Unit Auxiliary Transformer (UAT) Relay Loadability Report

Background and Objective

Reliability Standard, PRC-025-1 – Generator Relay Loadability (standard), developed under NERC Project 2010-13.2 – Phase 2 of Relay Loadability: Generation, was adopted by the NERC Board of Trustees (Board) on August 15, 2013. Subsequent to the standard's adoption, the Board asked if a potential reliability gap exists on load-responsive protective relays that are installed on the low-voltage side of the unit auxiliary transformer (UAT). Only the relays installed on the high-voltage side of the UAT are applicable to the standard. The request by the Board was in response to unresolved minority comments made by industry stakeholders arguing that relays on the low-voltage side of the UAT should be applicable to the standard.

In response to the Board's question, the standard drafting team conducted a basic study to investigate whether relays on the low-voltage side of the UAT experience loadability challenges during the stressed system conditions anticipated by the standard. Additional information regarding the basis for the standard and its criteria is found in the Guidelines and Technical Basis section of the standard or on the Project 2010-13.2[1] project page. The approach of this study was to develop a model for an actual event that presented a depressed voltage to the plant's auxiliary systems and validate that model using recorded data from that event. The study data was used to determine the expected relay loadability response on the low-voltage side of the UAT under the stressed system conditions and to determine if the low-voltage side relays are challenged by the loadability conditions addressed in the standard.

Approach

Using the Electrical Transient Analyzer Program® (ETAP) modeling software, a basic model of an actual generating plant's auxiliary system was built and is shown in the Appendix. A composite model of plant auxiliary equipment (connected load) such as motors, station service transformers, and variable frequency drives was used because actual event data facilitated fine tuning of the model to match the actual event. This resulted in composite loads being placed at four low-voltage side buses to represent the connected load.

Two different low-voltages were used to be representative of a typical generating plant's auxiliary systems. The load on both the 7 kV and 4 kV buses were a mixture of impedance type loads with induction motors. The 7kV bus load was 75-80% induction motors and the 4 kV bus load was 70-75% induction motor. The simplified bus loads, modeled as composite loads, were determined to have sufficient accuracy.

A digital fault recorder (DFR) captured an actual event at the plant being modeled where the balanced three phase voltage was depressed to approximately 85% of the nominal system voltage, representative of the stressed system conditions. The event lasted for approximately 0.4 seconds with the generating unit(s) remaining on-line during and after the event. The generator excitation system responded as expected by increasing field voltage to support the automatic voltage regulator generator voltage setpoint.

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[1] http://www.nerc.com/pa/Stand/Pages/Project-2010-13-2-Phase-2-Relay-Loadability-Generation.aspx

Additional analysis was performed using the Siemens PTI PSS®E powerflow and transient stability analysis software. This additional analysis was used to assess the time-varying nature of the station service load.

Model Validation

The ETAP plant model was verified using real-time data from the on-site DFR and revenue meter. Table 1 shows a comparison between the available field data and results from the ETAP load flow simulation for the normal operating condition. All results were within ±2%; except for generator gross MVAR (5.9%) which is negligible for this study. The simulation results when compared to the DFR event data confirm that the model is accurate for this steady state operating condition and suitable for the study.

Table 1. ETAP Study Model Validation

Generator/Switchyard Values	DFR	ETAP
Gen kV	19.76	19.78
Gen kA	24.37	24.3
Switchyard kV (Transmission)	348.53	348.5
MW (gross)	827	827
MVAR (gross)	102	96
Auxiliaries	**DFR**	**ETAP**
UAT 2-1 High-side kA	Not captured	0.92
2A1 kA	1.29	1.28
2B1 kA	2.08	2.1
UAT 2-2 High-side kA	Not captured	1.03
2A2 kA	1.3	1.3
2B2 kA, 12B2	2.48	2.45

