$$I_{sys} = \frac{V_s - V_R}{Z_{Sys}}$$

Where:
Vs is the source line-to-ground voltage at $1.05\angle 120^{\circ}$
$V_R$ is the generator line-to ground voltage at $1.05\angle 0^{\circ}$
$Z_{sys}$ is the sum of the sending-end source impedance, the line impedance and the receiving-end generator impedance.

### B. *Loss-of-Excitation Function*

Generator Loss-of-Excitation (LOE), or Loss-of-Field protection is used to detected the abnormal operation condition where the generator excitation is completely or partially lost. Typical approach for this protection is a distance protection with two zones, as shown in Fig. 4. The two mho relays are both offset by Xd"/2 from the origin. The smaller zone is used to detect LOE under full load and down to 30% load condition. There is no intentional time delay of this zone, since this is a severe case where fast tripping is needed. The larger zone is used to detect full or partial LOE under less severe operation condition, where a time delay of 30 to 40 cycles are used [1].

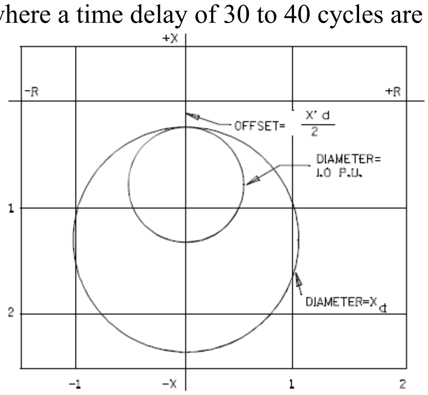



Fig. 4. Loss-of-Excitation Protection with Distance Relays [1]

PRC-019 requires the relay LOE function to coordinate with the excitation limiters. There are over and under-excitation limiters in the excitation control system. It is the under-excitation limiter that the LOE needs to coordinate. When generator is under-excited but the excitation system is still functioning, the LOE shall not operate before the under-excitation limiter is activated. These two functions need to coordinate in both pickup and time. Usually the limiter is fast action, so the time coordination is not a problem. While the LOE function is plotted on the R-X diagram, the excitation limiter is depicted in generator P-Q capability curve. To determine their coordination, the two characteristics need to be plotted on the same graph, either on P-Q or R-X. The equations used for converting between these two graphs are as follows [7]:

With a given power angle β,

From P-Q graph to R-X graph:

$$Z = \frac{(kV)^2}{MVA}$$

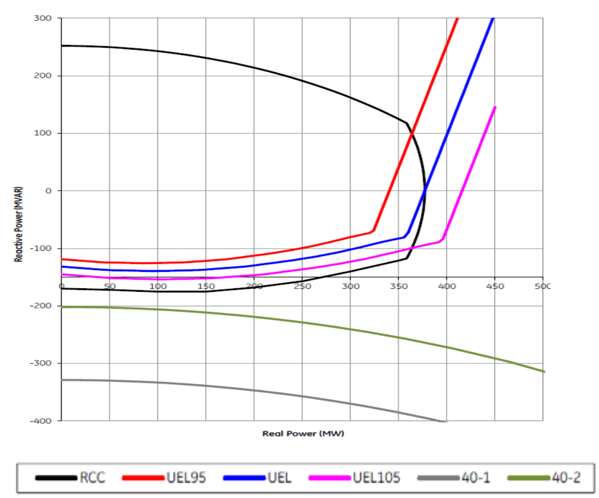
From R-X plot to P-Q plot:

$$MVA = \frac{(kV)^2}{Z}$$

Where:

kV is the rated generator voltage;
MVA is the complex power of the generator capability curve corresponding to the power angle β;
Z is the impedance value (in primary ohms) of the LOE characteristic corresponding to the power angle β;

An example of LOE R-X characteristic conversion to P-Q and plotted with generator capability and UEL was shown in Figure [5]. There are two LOE P-Q curves due to the two LOE elements. The LOE coordinates with the UEL in this example, since both curves are below the UEL curves. Note that there are multiple P-Q curves for the excitation system UEL in this example, corresponding to 95%, 100% and 105% generator terminal voltages.




