NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

White Paper: Implementation of NERC Standard MOD-025-2

NERC Power Plant Modeling and Verification Task Force (PPMVTF)
July 2019

Executive Summary

The purpose of MOD-025-2 states that verification and data reporting activities of GOs regarding generator (and synchronous condenser) active and reactive power capability testing are performed "to ensure that accurate information on generator gross and net Real and Reactive Power capability and synchronous condenser Reactive Power capability is available for planning models used to assess Bulk Electric System (BES) reliability." However, in most cases, the test data should not be directly used for transmission planning modeling purposes.[1]

Reaching the reactive power capability limits, particularly the excitation system over-excitation (OEL) and under-excitation (UEL) limiters, during operation is a fairly rare event during quasi-steady state and dynamic events.[2] Therefore, historical operational data might help the verification of the active power capability of the unit, but might not contain a single event (ever) where the equipment reached its limits regarding reactive power capability. While MOD-025-2 includes the option for using historical operational data, this operational data is typically insufficient for verifying reactive power capability (i.e., likely only capturing one of the four data points required to verify per MOD-025-2).[3] Therefore, this white paper is focused on the staged verification testing aspects of MOD-025-2 for synchronous machines.[4]

The major issue with staged verification testing is that the generator reactive power capability may not be fully demonstrated; rather, other constraints such as generator terminal voltage, plant auxiliary bus voltage,[5] or system operating voltage limits prevent reaching the generator reactive power capability. Alternatively, even if the machine reaches its limits, the reactive power output during testing will not be as much as at nominal voltage unless calculations are performed to adjust the capability to nominal voltage. While it is suggested in Attachment 1 of MOD-025 that engineering analysis be used to adjust the data to account for the effects for voltage, it is not required. Therefore, if the staged verification test values are reported and used in planning studies (as stated as the intent of MOD-025-2), the generating unit reactive

[1] Data from MOD-025 staged verification testing should only be used in the rare instances where actual generator capability limits (including limiters) are reached at rated voltage during the test procedures.
[2] The overexcitation limiters have inverse-time or definite-time limits associated with limiter settings. For example, the OEL in most systems will allow the unit to exceed the unit capability curve within the rotor winding short-time thermal requirements outlined in IEEE C50.13. In particular, the short time duration limits are not related to quasi-steady state conditions and are not the purpose of staged verification testing in MOD-025.
[3] For this reason, most generating facilities will use staged testing for the purposes of meeting the requirements of MOD-025-2.
[4] Note that inverter-based resources will face similar issues related to reaching voltage limits that may prohibit staged verification testing from reaching actual plant reactive capability.
[5] Typically the auxiliary buses are not represented in the transmission planning models. Further, bus voltage limits are modeled or monitored separately from generator capability. Unexpected tripping of a generating unit caused by auxiliary limits is generally not considered acceptable, and should be explicitly reported and addressed as part of any MOD-025 staged verification testing. In the current version of MOD-025-2, this is not a requirement and does not need to be reported.

capability will be underestimated (perhaps severely). For this reason, the activities that GOs are taking to meet compliance obligations for MOD-025-2 are not serving the intended purpose of the standard.

It is therefore recommended that a Standard Authorization Request (SAR) be developed, and a Standard Drafting Team (SDT) be created, to address the issues described in this white paper related to MOD-025-2. The PPMVTF is of the opinion that the existing MOD-025-2 standard should be either (i) altered or (ii) withdrawn and replaced with a new standard entirely.[6] The changes needed to MOD-025-2 are to prevent inaccurate data from being used to represent generating resources (and synchronous condensers) in the planning models. The PPMVTF believes that there is value in performing the staged verification tests since they can uncover unexpected limiting factors; however, the PPMVTF agrees that the data acquired during MOD-025-2 testing may not be directly usable to represent the actual capability of the machine in power system models, and that the tests do not generally accomplish the stated purpose of the standard.

Background

The curves on a generator capability diagram are depictions of the thermal limits of the rotor, stator, and stator end iron at generator rated voltage (and various pressures (e.g., hydrogen, if hydrogen-cooled) and temperatures) at given generator active and reactive loading conditions. To prevent damage due to the automatic voltage regulator response, the exciter is equipped with automatic limiters (i.e., underexcitation limiter (UEL) and overexcitation limiter (OEL)). The capabilities of the generator as set by the OEL and UEL are typically supplied as part of MOD-032-1 submittals and represent the active and reactive power capabilities at rated generator terminal voltage.[7] This information is also made available from the activities performed in PRC-019. To manipulate reactive power output of a generator for MOD-025-2 data collection, either the local transmission system voltage or the generator terminal voltage must be varied. As it may often be infeasible to sufficiently alter local