ETAP Simulation Results

Two studies were conducted. Study 1 simulated the expected results on the low-voltage side of the UAT based on the actual event modeled. The low-voltage buses in Study 1 observed current changes ranging from 6.8% to 10%, versus -1.9% to 8.1% for the actual event as shown in Table 2. Thus the results from Study 1 are conservative and provide additional margin. The percentage difference in 4kV bus load currents in the study comparing the ETAP values to field results (10%) are attributed to using a single composite lump load. In order to obtain ETAP values closer to the field results, a detailed model for motors and impedance loads at each 4kV bus would be required. Since the information would be difficult to obtain, it is not feasible to perform the study in the time allowed. The ETAP study also does not consider the effects of field forcing the AVR would contribute during the time frame of the event.

While the study was performed for one plant auxiliary configuration using approximately a 70% to 80% inductive load ratio depending on the bus loading, the types of auxiliary load (e.g., pumps, fans, compressors, and other impedance loads) are common to all generating units and generating plants. The primary difference among various types of generating units and plants are the quantity and size of the loads. Thus, the percent current increases in response to depressed voltage are typical values that would be expected for other plant auxiliary configurations.

The results in Table 2 for this particular event (Study 1) indicate there are small changes in current on the low-voltage side of the UAT. The standard drafting team theorizes that the ratio of induction motor load to constant impedance load resulted in a low overall increase in current. During stressed system conditions, induction type loads tend to have an increase current while impedance type loads tend to have a decrease in current.

Since inductive loads are constant kilovolt ampere (kVA) loads which will increase current in response to a depressed voltage, a second study (Study 2) was conducted to test the sensitivity of the Study 1 results. To test the expected range of increased current, Study 2 simulated the low-voltage side of the UAT by holding the total kVA load constant while increasing the inductive load ratio to 90% at each bus and is only used in this study to illustrate a relative magnitude increase in current for the 85% stressed system voltage condition. Using a value higher than 90% is not practical as all generating unit and plant configurations have some level of constant impedance loading. Table 3 lists the percent increase in current resulting from the 90% inductive load ratio. The low-voltage buses in Study 2 observed current changes ranging from 11.0 to 14.4%.

Table 2. ETAP Study 1 at 85% Transmission Voltage to Event Conditions

Generator & Switchyard	**Pre (Actual)**	**Pre (ETAP)**	**During (Actual)**	**During (ETAP)**		
Gen kV	19.7	19.7	17.29	17.24		
Gen kA	20.2	20.17	24.14	23.89		
Gen MW (gross)	688	688	688	688		
Gen MVAR (gross)	2	15	159	188		
Auxiliaries	**Pre (Actual)**	**Pre (ETAP)**	**During (Actual)**	**During (ETAP) Study 1**	**% Change (Actual)**	**% Change (ETAP) Study 1**
UAT 2-1 HS kA	-	0.88	-	0.94	-	6.8
2A1 kA (7 kV)	1.23	1.23	1.3	1.34	5.7	8.9
2B1 kA (4 kV)	1.97	1.95	1.92	2.09	-2.4	7.2
UAT 2-2 HS kA	-	1.0	-	1.09	-	9.0
2A2 kA (7 kV)	1.49	1.5	1.61	1.65	8.1	10.0
Composite 2B2 , 12B2 (4 kV)	2.14	2.12	2.1	2.27	-1.9	7.1

Table 3. ETAP Study 2 at 85% Transmission Voltage with Higher Inductive UAT Loading

