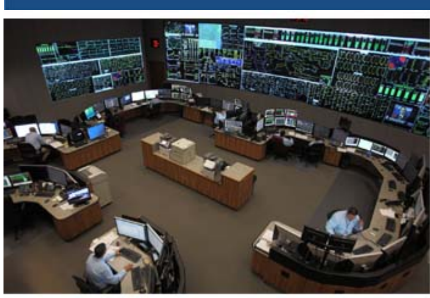
NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Unit Auxiliary Transformer Overcurrent Relay Loadability During a Transmission Depressed Voltage Condition

NERC System Protection and Control Subcommittee

March 2016

RELIABILITY | ACCOUNTABILITY



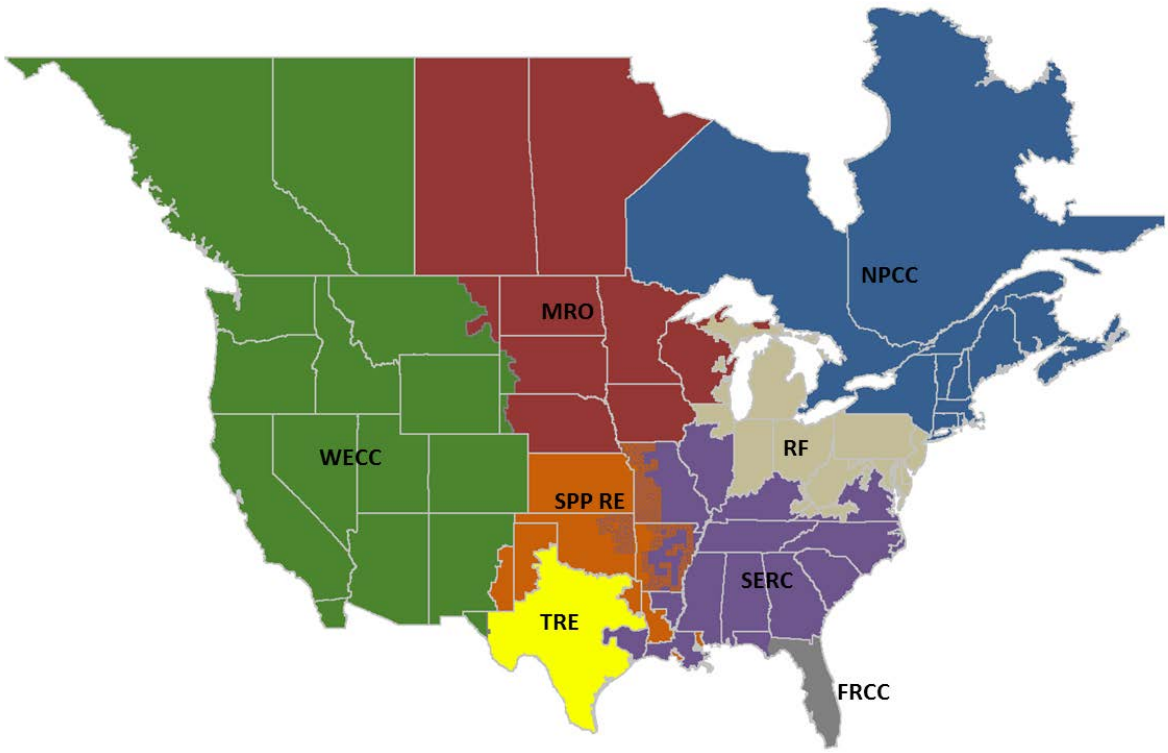

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Table of Contents

Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into several assessment areas within the eight Regional Entity (RE) boundaries, as shown in the map and corresponding table below.



The Regional boundaries in this map are approximate. The highlighted area between SPP RE and SERC denotes overlap as some load-serving entities participate in one Region while associated transmission owners/operators participate in another.

FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
TRE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Executive Summary

The NERC Board adopted proposed Reliability Standard PRC-025-1 – Generator Relay Loadability on August 15, 2013 and requested NERC staff and the standard drafting team to investigate whether a potential gap in reliability exists for unit auxiliary transformer (UAT) protective relays not applicable in the proposed Reliability Standard. The standard drafting team drafted a report on UAT relay loadability[1], which NERC subsequently submitted as part of a Supplemental Filing to FERC.[2] The report recommended a three tiered approach to assessing and mitigating any risk not revealed in the study: monitoring, and if needed, a guideline or enhancement to the Reliability Standard(s). NERC staff determined that the GADS and TADS applications were not organized in a manner that would lead to meaningful conclusions in monitoring. Therefore, the NERC Planning Committee (PC) tasked the NERC System Protection and Control Subcommittee (SPCS) to study the application of the load-responsive (in this case, phase overcurrent) unit auxiliary transformers (UAT) low-side protective relays to account for increased loading during depressed transmission voltages.

Depressed voltage will cause an increase in the loading on the UAT transformer. The relaying applied on the UAT transformer must not operate due to the increased load. A depressed transmission system voltage of 85% is based on studies and recommendations from the *Technical Analysis of the August 14, 2003, Blackout* report[3] and subsequent reliability requirements in various NERC Reliability Standards (i.e. PRC-023[4] and PRC-024[5]). The relay must not operate for at least three (3) seconds based on the low voltage ride through requirements derived in NERC Reliability Standard PRC-024. This provides the minimum requirements for the relay in question.

The SPCS has determined that a load-responsive relay applied on the low side of the UAT set with a minimum pickup value of 135% of the transformer nameplate is adequate to prevent the UAT protection relays from operating due to depressed voltage conditions. This includes a 20% conservative margin to account for higher percentages of motor loads, inaccuracies of current transformers, and inaccuracies of relays. The 135% pickup value also aligns with industry recommendations for the protection of transformers. Setting the protection for UAT per the guidelines in this paper supports the low voltage ride-through requirement of NERC Reliability Standard PRC-024.

In some situations it may be desirable to set this relay lower than 135% of the transformer nameplate. This could be to protect equipment or because the load on the transformer may be much less than the nameplate rating of the transformer. If this approach is used, then it is recommended the settings must be 135% of the maximum load on the UAT.

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[1] PRC-025-1 Standard Drafting Team report on UAT relay loadability, *see* Exhibit E

[2] As part of a Supplemental Filing to FERC, NERC submitted a report on UAT relay loadability to address concerns raised by minority commenters during the development of PRC-025-1 as to whether UAT relays on the low-voltage side should be included. The report concludes that there is no adverse reliability impact from Reliability Standard PRC-025-1 as proposed, and finds that "based on a comparison of the simulation models and the actual event data, the simulation results are conservative. The model results, coupled with the NERC Generating Availability Data System (GADS) analysis, are indicative that a reliability gap does not result from excluding relays on the low-voltage side of the UAT from PRC-025-1."

[3] Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn?

[4] Standard PRC-023-2 — Transmission Relay Loadability

[5] Standard PRC-024-2 — Generator Frequency and Voltage Protective Relay Settings

Introduction and Background

The NERC Board adopted proposed NERC Reliability Standard PRC-025-1 – Generator Relay Loadability on August 15, 2013, and requested NERC staff and the standard drafting team investigate whether a potential gap in reliability exists for unit auxiliary transformer (UAT) protective relays not addressed in the proposed Reliability Standard. The UAT, for the purposes of this report, supplies the overall auxiliary power necessary to keep the generating unit online. This study was in response to one unresolved minority issue raised by industry:

Problem Statement: "The application for UAT Facilities may not address all the load-responsive protective relays that potentially impact the operation of a generating unit or generating plant during the conditions anticipated by the proposed Reliability Standard."

NERC Reliability Standard PRC-025-1 – *Generator Relay Loadability* did not include certain UAT protective relays; specifically, the low-voltage side load-responsive protective relay(s). In a study prepared in response to the Board's request, the standard drafting team determined that there is no adverse reliability impact resulting from excluding these UAT protective relays in the proposed Reliability Standard. However, the standard drafting team noted that the Protection System margins typically applied on these UAT protective relays by industry are an important consideration in the loadability of the UAT. Therefore, the standard drafting team recommended a three tiered approach to assessing and mitigating any risk not revealed in the study: monitoring, and if needed, a guideline or enhancement to the Reliability Standard(s). The three tiers are:

1. Monitoring – Investigate the feasibility to revise or append the NERC GADS cause codes with greater granularity to facilitate the monitoring and tracking of the UAT, for both load-responsive high-side and low-side protective relay(s) that cause the loss of generation due to a depressed voltage as anticipated by the PRC-025-1 standard.
2. Guideline – Solicit industry input through the appropriate NERC committee for establishing a guideline for setting load-responsive UAT low-side overload protective relays to account for increased loading during depressed voltages. This guideline should be based on information revealed through monitoring that demonstrates a need for industry guidance and not a reliability standard. This option is next if monitoring is not feasible.
3. Standard – Revise the PRC-025-1 standard or create a new standard to address the loadability of the load-responsive UAT high-side and low-side protective relays if lessons learned through monitoring and/or developed guidance do not demonstrate the necessary reliability described in the standard.

NERC staff completed the first step in the tiered approach to start with monitoring generator outages that might involve UAT protective relays not included in the NERC Reliability Standard PRC-025-1 through the NERC Generator Availability Data System (GADS) and/or Transmission Availability Data System (TADS) applications. The expectation was that reported occurrences identified through monitoring would be assessed through NERC's risk analysis processes and matched appropriately with the next two recommended tiers of industry action, including the initiation of an industry guideline or revision to NERC Reliability Standard PRC-025.

NERC staff determined that the GADS and TADS applications were not organized in a manner that would lead to meaningful conclusions about the risk that UAT low-side protective relays might have to tripping during a depressed voltage of 0.85 per unit event. Because of this, the NERC Planning Committee directed the NERC System Protection and Control Subcommittee to analyze the risk concerning the loadability of unit auxiliary transformers' (UAT) protective relays.

Risk Assessment

UAT low side phase time overcurrent protection is backup protection that operates infrequently for normal fault conditions. In order to assess the risk of this protection operating under stressed system conditions accompanied by low system voltage, the SPCS reviewed available information including the experience of its members.

In the introduction of the "NERC Technical Reference on Power Plant and Transmission System Coordination"[6] NERC reported that 290 generating units totaling 52,745 MW tripped during the 2003 blackout. 194 of the 290 generation trips were attributed to 13 types of power plant protection elements, none of which were UAT low side phase time overcurrent protection. The other 96 generation trips were categorized as unknown. No instances of UAT low side phase time overcurrent relay trips are known to have occurred during the 2003 blackout.

NERC event analysis members participate in the SPCS. These members are directly involved in reviewing all power system disturbances that rise to the level of a NERC review. These disturbances often include severe system conditions including degraded system voltage and generation unit trips. The event analysis members participating in the SPCS are not aware of any past events where UATs have tripped automatically due to UAT low side phase time overcurrent protection operation. Further, the event analysis members are not aware of any NERC alerts or awareness notices related to tripping of UAT low side phase time overcurrent protection.

The SPCS is comprised of members from large investor owned utilities, generating companies, regional reliability organizations, independent system operations, and supported by NERC staff. Most SPCS members specialize in protection and are involved in analysis of disturbances in their companies, regions, and/or NERC. The collective experience of the SPCS is that UAT low side phase time overcurrent protection has not operated automatically during a stressed transmission system condition or event.

UATs are critical to a generating plant, as a UAT trip may result in a trip of the generator. Damage to a UAT could result in a protracted generator outage. Thus, there is a high motivation for a generator owner to size the UAT such that the chance of overload and potential damage to the UAT is minimized.

Industry guidance for developing settings related to phase time overcurrent protection on transformers already exists, and is widely known and used in the industry. For example, IEEE C37.91-2000 (IEEE Guide for Protective Relay Applications to Power Transformers) and IEEE C37.91-2008 (IEEE Guide for Protecting Power Transformers) states provides industry direction on how to apply the phase time overcurrent relay and settings. These guides state that "a setting of 125-150200% of the maximum kVA nameplate rating of a transformer is common" for transformer protection. The conclusions of this report are consistent with the IEEE guide.

Thus, a SPCS review of event experience and industry practice in setting UAT low side overcurrent protection relays indicate that existing practices for applying UAT low side phase overcurrent protection do not pose a power system reliability risk.