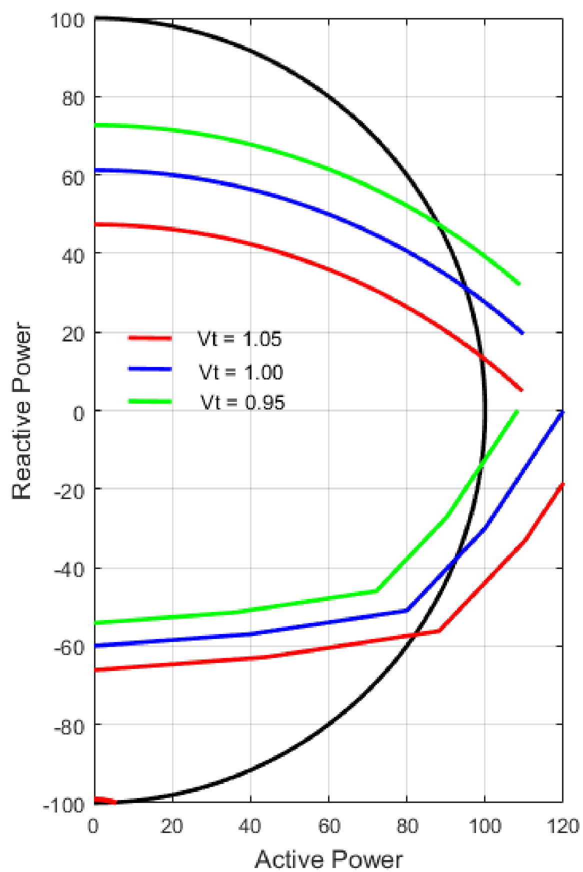

Figure 1: Generator Capability Sensitivity to Terminal Voltage

[6] A minority opinion is that MOD-025-2 should be withdrawn and not replaced with another standard.
[7] Sometimes these curves can be provided by the manufacturer at different terminal voltage values.

transmission system voltage for such a test,[8] the test is generally conducted by varying the generator terminal voltage. Based on the short circuit strength of the system at the generator interconnection, this could result in a significant increase or decrease in generator terminal voltage during testing. As illustrated in Figure 1, the generator *composite* capability (including the OEL and UEL) may be dependent on generator terminal voltage.

If MOD-025-2 data is collected by raising and lowering generator terminal voltage (from a starting point near the rated value) to reach the reactive capability limit of a generator (e.g., as determined by an OEL and UEL),[9] the reactive power limit will change with terminal voltage if the OEL or UEL are the limiting factors during the test.[10] The net reactive power production and absorption when the machine is operating at the excitation limiter setting during the test can be significantly less than the generator would provide at the same limit but under rated voltage conditions. As shown in Figure 2, the targeted reactive power capability operating test points are shifted with the changing voltage, and less reactive power is achieved.

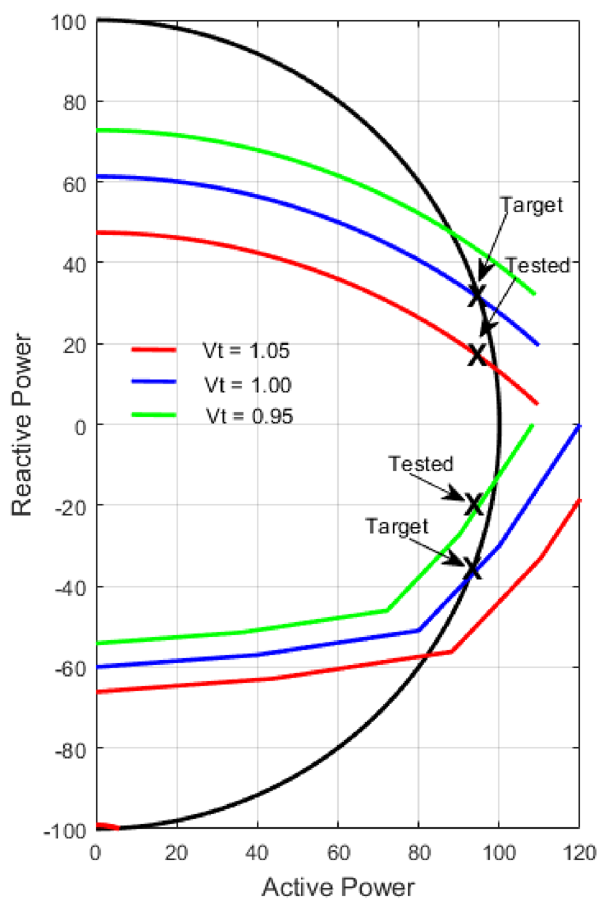

Figure 2: Reactive Capability – Test versus Target Limits

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[8] Note that the transmission system voltage limits are usually defined by a voltage schedule provided by the Transmission Operator, and must be adhered to by the GO per their established policies and NERC Reliability Standards.
[9] As a point of interest, the OEL by most manufacturers is set to 102-105% of field current full load and the capability curve is reached before limiter action.
[10] Note that if other limits are reached (e.g., voltage limits), then the test is stopped regardless of whether the capability curve or the OEL/UEL are reached.