Generator & Switchyard	**Pre (Actual)**	**Pre (ETAP)**	**During (Actual)**	**During (ETAP)**		
Gen kV	19.7	19.7	17.29	17.24		
Gen kA	20.2	20.17	24.14	23.89		
Gen MW (gross)	688	688	688	688		
Gen MVAR (gross)	2	15	159	188		
Auxiliaries	**Pre (Actual)**	**Pre (ETAP)**	**During (Actual)**	**During (ETAP) Study 2**	**% Change (Actual)**	**% Change (ETAP) Study 2**
UAT 2-1 HS kA	-	0.88	-	0.99	-	12.5
2A1 kA (7 kV)	1.23	1.23	1.3	1.38	5.7	12.2
2B1 kA (4 kV)	1.97	1.95	1.92	2.23	-2.4	14.4
UAT 2-2 HS kA	-	1.0	-	1.11	-	11.0
2A2 kA (7 kV)	1.49	1.5	1.61	1.68	8.1	12.0
Composite 2B2 , 12B2 (4 kV)	2.14	2.12	2.1	2.39	-1.9	12.7

PSS®E Model and Simulation Results

The station service model used in the ETAP analysis was added to a 955 MVA generating unit in the Eastern Interconnection model. This generating unit is similar in size to the unit modeled in the ETAP analysis. The unit in the PSS®E model was selected because it was one the units used in simulations supporting the NERC System Protection and Control Subcommittee (SPCS) *Power Plant and Transmission System Protection Coordination* report, which was one of the reference documents used in development of PRC-025-1. This generating unit also is one for which recorded data is available from the August 14, 2003 event. This unit is located in western Michigan and responded to a depressed transmission system voltage until the local transmission voltage recovered after the east-west system separation occurred.

The model was modified to account for a difference in generator terminal voltage by adjusting the UAT turns ratio. The PSS®E complex load model (CLOD) was used to represent the station service load using the same percentages of large motor load and constant impedance load as the ETAP Study 1 (75-80% for the 7 kV buses and 70-75% for the 4 kV buses).

The simulation is based on the “synchronous generator simulation criteria” described in the Guidelines and Technical Basis of PRC-025-1. In this method a reactor is switched on the high-voltage side of the generator step-up (GSU) transformer to lower the transmission system voltage to 0.85 per unit prior to response of the generator excitation system. In these simulations the maximum load current on the UAT occurs when the station service load responds to the initial voltage drop. The load current is reduced as the generator increases its reactive output to support its terminal voltage. A maximum excitation limiter (MEL) was modeled in the simulation. As the MEL reduces the reactive output of the generator, the generator and station service voltage decrease. As a result, the load current increases and settles at a level higher than the pre-event current, but lower than the maximum observed current. For the conditions modeled in this simulation, the MEL reduced the reactive output approximately 15 seconds after the initial event. MEL parameters vary among generating units. However, variations in these parameters are not expected to affect the maximum current or the final current. This is because the MEL is set to allow full field-forcing for a period of time within the generator short-time capability, and to reduce the reactive output to a final value with the generator steady-state capability.

The results for the simulation are presented in Table 4. The pre-event and maximum currents are similar to the results obtained in the ETAP analysis. Differences in current on the high-voltage side of the UAT are a result of the different generator terminal voltages. The table lists the pre-event and maximum load current on each bus, and also lists the current at four discrete times (1 s, 5 s, 10 s, and 20 s) after the initial event. The maximum current is observed approximately 0.4 s after the initial event. The current is listed in kA in the top half of the table and as a percentage difference from the pre-event current in the bottom half. The simulation demonstrates that the maximum load current is in the range from 4.8 to 10.0% higher than the pre-event load current. The load current begins to drop from the maximum value within 1 s of the initial event. The final current after MEL operation is in the range from 2.2 to 5.4% higher than the pre-event current.

