An Introduction to Completing a NERC PRC-019 Study for Traditional and Distributed Generation Sources

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Abstract -- **NERC PRC standards have been implemented as a comprehensive plan to increase utility reliability in response to the 2003 Northeast United States blackout. The intent of PRC-019 is to verify regulating controls, limiters, equipment capabilities, and protection controls installed at generation facilities are appropriately coordinated so as to not exacerbate adverse power grid conditions during a system disturbance. PRC-019 provides fairly explicit guidance for what is expected to show compliance for synchronous generator facilities. PRC-019 does not contain explicit guidance on how to show compliance for asynchronous or distributed generation resources.**

This paper describes the approach, challenges, and lessons learned from performing NERC PRC-019 studies of both typical synchronous and asynchronous generators. Both the commonalities and variances of synchronous and asynchronous generation facilities are highlighted to provide the connecting link between what is explicitly stated in PRC-019 requirements and what is commonly expected by compliance authorities. While the interpretation for what is necessary to demonstrate compliance can vary between reliability coordinators; this paper provides examples of proven compliance documentation for a recent PRC-019 wind farm study.

I. Introduction

In response to the 2003 Northeast United States blackout and subsequent governmental regulation, NERC Protective and Control Standards (PRC) were created. The intent of these standards is to improve the performance and reliability of the North American Bulk Electric Power System (BES). Most PRC standards have clearly defined requirements with very specific examples for what analysis and documentation is required to demonstrate compliance. The recent NERC redefinition of what transmission systems are included within the BES has led to many revisions to the standards to include distributed generation resources (DG) as applicable facilities. Inclusion of DG facilities without explicit PRC standard criteria has created room for interpretation in what analyses and documentation needs to be provided to show compliance.

This paper intends to provide an outline of how a PRC-019 study is completed for traditional synchronous generator facilities and an interpretation for how to complete a PRC-019 study for asynchronous DG resources. This paper also provides perspective on how those two studies compare, contrast, and lessons that have been learned while completing them.

II. NERC PRC-019-2

According to the NERC PRC-019 standard, its purpose is to "verify coordination of generating unit Facility or synchronous condenser voltage regulating controls, limit functions, equipment capabilities and protection system settings [1]." The goal of PRC-019 is to improve BES reliability during short time system transients by keeping available generation in service to support the BES, reducing the risk of a cascading blackout event.

The standard establishes criteria for which facilities PRC-019 applies to and what coordination items at those facilities are required to be verified. Facilities which fall under PRC-019 requirements are:

- *Generators over 20MVA*
- *Synchronous condensers over 20 MVA*
- *Multiple generator facilities with an aggregate nameplate rating over 75MVA*
- *Black start generators identified in Transmission Operator's restoration plan(s)*

Both Generation Owners (GO) and Transmission Owners (TO) of synchronous condensers are required to demonstrate compliance for BES generating facilities under their control. An addition made to the second revision of the PRC-019 standard is section 4.2.3.1. This description explicitly states dispersed power producing resources, even if they are performing voltage regulation at the individual unit level, are included in PRC-019-2 requirements. Before this revision, dispersed generating resources such as a type I wind farm would have been excluded from the requirements.

The standard outlines two requirements:

Requirement R1 states that *"At a maximum of every five calendar years, each Generator Owner and Transmission Owner with applicable Facilities shall coordinate the voltage regulating system controls, (including in-service limiters and protection functions) with the applicable equipment capabilities and settings of the applicable Protection System devices and functions.*

Requirement R1 section 1.1 defines two coordination items that are to be verified, with the assumption of normal automatic voltage regulating control loop and steady-state operating conditions:

1.1.1 *"The in-service limiters are set to operate before the Protection System of the applicable Facility in order to avoid disconnecting the generator unnecessarily."*

1.1.2 *"The applicable in-service Protection System devices are set to operate to isolate or de-energize equipment in order to limit the extent of damage when operating conditions exceed equipment capabilities or stability limits."*

Requirement R2 requires GOs & TOs to resubmit PRC-019-2 compliance documentation within 90 calendar days following applicable system equipment or voltage regulating and protection system setting changes.

III. Synchronous Machine Study

A. Study Goals

To show compliance with PRC-019, GOs & TOs must provide evidence of equipment capability, protection and voltage regulating coordination in the form of P-Q, R-X, Inverse Time diagrams, or a combination of the above. In some cases available machine manufacturer's data is not provided in a format that can be displayed on one of these diagrams and in that case PRC-019-2 does make allowance for equivalent tables or other evidence.