[6] NERC Technical Reference on Power Plant and Transmission System Coordination

Discussion

The plant station service bus has a combination of resistive (non-motor) and inductive (motor) loads. Under normal operating conditions, the aggregate current of these loads is not enough to cause operation of the overcurrent relay on the UAT. However, during an event that causes depressed transmission voltage (85% of nominal), increased current draw by plant loads will occur. The motor load portion of the plant will draw increased current as a consequence of a depressed voltage; resistive loads draw lower current in response to depressed voltage. A load analysis is needed to determine if the UAT relay will operate during a depressed transmission voltage event.

The following analysis will study the applications of overcurrent relays on UATs and the relay response during depressed system voltages. Other factors that are unique to the plant and the operation and protection of the transformer have also been considered within this paper, and where significant, they are discussed in detail. There are references provided for other factors that were considered that had negligible impact on the loadability of the low side relays. This paper assumes that the low voltage event has occurred while the generating plant is operating under normal conditions.

The UAT loads typically consist of up to 90% motor loads with the remainder as resistive load.[7] However, this paper will also examine the effect of various percentages of motor loads on the UAT (including 100%). The percentage of motor load on UATs varies based on the type of generating plant. The lower the percentage of motor loads within the plant, the lower the potential for any adverse impact on the loadability of the UAT protection resulting from low voltages.

The UAT can be connected in at least three (3) different configurations. This paper considers the UAT to be connected to the same transmission bus as the GSU (shown in Figure 1 below). This configuration provides a more severe impact to the loads on the UAT than the connection of the UAT to the generator bus.

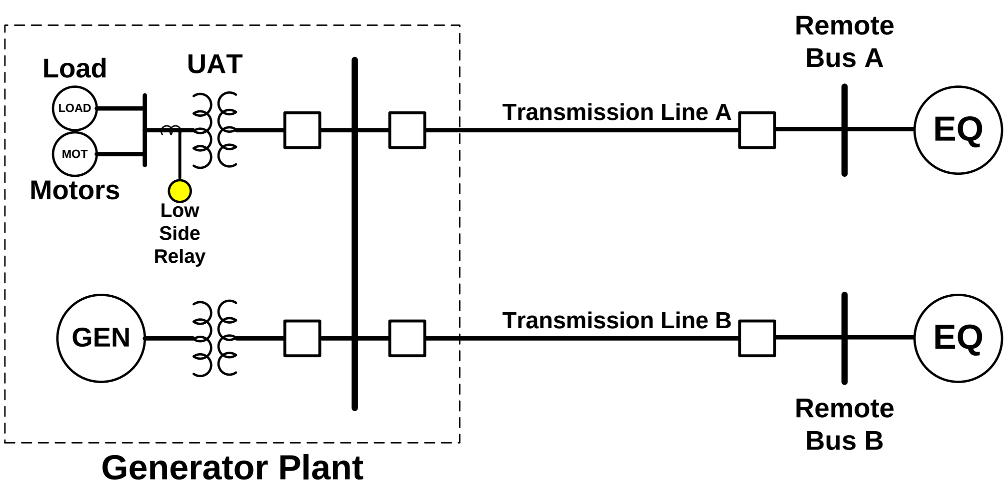

Figure 1: Station Service Transformer Connection

[7] Variable speed drives were considered; however, they operate similar to induction motors during depressed voltage conditions.

Impact of Motor Loads

The following section addresses the impact of motor loads on setting overcurrent relays on the UAT. Motors operating at rated speed and normal voltage can be considered constant kVA devices which try to maintain load under low voltage conditions. Therefore, a decrease in voltage results in an increase in current. Conversely, non-motor loads are generally constant impedance devices where the current goes down in proportion to voltage.
The graph seen in Figure 2 is commonly used to show the effect of voltage variation on full load amps of the motor.[8] This graph also supports that the motors are a constant KVA device for a decrease in voltage and the graph indicates that at an 85% undervoltage condition, the motors would require 117% more current.

Each motor installed on the UAT must have individual protection of the motor. This protection must take into account motor starting time, locked rotor current, service factors, coordination with upstream relaying and other considerations. Motor protection can be reviewed in IEEE Std. C37.96-2012.[9] These individual motor characteristics are taken into account when operating the generating unit and individually do not impact the loadability of the UAT. This paper considers the aggregate impact of all the motors installed and operating on the low side of the UAT when subjected to a depressed voltage of 85% nominal rather than the impact of any individual motor.