Table 4. PSS®E Study 1 at 85% Transmission Voltage with Original UAT Loading

Auxiliaries	**Pre-Event**	**Max**	**1 s**	**5 s**	**10 s**	**20 s**
UAT 2-1 HS kA	0.805	0.874	0.846	0.818	0.817	0.831
2A1 kA (7 kV)	1.256	1.349	1.326	1.279	1.276	1.305
2B1 kA (4 kV)	2.016	2.120	2.093	2.038	2.034	2.066
UAT 2-2 HS kA	0.918	1.006	0.972	0.936	0.932	0.957
2A2 kA (7 kV)	1.523	1.675	1.638	1.562	1.555	1.606
Composite 2B2 , 12B2 (4 kV)	2.179	2.283	2.256	2.199	2.195	2.228
Auxiliaries		**% Max**	**% 1 s**	**% 5 s**	**% 10 s**	**% 20 s**
UAT 2-1 HS kA		8.3	4.8	1.6	1.5	3.1
2A1 kA (7 kV)		7.6	5.7	1.8	1.6	3.9
2B1 kA (4 kV)		5.3	3.8	1.1	0.9	2.5
UAT 2-2 HS kA		9.6	5.9	2.0	1.5	4.2
2A2 kA (7 kV)		10.0	7.6	2.6	2.1	5.4
Composite 2B2 , 12B2 (4 kV)		4.8	3.5	0.9	0.7	2.2

Similar to the ETAP analysis, a second simulation was run using 90% large motor load on each bus. As expected, these simulations resulted in high loader current than Study 1. Results for the second simulation are presented in Table 5. In the second study the maximum current on each load bus is in the range from 9.6 to 13.4% above the pre-event current and the final current is in the range from 5.1 to 7.4% above the pre-event current.

Table 5. ETAP Study 2 at 85% Transmission Voltage with Higher Inductive UAT Loading

Auxiliaries	Pre-Event	Max	1 s	5 s	10 s	20 s
UAT 2-1 HS kA	0.798	0.909	0.871	0.823	0.819	0.849
2A1 kA (7 kV)	1.240	1.396	1.358	1.282	1.274	1.328
2B1 kA (4 kV)	2.054	2.266	2.210	2.106	2.096	2.167
UAT 2-2 HS kA	0.913	1.042	0.999	0.942	0.935	0.975
2A2 kA (7 kV)	1.518	1.722	1.672	1.571	1.561	1.631
Composite 2B2 , 12B2 (4 kV)	2.230	2.445	2.392	2.282	2.275	2.344
Auxiliaries		**% Max**	**% 1 s**	**% 5 s**	**% 10 s**	**% 20 s**
UAT 2-1 HS kA		13.9	9.1	3.1	3.6	6.4
2A1 kA (7 kV)		12.6	9.5	3.4	2.7	7.1
2B1 kA (4 kV)		10.3	7.6	2.5	2.0	5.5
UAT 2-2 HS kA		14.1	9.4	3.2	2.4	6.8
2A2 kA (7 kV)		13.4	10.1	3.5	2.8	7.4
Composite 2B2 , 12B2 (4 kV)		9.6	7.3	2.3	2.0	5.1

During the event modeled in ETAP, the actual plant output was lower than reported full load output; therefore, increases in UAT loading would occur at reported full load. A sensitivity analysis was performed in PSS®E to model higher station service load. In this assessment the load was increased proportionally until the load on one of the UAT windings was equal to the winding rating – an increase of approximately 34% on UAT2-1 and 10% on UAT2-2. In these cases the load current is proportionately higher; however, the observed increases in current are not significantly different. The base model with 70-80 % motor load exhibited load current increases in the range from 5.1 to 10.0% (compared to 4.8 to 10.0%) and the higher inductive load model with 90% motor load exhibited load current increases in the range from 10.1 to 13.6% (compared to 9.6 to 13.4%).Thus, if the actual plant had been at full load, the expected incremental increases in UAT loading during such an event would be of the same magnitude as for the actual event modeled.

Analysis of NERC GADS Data

The NERC Generating Availability Data System (GADS) contains outage data for generating stations across North America. Outages were analyzed for UATs and other station service transformers with primary winding voltage of 4.16 kV and 480 V. This analysis included 217 UAT outages, 28 outages of 4.16 kV transformers, and 49 outages of 480 V transformers. The cause codes do not provide adequate granularity to determine why the transformers tripped;

however, approximately 85% of the outage entries included descriptive comments. The majority of UAT outages with descriptions were scheduled, approximately one-half of the 4.16 kV transformer outages were scheduled and one-half forced, and the majority of 480 V transformer outages were forced.