If the machine is operating up against the limiters but has not reached the estimated reactive power output displayed on the capability curves, then an engineering analysis can be done to calculate the power output that would result if the terminal voltage was at the rated value. Figure 3 shows an example of this.[11]

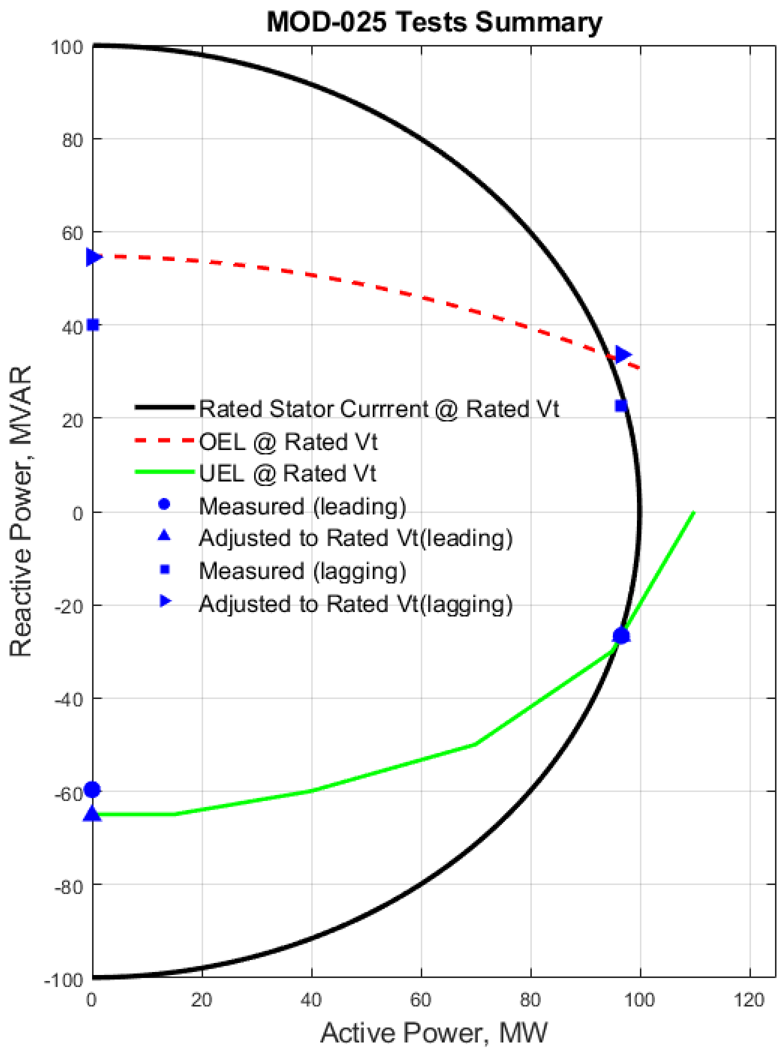

Figure 3: Calculation of Limits at Nominal Voltage

In this case, the voltages were adjusted until the OEL and UEL were reached. The tested values of voltage, active power, reactive power, and field current were used to recalculate the generator output if voltages were adjusted to the rated value. The capability curves are then verified by test and accurate for studies. Since testing is most often conducted by changing the terminal voltage, it is possible to reach a reactive power output where restrictions will apply before the actual generator capability limit is reached. In this case, the demonstrated test values will underestimate the reactive capability of the generator. A detailed

[11] This does not consider if any auxiliary equipment limits or other voltage limits prohibit the test from reaching the limiter settings or machine capability, which is a limitation of the current MOD-025-2 standard.

discussion can be found in the NERC *Reliability Guideline: Power Plant Model Verification and Testing for Synchronous Machines*.[12]

The reactive capability of a generator is used to maintain transmission system voltages within the acceptable operating range, by supplying reactive power to the system when voltage is too low, and absorbing reactive power when voltage is too high. Currently, commercial load flow software does not account for the relationship between voltage and generator reactive power limits. The software considers a fixed value for reactive power capability that is not dependent on generator terminal voltage. The most common practice is to use capability values for rated terminal voltage (from the composite D curve) as shown by the blue curve in Figure 2. Using the tested values in MOD-025-2 at off-nominal voltage may underestimate the capability of the machine (severely, in some cases). This is illustrated by the red curve in Figure 2 for the over-excited region. This leads to pessimistic[13] data used in transmission planning studies.[14] TPs and PCs should ensure that the appropriate capability data is used in planning models; this data could come from PRC-019 information (if it were required) or could come from MOD-032 data submittals, not from MOD-025 staged verification testing capability data that may or may not represent actual realistic limits used in planning models.

Pre-test adjustments may be required to collect a more accurate raw data that better reflect the steady-state generator capabilities. An example of pre-test adjustments is to utilize other generating units within the same plant or in close electric proximity to withdraw reactive power from the transmission system during reactive power injection testing of the generating unit under test, and vice versa. Another example is to coordinate the time of test with the Transmission Operator to allow for some transmission system adjustments (possibly an abnormal system voltage level or reactive devices such as capacitor banks in the local area switched on to absorb some of the reactive power produced by the unit under test). While these types of system adjustments may facilitate MOD-025-2 testing of a unit, they could also represent a reliability concern (i.e., voltage excursion) if the generating unit under test were to trip.[15] If pre-test adjustments are not achievable, engineering analyses can be performed to modify the collected raw test data to reflect more accurate generation capabilities or use in planning models. An example of engineering analyses is to scale the rated rotor current curve or OEL curve to reflect rated voltage. Although engineering calculations can be used in some cases to reflect the test data to rated voltage capability limits, this is not a mandatory task (nor always usable) per MOD-025-2.