(RCC: Reactive Capability Curve)
Fig. 5. LOE characteristic P-Q Plot and comparison with Generator Capability and UEL curves

LOE function is also subject to the PRC-026 compliance to prevent operation from unstable power swing. Since the PRC-026 is only applicable to protection elements with operating time faster than 15 cycles, usually only the fast LOE element needs to be verified for compliance. The characteristic of LOE, if set strictly per IEEE guideline, will fall below the Es/Er=0.7 unstable power swing curve shown at the bottom of Figure 8, indicating that the LOE will not operate during a stable power swing condition and satisfies PRC-26 compliance.

### *C. Over and Under-frequency Functions*

Generator over and under-frequency protection is designed to protect generator and the prime movers under abnormal frequency conditions. Over-frequency most likely happens under load rejection while under-frequency can happen when major disturbance causes a system wide low frequency condition. Governor regulation and load shedding are the primary methods to restore the frequency back to the normal range. Disconnecting generators prematurely by protective relays due to system disturbances can exacerbate the problem, which is the main issue the NERC PRC-024 standard tries to address. PRC-024 defines frequency "no-trip" zone, where each regional interconnection entity can define its own no-tripping limits, shown in the following figure.

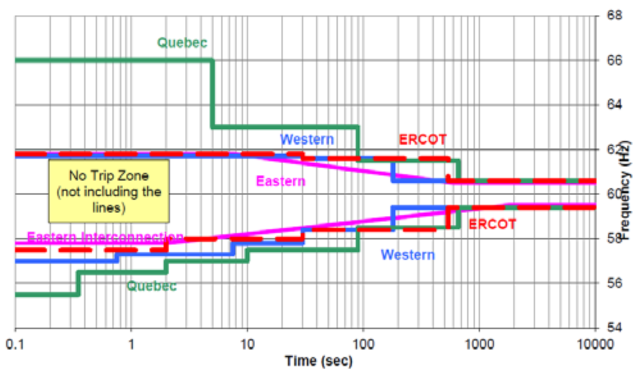



Fig. 6. Generator Off Nominal Frequency Capability Curve [3]

The generator and prime mover withstand capability under abnormal frequency is generally much greater than the no-trip boundaries in the PRC-024. In general, there is no difficulty for the generator protective relay under and over-frequency protection setting to satisfy the "no-trip" limits. Should the generator/prime mover have limitations on abnormal frequency capabilities, the relay can be excluded from the PRC-024 requirement in order to provide adequate protection. In this case, evidence and documents are required to demonstrate these equipment limitations.

### *D. Over and Under-voltage Functions*

Per IEEE C37.102-2006 standard, generators are normally designed for continuous operation at a maximum of 105% of rated voltage with rated power and rated frequency. Generator overvoltage is usually caused by sudden load rejection or failure of the voltage regulator. In case of Steam Turbine generators and Gas Turbine generators, this problem is mitigated by the fast response of AVR and speed control systems. Operating at higher than permissible overvoltage may result in over-fluxing and excessive electrical stress on the insulation system. Overvoltage protection can be applied with one inverse and instantaneous time delayed relays or two definite time delayed relays based on the generator manufacturer's recommendations. Generator under-voltage can be caused by delayed fault clearing on either the generator terminal or on the interconnection line where the generator is connected.

The over and under-voltage functions should monitor the phase-to-phase or positive sequence voltages. Phase-to-neutral voltage can rise due to ground fault; thus, it is not a suitable voltage to use for monitoring system voltage. Over and under-voltage protection must also satisfy the PRC-024 voltage ride-through requirements, shown in the following figure. The purpose of this requirement is to prevent the generator be disconnected prematurely due to transient voltage fluctuation caused by faults or disturbances on the power system.