B. Study Process

The study process begins with acquiring information about the subject generator's capabilities, in-service limiters and protection system. Generator properties include: impedances, MVA capability, rotor and stator current withstand, and V/Hz withstand are provided by generator manufacturers. The data is typically provided in P-Q or Time Current Coordination (TCC) plot format. Excitation system limit settings are typically provided in the form of exciter programming documentation or settings report. Generator protection settings are typically provided as plots in the case of electromechanical relays, settings report or a settings file in the case of microprocessor based relaying. An ideal data set would include information about:

- Generator Capability & Impedances
- Unit Transformer (GSU) Rating and Impedance
- Loss of Excitation Protection Settings
- Over Excitation Limiter Settings
- Over Excitation Protection Settings
- Generator Rated Power Factor
- Under Excitation Limiter Settings
- GSU & Generator Volts/Hertz Capabilities
- Volts/Hertz Limiter Settings
- Voltage regulation system manuals
- One line diagrams
- Three line diagrams

After receiving data from an initial request for information (RFI) it must be reviewed to determine if it is adequate to perform a PRC-019 study. The type of data used in a PRC-019 study is not typically used in day-to-day plant operation of a synchronous generator and as such it is often misplaced, forgotten about or was never delivered. As a result it is typical to issue one or more follow up RFIs before receiving a complete data set for a PRC-019 study, and to assist the GO in issuing RFIs to equipment manufacturers.

Once a complete data set is compiled the data is plotted on diagrams appropriate to the data received, typically P-Q, R-X and inverse time-current or inverse time-voltage plots. The PRC-019 standard document provides examples of these plots. Figure 1 is a typical P-Q plot example shown in PRC-019-2. Microsoft Excel has proven to be a useful tool for creating plots since capability data can be input directly and characteristics such as steady state stability limit (SSSL), loss of field protection and limiter characteristics can be calculated in the same work book that is used to produce the plot.

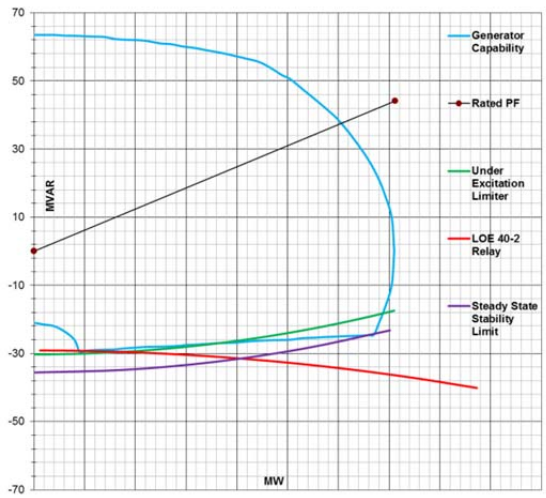

Figure 1: PRC-019-2 Example P-Q Plot

Once plotting is complete, evaluating PRC-019 compliance is straight forward. Non-compliant limiters and protection characteristics are apparent by visual inspection of the plots. Figure 2 shows an example of a non-compliant P-Q plot. Observe in this example that the under excitation limiter is set below the steady state stability limit curve, which does not meet PRC-019 Requirement R1 because the machine may go out of synchronism before the limiter takes action.

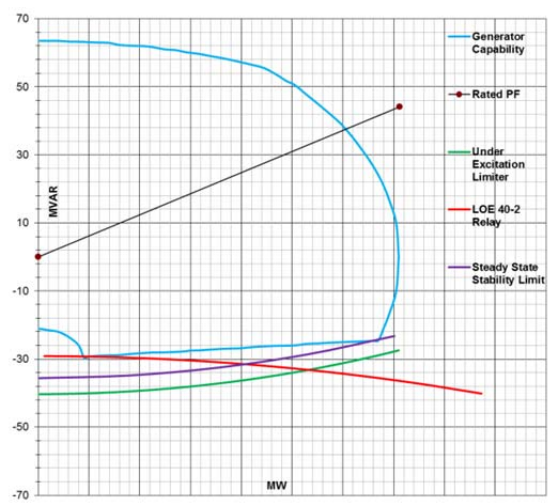

Figure 2: Example Non-Compliant P-Q Plot

Figure 3 shows the typical synchronous generator PRC-019 study process in flow chart form.