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[12] Refer to Figure 3.10 of the NERC *Reliability Guideline: Power Plant Model Verification and Testing for Synchronous Machines* for another example of impacts of terminal voltage on generator reactive capability. Refer to Appendix D for a detailed description on MOD-025-2 testing and calculation examples: https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_-_PPMV_for_Synchronous_Machines_-_2018-06-29.pdf

[13] Pessimistic or overly restrictive generator reactive capability modeled in planning cases could lead to BPS reactive power deficiencies, which could lead to unnecessary system upgrades.

[14] Both overly optimistic and overly pessimistic models and modeling assumptions have their challenges regarding reliability studies. Optimistic assumptions and models may miss potential reliability issues or performance violations; pessimistic assumptions and models can lead to additional investments that may not be necessary (leading to additional costs to ratepayers or to GOs). Neither situation is ideal and efforts should be made to develop reasonably accurate models for each element of the BPS.

[15] Therefore, based on experience performing MOD-025-2 testing, generally the Transmission Operator will not be amenable to significant modifications to scheduled voltages for the purposes of MOD-025-2 testing (to ensure reliable operation).

Furthermore, it is very common during staged verification testing for external constraints such as generator terminal voltage or auxiliary plant bus voltage limits to limit the test prior to reaching the excitation limiters or machine capability. This makes any correction to nominal voltage not possible for determining the true generator reactive capability limits. This is a significant issue with the concept of "engineering analysis" and should be addressed in a future revision to the standard.

Therefore, the only generator capability information that should be submitted for planning models to assess BPS reliability is that information which is defined on the generator rated terminal voltage and as reported in accordance with MOD-032-1. MOD-032-1 does not require validation or measurements to verify the accuracy of the capability curves; however, there may be simpler and more effective means of performing some form of data submittal verification (e.g., comparison with PRC-019 reports) than performing MOD-025 tests that do not provide the necessary data to perform such verification.

Note 1 and Note 2 of Attachment 1 of MOD-025-2 acknowledge that the data collected in accordance with the standard will often not conform to the rated voltage generator capability diagram, and will thereby not result in the verification of the actual generator reactive power capability. Since the stated purpose of MOD-025-2 is to ensure the accuracy of generator capability information for planning models, there is a conflict between MOD-025-2 and MOD-032-1 if it is interpreted that data collected in accordance with MOD-025-2 should be used to set limits in the planning models. This should not be the case, and has led to industry confusion, and potentially inaccurate modeling. MOD-032-1 is the standard for reporting this data and should use the actual expected composite capability curve limits (generator capability curve and associated OEL and UEL) in the models.

Some of the benefits of performing the testing in MOD-025-2 include, but are not limited to, those listed below. These are provided here as reference to the operational benefits, although it is noted that these do not support the development of planning models (the stated purpose of MOD-025-2).

1. Identification of previously unknown trips or limiting conditions, such as: motor control center undervoltage relay trips, underrated GSUs, overlooked auxiliary motor voltages, operation of cooling systems below rating (e.g., hydrogen pressure set to levels below rated capability curves), etc. Once understood, plants can take action to eliminate or mitigate potential issues from these by correction of settings, provisions of alarms, training, operational procedures, etc.
    a. However, there are no requirements in MOD-025-2 for correcting those limiting factors nor notification of the unexpected limits (if they cannot be corrected) to the TP/PC or TOP/RC. Correcting any unexpected trip issues (specifically for Protection System tripping) would be performed under PRC-019; however, there are no requirements in PRC-019 to report this information to the TP, PC, TOP, or RC.
2. While NERC PRC-019-1 (and to an extent PRC-024-2) requirements have improved coordination of relays to prevent unexpected trips, there is no replacement for actual testing of units to reasonable limits to ensure that no possible default setting, incorrectly operating relays, etc. will occur when needed. Note such trips have been found, along with identifying incorrect relay, meter, and readings.

3. Allowing plants to better understand their operations (e.g., reactive power output). During testing site personnel who often do not deal with or significantly understand reactive power output are permitted to see how the unit can operate under such conditions so that they are better prepared in case of grid critical conditions.

MOD-025-2 Statistical Results and Analysis

The following statistical data was compiled for analysis by a large utility at the completion of the MOD-025-2 July 1st, 2019 deadline. As described below, the information collected shows that MOD-025-2 does not meet its intended objective for demonstration of the generators' reactive capability. Where possible, adjacent unit(s) were utilized to aid the unit under test in obtaining its reactive capability. The generation mix consisted of nuclear, coal, natural gas, hydro, solar, wind, and biomass units. Transmission voltages were allowed to vary within a maximum range[16] during testing per regional transmission policies.

Figure 4 shows that 897 tests were performed on 261 generators. Less than 10% of the tests demonstrated the generators' reactive "D curve" capability,[17] due to various limits encountered during the tests. Not one generator successfully achieved its "D curve" reactive capability and UEL limiter for all tests. Figures 5 and 6 categorize the results by test. Although slightly better results were achieved in reactive power production, the results fall short of the desired objective. Figures 7 and 8 summarize the limiting factors for each test category. In all cases, the generator terminal voltage limits were the predominant limiting factor, followed by the AVR UEL, station service auxiliary bus voltage limits,[18] and transmission system voltage limits.