The descriptions for the forced outages include issues such as transformer failure, overheated transformer or associated equipment, auxiliary power transfer problems, breaker failure, failure of equipment supplied by the transformer (e.g., induced draft fan), problems with transformer outlet leads, current transformer ground, and differential relay operation. Four event descriptions identify improper or incorrect relay settings – one event on a 480 V transformer was for a ground fault for which PRC-025-1 would not be applicable; three events on a 4.16 kV transformer appear to be related to the same relay setting with no other information. While not definitive, there is nothing in the GADS data to suggest that any generating unit outages occurred due to UAT or other station service transformer relay loadability issues during a depressed voltage condition.

Conclusion

Many of the plant auxiliaries (e.g., 4 kV and 7 kV) have a ±10% voltage operating range with most operating above the nominal; such an operating range allows for increased current during lower voltages. Industry practice is to set plant auxiliary relays on the low-voltage side of the UAT to account for a depressed voltage according to equipment ratings. These relays are generally set with a 10 to 15% margin above the expected lower voltage range of the equipment rating. Relays on the low-voltage side of the UAT are also set to account for the starting of large plant auxiliary motors which depresses voltage. The margin in the relay settings accounts for measuring inaccuracy in current transformers and relays, and other uncertainties associated with the equipment and operating conditions.

The maximum current deviations observed in these simulations would be under or marginally above the current threshold (pickup setting) at which the relays on the low-voltage side of the UAT would begin to operate. These relays operate with an inverse-time characteristic such that an overcurrent condition marginally above the pick-up setting must persist for several seconds before the relay will assert a trip output. In these simulations the maximum motor load duration is short in comparison to the operating time of the relay when current is marginally above pickup, and the load current settles to a value below the pickup setting allowing the relay to reset.

Based on a comparison of the simulation models and the actual event data, the simulation results are conservative. The model results, coupled with the 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. However, industry practice may vary and the conservatism in the model does not fully offset the potential inaccuracies and uncertainties in the relay setting. Thus, while indicative that a reliability gap does not result, this analysis is not definitive.