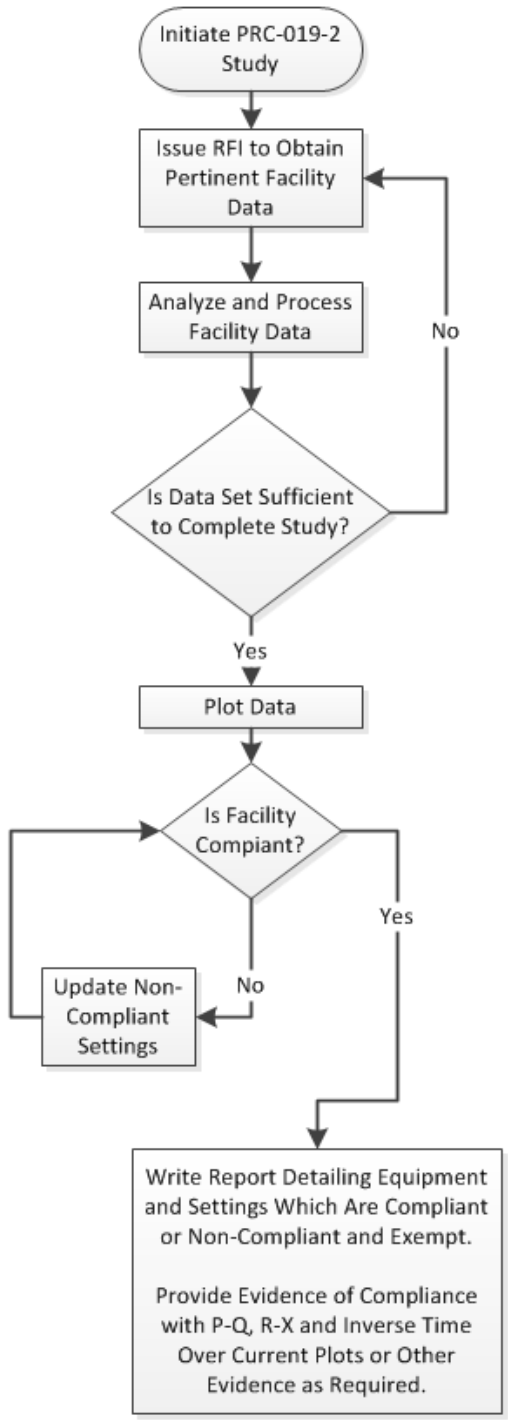

Figure 3 – Typical PRC-019 Study Process

C. Common Stumbling Blocks

Manufacturer's machine data quantity and quality varies widely between manufacturers. It also tends to vary with the age of the generator. Newer generators tend to have more data available as less time has passed for it to be misplaced or destroyed, and with modern numerical controls and protective relays, the O&M manuals usually include extensive listings of settings. Older generators tend to have less data available for the reason noted above. In addition, data for older generators tends to be of poorer resolution, either in the original document or in scans and copies over time, which can be difficult to interpret. Older generators may also make use of analog excitation controls that are obsolete and not currently supported by the OEM, requiring extensive research to determine how limiters are implemented, or even if the function exists.

D. Report

A PRC-019 compliance report must convey to a compliance auditor that the subject generator or synchronous condenser meets the requirements stated in the PRC-019 standard. A secondary audience is typically engineering staff responsible for the generation or transmission facility the subject unit belongs to. A tertiary audience of managers may also need to be able to glean information from the report, such as the need for replacement of relays or voltage regulating equipment.

The report should progress from a high level overview to a detailed discussion of the analysis and results. The report must include a detailed description of any assumptions that were made about the subject generating unit or data interpretations that were required. The report structure should allow management personnel to be able to read the initial overview and summary and see at a glance where problems were identified in a specific subsystem. The body of the report will include figures as described in PRC-019, and tables and text as necessary to demonstrate to a compliance auditor that limiters, protection and unit capability are coordinated per the requirements of PRC-019. The body of the report should also contain all of the detail a protection engineer would need to understand the analysis that was performed and to reproduce any portion of the study if needed to confirm the results.

To assist GOs in generating RSAW (Reliability Standard Audit Worksheet) documents in a uniform manner, NERC has developed a standard RSAW template for PRC-019 and many other compliance standards. The PRC-019 report writer is strongly advised to use the RSAW template as reference to insure the report includes all the necessary information. The report itself is then used to provide backup evidence of study completion when the RSAW package is assembled and submitted for periodic reliability audit by the GO's compliance officer.

IV. Asynchronous Machine Study

A. Study Goals

Unlike completing a PRC-019 study for a traditional synchronous generator, there are no specified limiter functions, protective devices, or example diagrams in the PRC-019 standard related to asynchronous generators. Asynchronous generators are typically found in a network of multiple similar generators connected into a collector substation, such as at a wind farm or solar PV facility. Although wind and solar PV generators are commonly combined at a central facility, wind and solar generation facilities are generally considered distributed generation (DG) or distributed energy resources (DER) because the facilities are an assembly of multiple individual generators that themselves are far smaller than the 20MVA minimum described above.