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[16] Those ranges were typically +/- 1 kV for 115kV, +/- 2kV for 230kV and +/- 4kV for 500kV system voltages.

[17] Tests that encountered field current limits could qualify as achieving the actual capability so long as engineering calculations are performed as described in Figure 3.

[18] For entities that are not vertically integrated, identification of optimized station service tap settings and other operational constraints are more common. However, these are not related to verification of generator capability (the purpose of MOD-025-2).

MOD-025-2 Results Summary

83	total number of tests achieving reactive capability
814	total number of tests NOT achieving reactive capability
897	total number of tests
261	total number of generators tested
9.3%	Generators achieving reactive capability
90.7%	Generators NOT achieving reactive capability
100.0%	

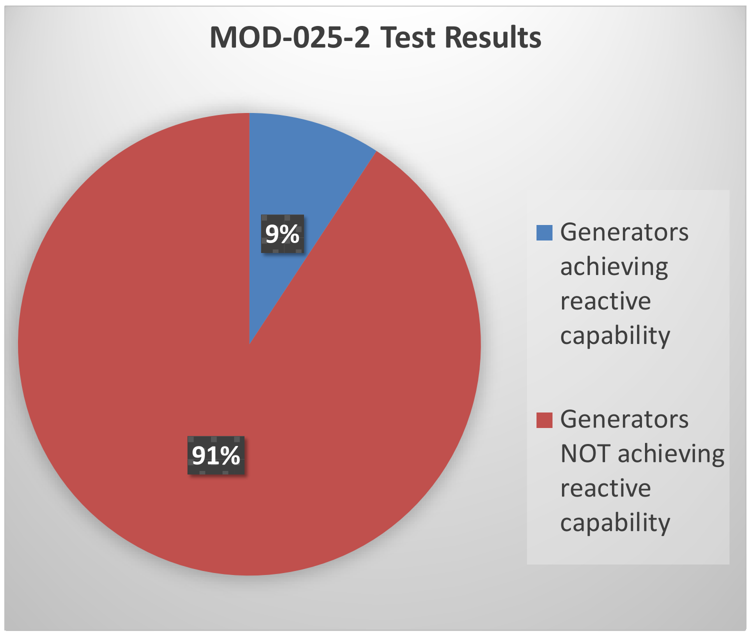
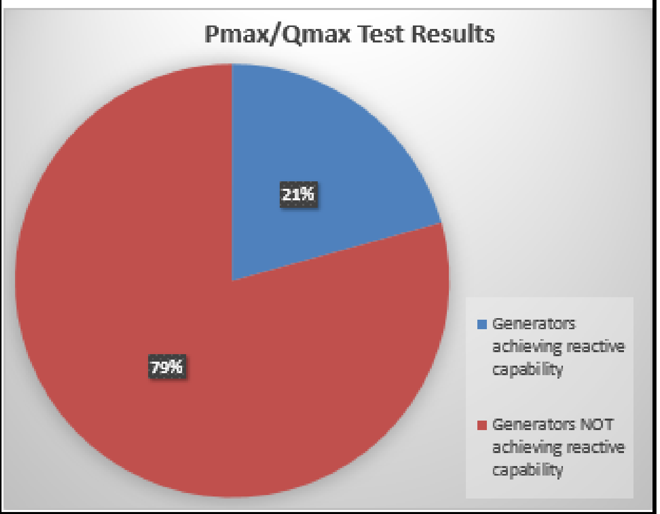


Figure 4: Summary of MOD-025-2 Testing

Test results summary for Pmax/Qmax

54	Generators achieving reactive capability	20.7%
207	Generators NOT achieving reactive capab	79.3%
261	total units	100.0%



Test results summary for Pmax/Qmin

3	Generators achieving reactive capability	1.2%
239	Generators NOT achieving reactive capabilit	98.8%
242	total units	100.0%