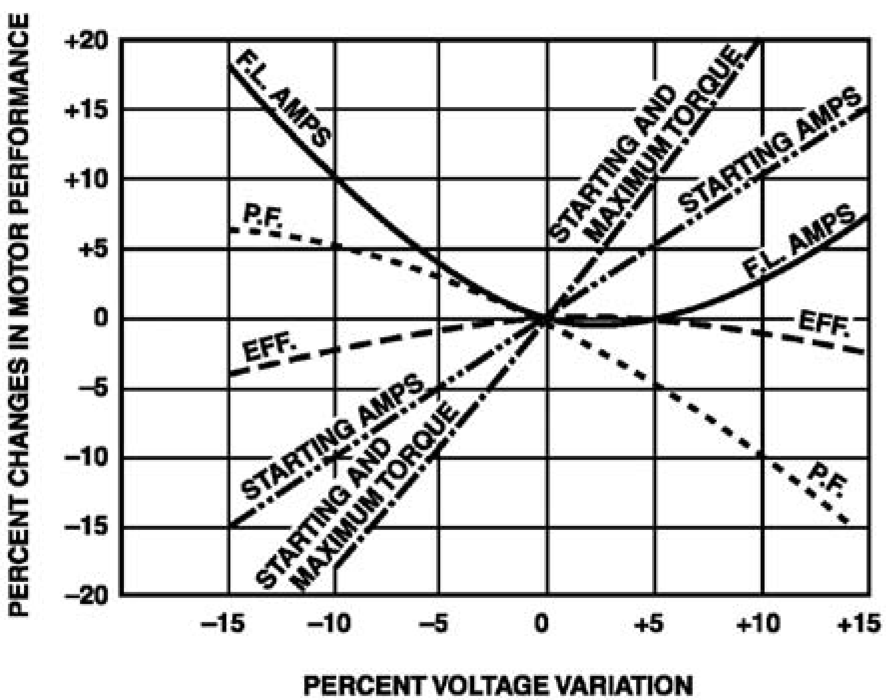

Figure 2: Effects of Voltage Variation on a Motor[10]

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[8] Joe Evans, Three-Phase Voltage Variation and Unbalance (First of Two Parts), *Pumps and Systems*, July 2014 (http://www.pumpsandsystems.com/motors/july-2014-three-phase-voltage-variation-unbalance-first-two-parts)
[9] IEEE Std. C37.96-2012
[10] Insert citation for figure 2 here

UAT Low-side Overcurrent Relay

The plant load on a UAT is typically 90% motor and 10% non-motor load. For other combinations, refer to Table 1 below.

The non-motor load is usually made up of constant impedance devices that have a characteristic of drawing less current at a lower voltage, so that a 15% drop in voltage would also result in a 15% drop in current. This characteristic reduces the effect of increased current drawn by motor loads. It is the aggregate of the current from all the loads that must be considered. This is shown in Table 1 below, in which the overload on a fully loaded transformer would be approximately 114% of UAT load. The figure below also includes a chart to describe the UAT load for various percentages of motor loads.

$$UAT\ load = (\%\ non - motor\ load) \times (voltage\ pu)\ + (\%\ motor\ loads) \times \frac{1}{(voltage\ pu)}$$

$$Sample\ Calculation{:}\ \ UAT\ load = (0.1) \times (0.85\ pu)\ + (0.90) \times \left(\frac{1}{0.85\ pu}\right) = 114\%$$

% Resistive Load	% Motor Load	UAT Load (at .85 per unit V)
20%	80%	111%
10%	90%	114%
None	100%	118%

Table 1: UAT Load Due to Depressed Voltage

<u>Operating Differences between UATs and Transmission Transformers</u>
Loading considerations are different for UATs and transmission transformers. Transmission system contingencies may require emergency loading of some transmission transformers to allow operators to reconfigure the grid and reduce the loading on other lines and transformers; therefore, these transformers must have the ability to be loaded above the nameplate of the transformer. The settings of relays on the transmission transformers must be set to allow emergency overload based on NERC Reliability Standard PRC-023. UATs are typically operated (even for emergencies) below the nameplate rating of the transformer. Generator Operators do NOT overload the UAT and the maximum load is known and not exceeded. The settings of relays on the UAT should be set to accommodate the effects of increased current during depressed voltage.