Completing a PRC-019 study of an asynchronous generator facility requires a different analysis method than the typical synchronous generator facility. PRC-019 compliance can be completed for wind or solar generators by understanding the goal of PRC-19 and likening functions found in asynchronous facilities to those at synchronous facilities. The following description will focus on Type I and Type III wind turbine facilities, but the same study process can be applied to any asynchronous DER facility.

B. Study Description

An asynchronous generator PRC-19 study begins with acquiring information about the individual generator, the collector system, and plant level controls. Each of the three sections represents a different analysis phase, and will require information specific to that area. Many of the same issues with data collection that occur in a synchronous generator study are encountered while gathering data for an asynchronous generator study. Turbine manufacturer, facility designer, and current operating entity can affect what documentation is available and what information is present in each particular document. Asynchronous generator and facility data tends to be much less standardized than data for traditional synchronous generators. As responses to the initial

RFI are returned, a more specific request for the outstanding information can be sent. Figure 4 shows a diagram for each of the four types of wind turbine generators (WTG) commonly used to date which include:

- Type 1: Induction generator
- Type II: Induction generator with variable rotor resistance
- Type III: Doubly-fed induction generator (DFIG)
- Type IV: Asynchronous or synchronous generator with full converter interface. This WTG can make use of DC or AC generators, and avoid the use of a gearbox.

Most existing wind farms are constructed of either the older Type I induction generators with static capacitor compensation or newer Type III DFIG WTG. Following advancements to the newest Type IV full converter synchronous WTG, it is possible that many of the same limiter and protection functions found in a typical synchronous generator could be present. If functions matched those specifically listed in the PRC-019 standard, it is reasonable a more standard analysis technique could be performed, including the creation of a typical P-Q plot. Considering the depth of information required in regards the generator characteristics, it would seem likely for a study of that type, the generator manufacturer would need to provide a majority of the information.

C. Phase 1 - Individual Generator Analysis

Depending on the manufacturer the following functions can be found in Type I machines:

- Normal condition shutdown limiter(s)
- Emergency condition shutdown limiter(s)
- Overcurrent or overpower relays
- Machine thermal overload curve
- Turbine main overcurrent relay (MCCB1)
- Step-up transformer specifications
- Step-up transformer protection (fuse or relay)

If the information above is available, individual analysis is a fairly simple task of plotting all functions on a TCC plot. Figure 4 shows an example TCC for a 1MW Type I WTG.

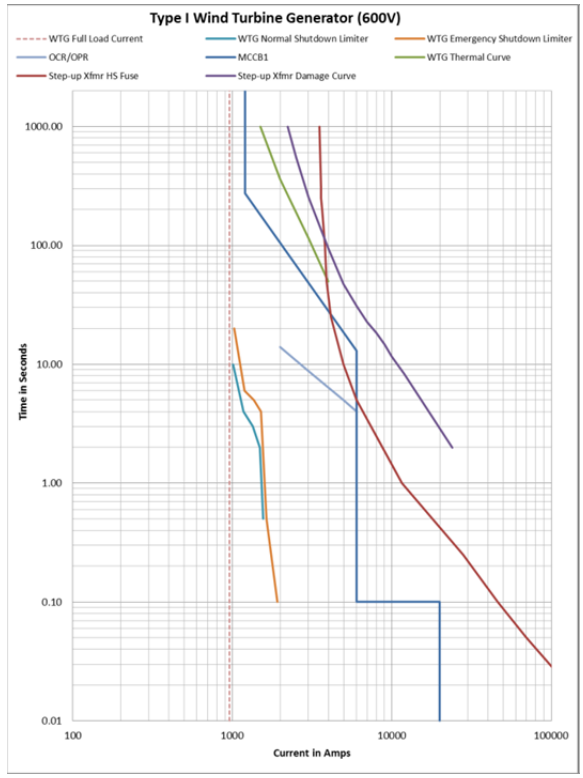

Figure 4 –Example Type I WTG TCC

Considering a simplified wording of the two coordination items 1.1.1 and 1.1.2 listed in R1 of the PRC-019-2 standard, limiters should operate before protective devices, and protective devices should operate to limit equipment damage. It is reasonable to consider that Figure 4 TCC verifies both required coordination items. If adequate wind conditions are present, all WTG is able to operate at full power output before a hard-stop limiter function operates by adjusting prop pitch to reduce power output. The normal and emergency limiters are properly coordinated to operate before either protective device would trip the generator offline thus demonstrating compliance for Requirement R1 1.1.1. All protective devices are properly coordinated to operate before damage would occur to either the WTG or the step-up transformer demonstrating compliance for Requirement R1 1.1.2. The decision to consider the step-up transformer protection and damage curve as part of the individual analysis is up to interpretation. While damage to the transformer would only occur for a near bus fault, it seems consistent to include those protection elements and damage curves in the individual analyses considering a damaged transformer will result in the WTG also being offline until equipment can be repaired or replaced.