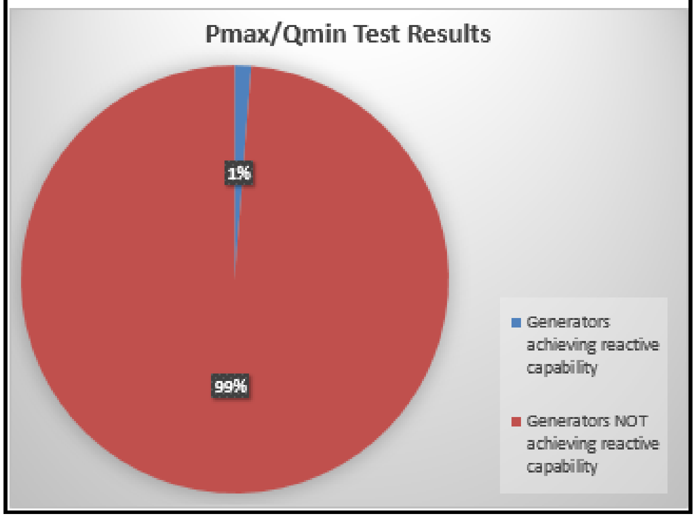
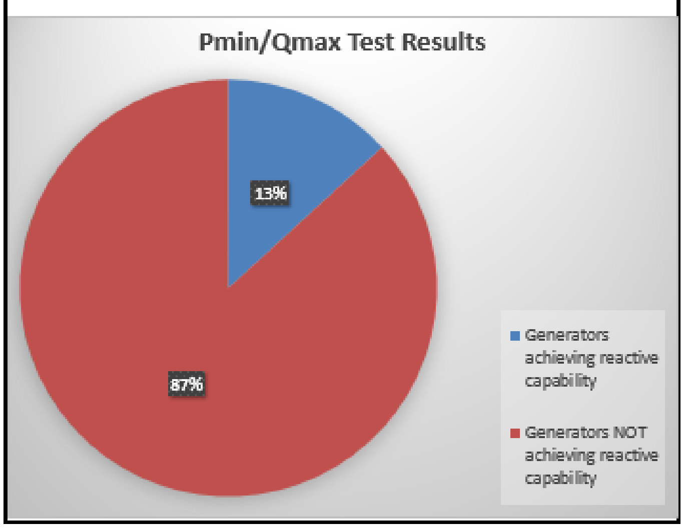


Figure 5: Pmax / Qmax and Pmax / Qmin Test Results

Test results summary for Pmin/Qmax

26	Generators achieving reactive capability	13.2%
171	Generators NOT achieving reactive capabil	86.8%
197	total units	100.0%



Test results summary for Pmin/Qmin

0	Generators achieving reactive capability	0.0%
197	Generators NOT achieving reactive capabi	100.0%
197	total units	100.0%

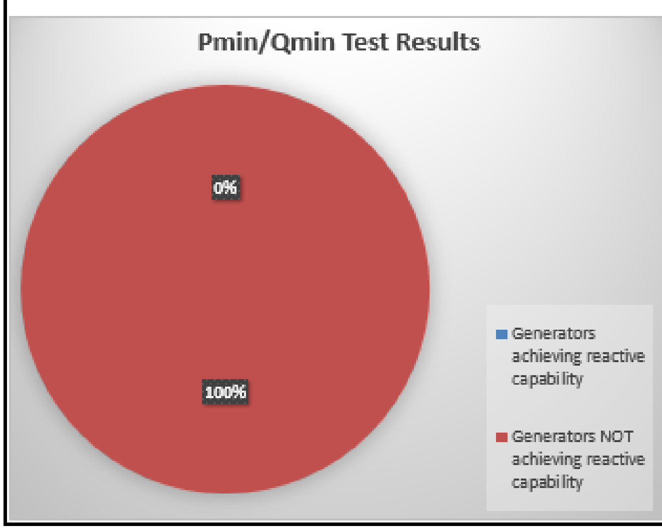


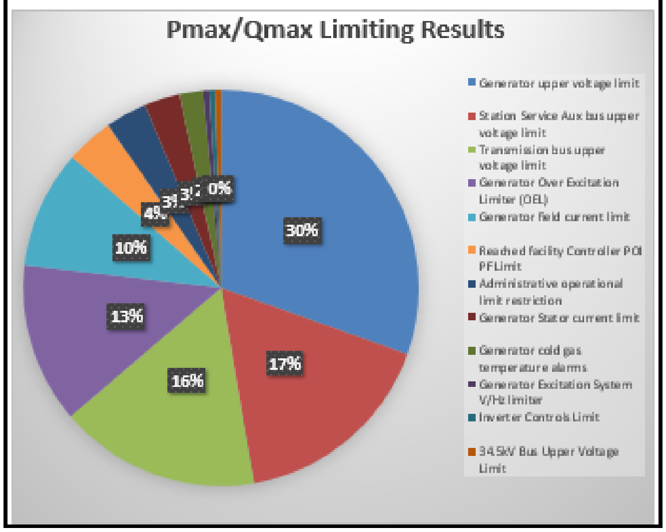
Figure 6: Pmin / Qmax and Pmin / Qmin Test Results

Test results summary for Pmax/Qmax in descending order

63	Generator upper voltage limit	30.4%
35	Station Service Aux bus upper voltage limit	16.9%
34	Transmission bus upper voltage limit	16.4%
27	Generator Over Excitation Limiter (OEL)	13.0%
20	Generator field current limit	9.7%
8	Reached facility Controller POI PF Limit	3.9%
7	Administrative operational limit restriction	3.4%
6	Generator Stator current limit	2.9%
4	Generator cold gas temperature alarms	1.9%
1	Generator Excitation System V/Hz limiter	0.5%
1	Inverter Controls Limit	0.5%
1	34.5kV Bus Upper Voltage Limit	0.5%
207	check	100.0%

Test results summary for Pmax/Qmin in descending order

106	Generator lower voltage limit	44.4%
87	Generator Under Excitation Limiter (UEL or MEL)	36.4%
15	Generator Stator current limit	6.3%
14	Transmission bus lower voltage limit	5.9%
8	Station Service Aux bus lower voltage limit	3.3%
8	Administrative operational limit restriction	3.3%
1	Unit tripped	0.4%
239	check	100.0%