<u>Phase Overcurrent Settings:</u>
Based on the discussion above, the minimum overcurrent settings should accommodate the calculated UAT load under depressed voltage conditions plus a margin. The recommended minimum settings for overcurrent relays on the low side of the UAT is 135% of load. This setting includes a margin of approximately 15% to account for inaccuracies in the CTs and relays.

As an alternative to basing the settings on UAT load, the setting may be established at a minimum of 135% of UAT nameplate[11] rating.

[11] UATs with multiple secondary windings; the capacity refers to individual windings.

Impact of Generator Exciter

The generator exciter will attempt to hold the voltage at the generator terminals to the generator set-point. As the voltage of the transmission system goes down, the generator will increase its reactive power output in an attempt to maintain its terminal voltage. Voltage on the high-side of a UAT that is connected directly to the generator bus is supported by the actions of the generator exciter, which can respond rapidly (less than a second) to hold voltage up as the system voltage drops. Therefore, for this type of UAT connection, it is likely that the generator bus and the UAT voltage would be higher than the system voltage when the system is experiencing a depressed voltage event (.85 per unit). The higher the voltage, the less current the motors will draw, and therefore reduce the loadability concern.

The PRC-025-1 standard drafting team conducted a study to investigate the impact of load on a low voltage event on the system. The study developed a model for an actual event that presented a depressed voltage to the plant's auxiliary systems and validated that model using recorded data from that event. The study data was used to determine the expected relay response on the low-voltage side of the UAT under the stressed system conditions. The study results indicated that for that event the increase in load was significantly below 135% of the capacity of the UAT. This further supports the use of a minimum setting of 135% pickup for the low side relays.[12]

When the generator auxiliary transformer is connected to the transmission system (sometimes called a station auxiliary transformer (SAT)), the impact of the exciter is lower, and may be insignificant. Under this configuration, the voltage on the low side of the SAT will decrease as the transmission system voltage decreases. The analysis of this configuration and the impact of the loads on the low side of UAT is for a depressed voltage of 85% nominal; therefore, this configuration was chosen to determine a conservative setting that covers all connections.

Unit Auxiliary Transformer (UAT)

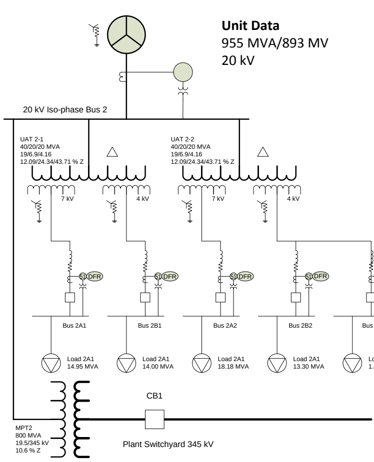

Figure 3: UAT Connection used in PRC-025 Standard Drafting Team Study

[12] *Id* at 1.

Conclusions

The collective experience of the NERC event analysis team participating in the SPCS, and the SPCS members, is that UAT low side phase time overcurrent protection has not operated during observed system events. Industry guidance on setting UAT low side phase time overcurrent protection exists and is similar to recommended settings derived in this paper. Thus, the SPCS concludes that the omission of UAT low side phase overcurrent protection from the existing NERC Reliability Standard PRC-025 standard does not pose a power system reliability risk.

As discussed in this report, the minimum overcurrent settings should accommodate the calculated UAT load under depressed voltage (.85 per unit) conditions plus a margin. A conservative recommended minimum setting for overcurrent relays on the low side of the UAT is 135% of load. This setting includes a margin of approximately 15% to account for inaccuracies in the CTs and relays.

As an alternative to basing the settings on UAT load, the setting may be established at a minimum of 135% of UAT nameplate[13] rating.

This will also complement the requirements of low voltage generator ride through as required in NERC Reliability Standard PRC-024.

Based upon the information contained within this report, the SPCS recommends no further action.

[13] UATs with multiple secondary windings; the capacity refers to individual windings.