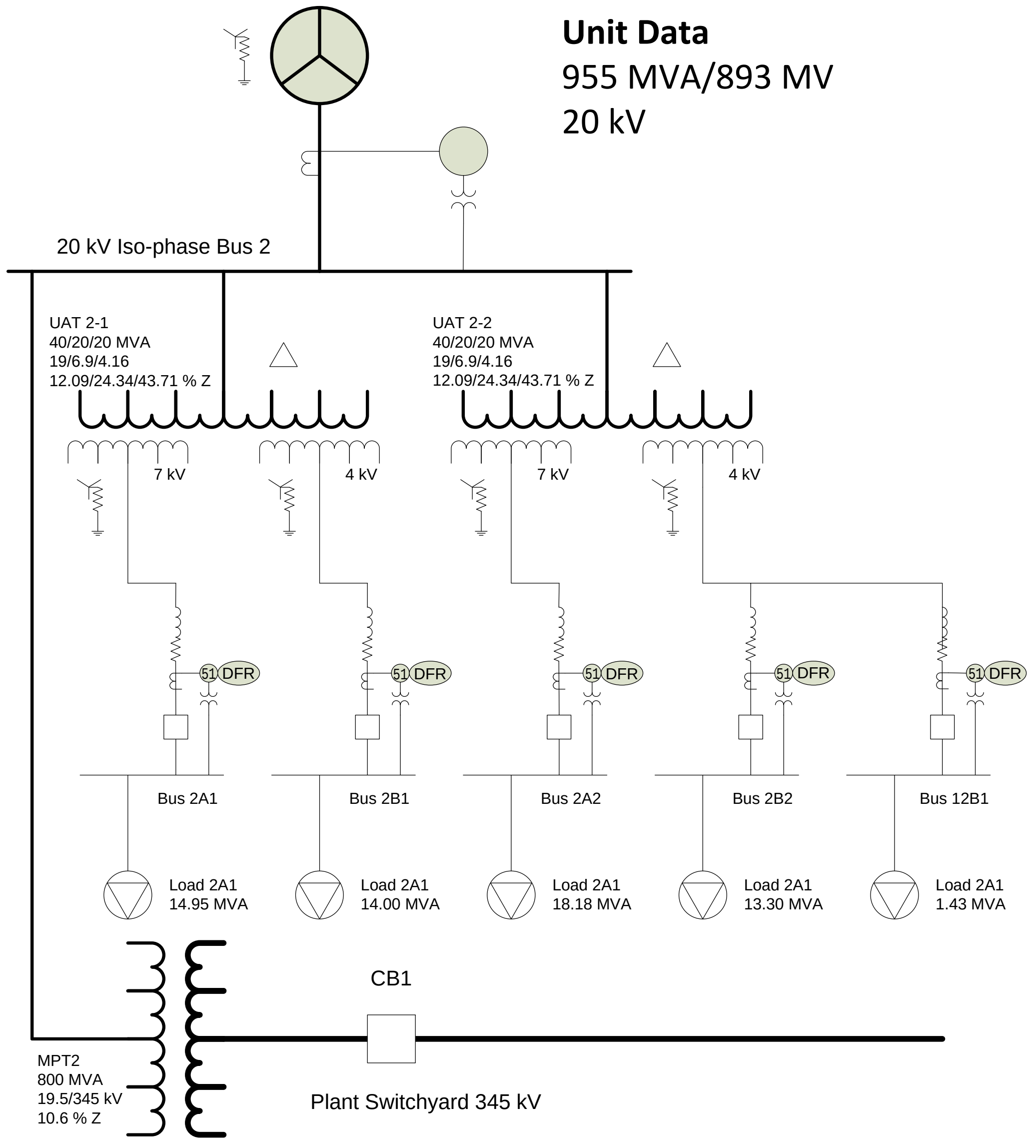
Recommendation

The study using both DFR event data and simulation, and the GADS data analysis, revealed there is not a material gap in reliability; therefore, the recommendation is not to include the low-voltage side relays in the PRC-025-1 standard.

Furthermore, the standard drafting team recognizes that the goal of PRC-025-1 is to prevent the unnecessary tripping of generators during a system disturbance for conditions that do not pose a risk of damage to the associated equipment. Since the study revealed that increased loading of the low-side UAT protective relays may reach margins generally employed by industry, other preemptive steps may be desirable. If so, the standard drafting team recommends to NERC a tiered approach to further address this risk.

1. <u>Monitoring</u> – 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. <u>Guideline</u> – 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. <u>Standard</u> – 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.

Appendix


Unit Data
955 MVA/893 MV
20 kV
20 kV Iso-phase Bus 2
UAT 2-1
40/20/20 MVA
19/6.9/4.16
12.09/24.34/43.71 % Z
UAT 2-2
40/20/20 MVA
19/6.9/4.16
12.09/24.34/43.71 % Z
7 kV
4 kV
7 kV
4 kV
51
DFR
51
DFR
51
DFR
51
DFR
51
DFR
Bus 2A1
Bus 2B1
Bus 2A2
Bus 2B2
Bus 12B1
Load 2A1
14.95 MVA
Load 2A1
14.00 MVA
Load 2A1
18.18 MVA
Load 2A1
13.30 MVA
Load 2A1
1.43 MVA
CB1
MPT2
800 MVA
19.5/345 kV
10.6 % Z
Plant Switchyard 345 kV