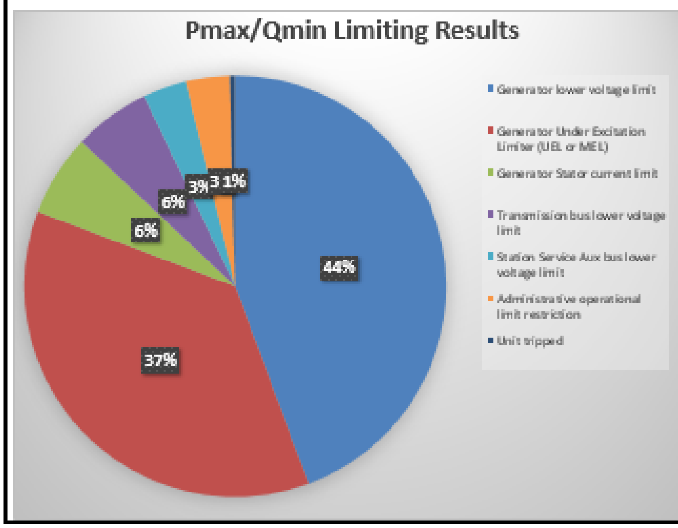
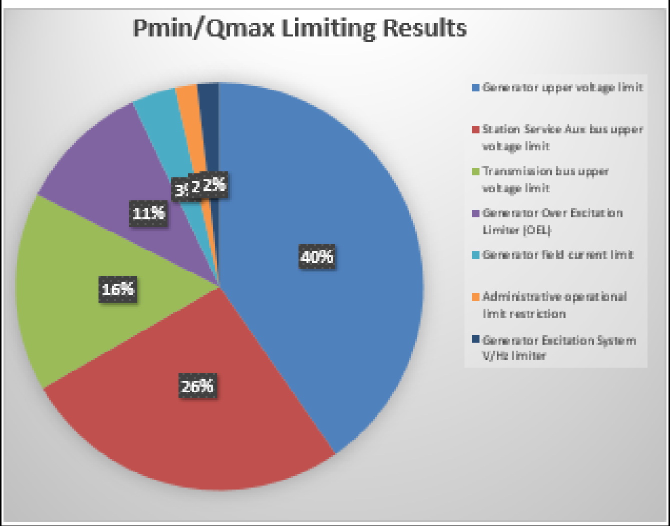


Figure 7: Pmax / Qmax and Pmax / Qmin Test Limiting Factors[19]

[19] Tests that encountered UEL or MEL, as well as those reaching the generator stator current limit could qualify as achieving the actual capability so long as engineering calculations are performed (although this is not required in MOD-025-2).

Test results summary for Pmin/Qmax in descending order		
69	Generator upper voltage limit	40.4%
45	Station Service Aux bus upper voltage limit	26.3%
27	Transmission bus upper voltage limit	15.8%
18	Generator Over Excitation Limiter (OEL)	10.5%
6	Generator field current limit	3.5%
3	Administrative operational limit restriction	1.8%
3	Generator Excitation System V/Hz limiter	1.8%
171	check	100.0%

Test results summary for Pmin/Qmin in descending order		
106	Generator lower voltage limit	53.8%
60	Generator Under Excitation Limiter (UEL or MI	30.5%
12	Transmission bus lower voltage limit	6.1%
9	Station Service Auxiliary bus lower voltage lir	4.6%
9	Administrative operational limit restriction	4.6%
1	Unit tripped	0.5%
197	check	100.0%



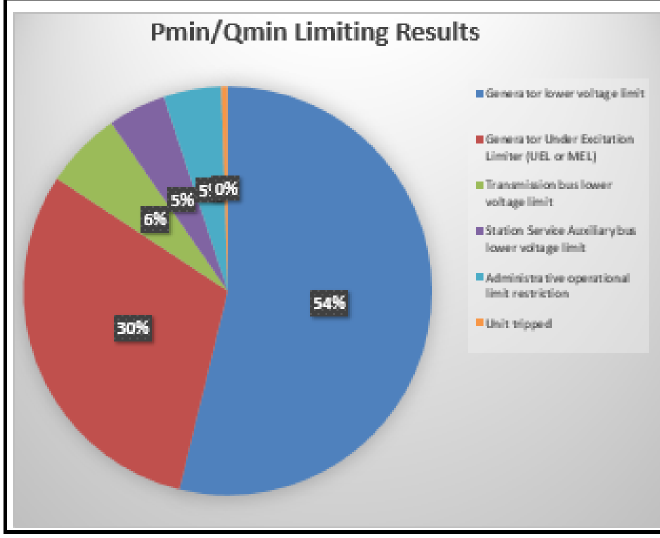


Figure 8: Pmin/Qmax and Pmin/Qmin Test Limiting Factors[20]

[20] Tests that encountered UEL or MEL, as well as those reaching the generator stator current limit, could qualify as achieving the actual capability so long as engineering calculations are performed (although this is not required in MOD-025-2).