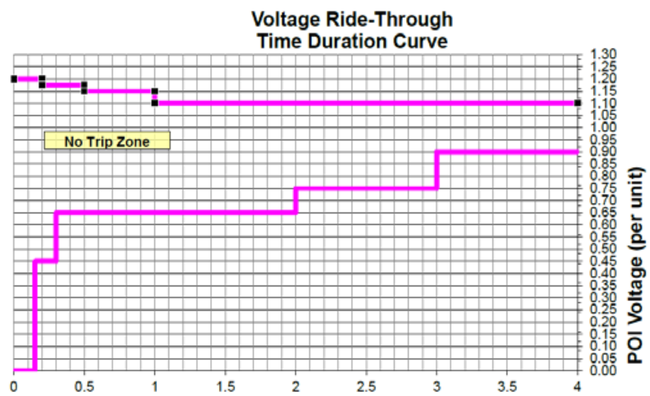



Fig. 7. Generator Voltage Ride-Through Time Duration Curve [3]

The voltage unit in the figure is per unit based, where the voltage basis is not the generator terminal voltage, but the "nominal operating voltage specified by the Transmission Planner". Usually Transmission Planner specify operation voltage at the GSU HV side, therefore, the generator voltage protection must be converted to the GSU high side to be evaluated with the voltage ride through chart. The GSU turn ratio and voltage drop due to load flow shall be considered in the conversion. The following example illustrates the voltage conversion method.

In this example, the generator rated voltage is 26 kV, GSU connected taps are 525/26kV, GSU impedance is 10.2% on 820MVA base. The generator rated power is 860MVA, power factor at 0.95 lagging. The normal voltage set-point requested by the transmission operator at the HV side is 530kV, which shall be used as the base voltage in the voltage ride through evaluation. If the GSU HV voltage rise to 1.10 times of the scheduled voltage, which is 1.1 * 530kV = 583kV, the generator terminal voltage will rise to 29.4kV, which is calculated based on the generator rated power output and considering the voltage drop across the GSU. Generator overvoltage protection operating time at voltage of 29.4/26=1.13 p.u. should be compared with the operating time of ride-through curve at voltage level of 1.10 p.u. If this generator overvoltage protection was set to operate in 4.0 sec at 1.12 p.u. generator terminal voltage base, it would not meet the PRC-024 voltage ride through requirement, though seemingly the operating point is above the curve.

*E. Volt/Hz Function*

Generator, GSU and auxiliary transformers can be subjected to overexcited condition. The V/Hz function is the most commonly used method to protect the equipment on over-excitation. Typically, two levels of definite time or inverse curves are used for protection, with the inverse curves the preferred curve because of its better fit to the equipment overexcitation withstand capability. The V/Hz function pickup is commonly expressed in per unit voltage over per unit frequency. Since the generator can operate over-excited at 1.05 p.u. and transformer at 1.1 p.u. at no load, the first level pickup setting is usually set at around 1.10 p.u. with 45 to 60 seconds time delay to alarm to trip. The second level is set at around 1.20 p.u. to trip in a few seconds. Generator and transformer over-excitation capability curve from manufacture should be checked to ensure the selected V/Hz pickup settings and time delay or curve can provide adequate protection.

PRC-019 requires that the V/Hz element coordinates with excitation control. When the generator is over-excited, the generator excitation system should act first to reduce the excitation before the protection relay operates. Most generator exciters are equipped with Over-Excitation Limiter (OEL), realized as excitation time-overcurrent and/or V/Hz element. Since the generator can operate with terminal voltage range from 95% to 105%, the OEL V/Hz limiter pickup is set in the range of 105-110% per unit. The protective relay V/Hz element pickup should be set slightly (i.e. 1%) higher than that of the exciter limiter to ensure the coordination requirement with accounting for measurement error.

It is important to note that a common voltage base must be used in evaluation of the V/Hz coordination. GSU low side connected tap voltage may not be the same as the rated generator voltage. Thus the transformer V/Hz protection must be converted to the per unit value on the generator voltage basis

$$V/Hz_{Tfmr\_on\_Gen\_basis} = V/Hz_{Tfmr\_limit} * \frac{V_{Tfmr}}{V_{Gen}}$$

When the GSU or UAT connected voltage tap is lower than the generator terminal voltage, the transformer V/Hz protection actual pickup value may be lower than the generator OEL V/Hz limiter setting, even though the V/Hz protection nominal pickup setting is higher. For example, a generator terminal rated voltage is 22.0kV, the GSU nameplate connection is 230/21.4kV and the unit auxiliary transformer is rated at 21.0/7.2kV. Both the GSU and UAT has V/Hz protection and the pickup is 1.10 p.u on their respective voltage base, and the generator exciter V/Hz OEL is set at 1.05p.u. on the generator voltage basis. The GSU and UAT V/Hz protection pickup converted to the generator basis will be:

For GSU,

$$V/Hz_{pickup} = 1.1 * \frac{21.4kV}{22.0kV} = 1.07\ p.u.$$

For UAT,

$$V/Hz_{pickup} = 1.1 * \frac{21.0kV}{22.0kV} = 1.05\ p.u.$$

The GSU V/Hz protection pickup of 1.07 p.u. is greater than the OEL V/Hz pickup of 1.05 p.u. Therefore, these two functions coordinate well. The UAT V/Hz protection pickup, on the other hand, is the same as the OEL V/Hz pickup. Considering the measurement error, they do not coordinate. By checking the UAT over-excitation withstand capability curve provided by the manufacture, the V/Hz can be raised to 1.12 p.u. to coordinate with exciter OEL, yet still provides adequate protection to the transformer.

Since the V/Hz protection could operate under over-excitation caused by overvoltage, this element is also subject to the PRC-024 compliance on voltage ride-through capability. The voltage disturbance on generator terminal targeted by the PRC-024 is of relatively short period, lasting no more than 4 sec. On the other hand, the thermal effect of over-excitation needs time to build-up. It is recommended that the V/Hz protection be set no faster than 4 seconds, then it can meet the PRC-024 compliance without further comparison with the voltage ride through curve.

*F. Out-of-step Tripping Function*

The resulting high peak currents and off-nominal frequency operation when a generator loses synchronism may cause winding stresses, pulsating torques and mechanical resonances that are potentially damaging to the generator. It is recommended that the generator be tripped without delay, perhaps in the first half slip cycle of a loss of synchronism. The out of step or synchronism protection uses single or double blinders with a mho element and timers. This function provides an out-of-step trip function and discriminates between stable and unstable power swing. PRC-026-1 requires the trip initiating blinders be set at an angle greater than the stability limit of 120 degrees and be completely contained within the unstable power swing region to remove the possibility of a trip for a stable power swing. Figure 8 below is an out-of-step detection function that uses a mho and two blinders that meets the PRC-026-1 Attachment B, Criterion A.

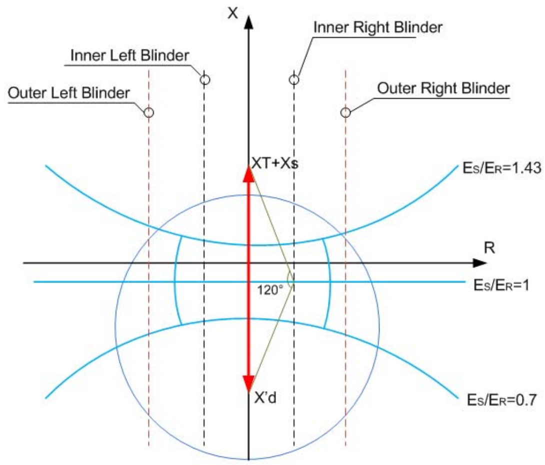



Fig. 8. Generator Out-of-Step Detection and PRC Compliance

## IV. Conclusions

The NERC generator Reliability Standards set limits to protection relays in order to avoid undesired operation under system disturbances. This is not in conflict to the IEEE Guide for AC Generator Protection, but rather a complement. Protection engineers shall be aware of these requirements, and also need some knowledge in generator operation and excitation control to set the generator and transformer protection relays in compliance. If non-compliance exists, parameters other than the protection relay settings, such as generator step-up transformer tap connection, or the exciter limiter settings may need to be reviewed to correct the issue.

Generating the compliance evidence requires extensive work of converting and comparing the relay settings with exciter settings and equipment capabilities. Various plots, tables or calculation sheets are needed as the evidence. This is an area where automation is needed to reduce the complex manual calculations. There have been some software solutions emerging but further improvement is necessary to make it more adaptive to use.

## References

[1] IEEE Std C37.102-1995, IEEE Guide for AC Generator Protection
[2] NERC Reliability Standard PRC-019-2, Coordination of Generating Unit or Plant Capabilities, Voltage Regulating Controls, and Protection
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## Biography:

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