MOD-025-2 Cost Results and Analysis

As with all NERC Reliability Standards, costs and cost effectiveness are critical factors. This is particularly important with respect to whether the standard is serving its intended purposes in the first place. Figure 9 summarizes the personnel costs associated with performing MOD-025-2 testing for 261 generators for one GO.[21] Not captured is the forgone cost of shifting the optimization of generation fleet assets due to minimum load testing requirements. Anytime a baseload generator is restricted in output, its output is often replaced with a generator that has a higher cost per MWh to operate.

GOs are required to perform capability testing per MOD-025 every five years for each applicable generating resource. This has proved useful in identifying unexpected or unknown operating limits within the plant; however, it has not proved effective for gathering modeling data as the purpose of the standard states. Therefore, this five year time horizon is not serving its intended purpose and should be re-evaluated to more accurately and effectively gather the data needed for planning models. As stated, this data may be more readily and accurately available from PRC-019 reports (if they were made available to the TP and PC). An SDT should explore alternatives to gathering this data, weighing the costs associated with performing staged tests.

Personnel costs to support NERC MOD-025-2 testing

Department	Personnel	Scope of Work (SOW) Responsibilities	Hours	Cost	Notes
ERO - Support	Principal Engineer	Coordinate testing schedule with applicable enties, prepare test procedures, prepare test report forms, prepare unit electrical limits	5001	$550,063	Hours were determined as constituinting 60% of the ERO engineers annual worked hours of 2000 hours over the 5.5 year
Electrical Field Support	Lead Site Engineer	Assist plant operations in performing tests and gathering data for submission to the ERO Support group	1680	$184,800	Hours were determined as 2 hours travel to and from plant site, 2 hours for Pfl/Qmax and 1 hour for all other tests.
	Sr. Engineer	Assist plant operations in performing tests and gathering data for submission to the ERO Support group	1680	$161,280	Hours were determined as 2 hours travel to and from plant site, 2 hours for Pfl/Qmax and 1 hour for all other tests.
Bulk Power Operations	Principal Engineer	Perform transmission system stabilities studies for risk assessment to system when performing the tests	897	$98,670	Hours were determined per category of test. 1 hour used as base.
Fleet Optimization	Project Manager	Schedule units for test and arrange alternative generating resource to cover for minimum loading testing. Schedule units that are not	224	$24,668	Hours were determined per category of test. 0.25 hours used as base.
Transmission Planner	Principal Engineer	Evaluate MOD-025-2 reported test results	112	$12,334	Hours were determined per category of test. 0.125 hours used as base.
Plant Operations (local or remote)	Plant Operator	Perform necessary tasks to operate generator for tests	1158	$97,272	Hours were determined as 2 hours for Pfl/Qmax and 1 hour for all other tests.
		Total Hrs	**10752**	**$ 1,129,086**	**Total Cost**
		Total Tests	**897**	**$ 1,259**	**Cost per test**
		Total Generators	**261**	**$ 4,326**	**Cost per generator**

Figure 9: MOD-025-2 Personnel Cost Analysis

[21] Anecdotally, other entities report substantially higher costs per unit for completing MOD-025-2. This data reflects one entity, and may not be representative of the average costs across all GOs.

Recommendation

Raw data collected as part of testing performed for MOD-025-2 should not be directly used for representing generating resources (or synchronous condensers) in system planning study models. The NERC PPMVTF recommends that the existing MOD-025-2 standard be either 1) altered, or 2) withdrawn and replaced with a new standard entirely.[22] The NERC PPMVTF recommends that a SAR be developed, and a SDT be created to address these issues with MOD-025-2. This white paper does not provide prescriptive solutions to these issues, yet lays out the reliability issues clearly and concisely. Further, Appendix D of the NERC Reliability Guideline on Power Plant Model Verification and Testing[23] provides technical examples as to why MOD-025-2 testing activities lead to data not suitable for planning models. An NATF reference document[24] is also available to describe testing activities. These industry reference materials, in conjunction with this white paper, serve as useful references for a future SDT to address these issues.

Changes are needed to MOD-025-2 to prevent inaccurate data from being used to represent generating resources (and synchronous condensers) in the transmission planning models. The PPMVTF believes that there is value in performing the tests since they can uncover unexpected limiting factors; however, the PPMVTF agrees that the data acquired during MOD-025-2 testing should not be directly used to represent the actual capability of the machine in power system models. Further, any unexpected limitations to reactive capability are not required to be addressed following testing, and that data is not required to be provided to the TP/PC or TOP/RC for situational awareness of these limitations (if they cannot be corrected). Therefore, the tests do not generally accomplish the stated purpose of the standard.

NERC PPMVTF recommends that a future SDT also consider the challenges that will be faced by inverter-based resources related to staged verification testing. These challenges are expected to be similar to those outlined in this paper.

[22] A minority opinion in NERC PPMVTF is that MOD-025-2 should be withdrawn and not replaced with another standard.
[23] https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_-_PPMV_for_Synchronous_Machines_-_2018-06-29.pdf
[24] https://www.natf.net/docs/natf/documents/resources/planning-and-modeling/natf-reference-document-reporting-and-verification-of-generating-unit-reactive-power-capability-for-synchronous-machines.pdf