Individual analysis of a type III WTG is very similar to the process described above for a type I WTG, but with one main difference: power output comes from both the stator and rotor converter of a type III WTG.

Along with a majority of the same information required for a type I turbine analysis, the output capabilities of both the stator and converter are needed for type III turbine analysis. Figure 5 shows an example TCC for a 2.08 MVA type III WTG.

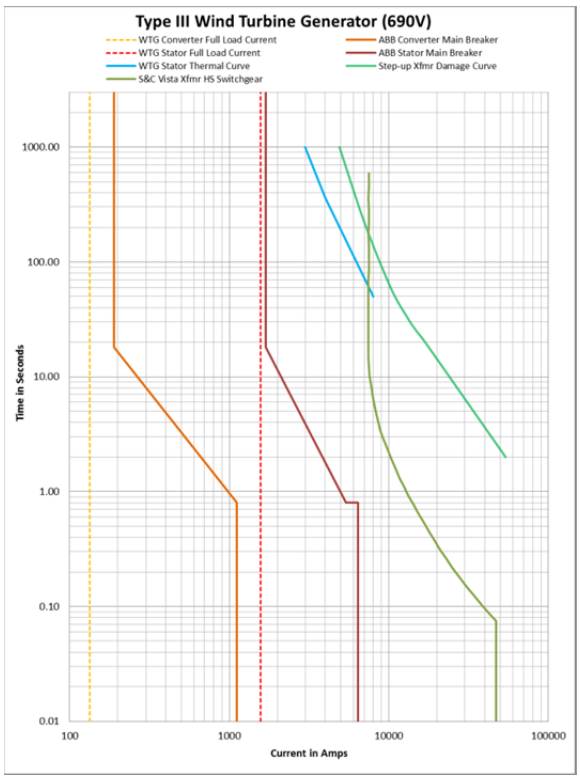

Figure 5 –Example Type III WTG TCC

Of a maximum 2080KVA combined power output, the stator produces 1887KVA and converter produces 193KVA of the total output. These output limits are typically not present in documentation available at the generation site, but can be normally be found in the manufacture's turbine specific O&M manual. Because of output from both the converter and stator, an individual breaker is usually installed on each. Much like the individual machine analysis for a type I WTG, analysis of a type III WTG simply requires plotting all limit and protection functions on a Time-Current Coordination plot. Due to the nature of a type III WTG by design there is very little coordination margin between the output limit function and the associated protective device. As shown in Figure 5, Both the stator and converter output limits are properly coordinated to operate before either protective device that would trip the generator offline, thus demonstrating compliance for Requirement R1 1.1.1. All protective devices (relays) are properly coordinated to operate before extensive damage would occur to either the WTG or the step-up transformer demonstrating Requirement R1 1.1.2. There is an argument to be made that this level of analysis is satisfactory to verify NERC PRC-019-2 compliance, but some protective elements as part of the collective system can behave in the manor of a limiter which requires additional analysis.

D. Combined System Analysis

Combined system analysis begins with the same process for individual generator analyses. The grouping of generators can typically be seen in two levels. The first level is a feeder string consisting of between 5-15 WTG, and the second is a collector or feeder bus made up of multiple strings with a total of 30-150 WTG. Depending on the overall facility configuration the collector bus connects to one or more generator step-up (GSU) transformers and voltage regulating equipment. Voltage regulating equipment can include switchable shunt capacitor banks, reactor banks, or control systems with capacitive capabilities such as a DVAR system. Protective relaying is typically present at each area listed above: feeder, collector bus, GSU transformer, and voltage regulating equipment. Feeder limits are the individual WTG power output limits multiplied by the number of interconnected WTG. Collector bus limit is the individual WTG power output limits multiplied by the total number of interconnected WTG plus the full VAR output of the voltage regulating equipment. Any protective device must be set above this these output limits to be compliant with PRC-019 Requirement R1. Figure 6 shows a combined TCC considering the heaviest loaded feeder, collector, and control system limits and protection functions.

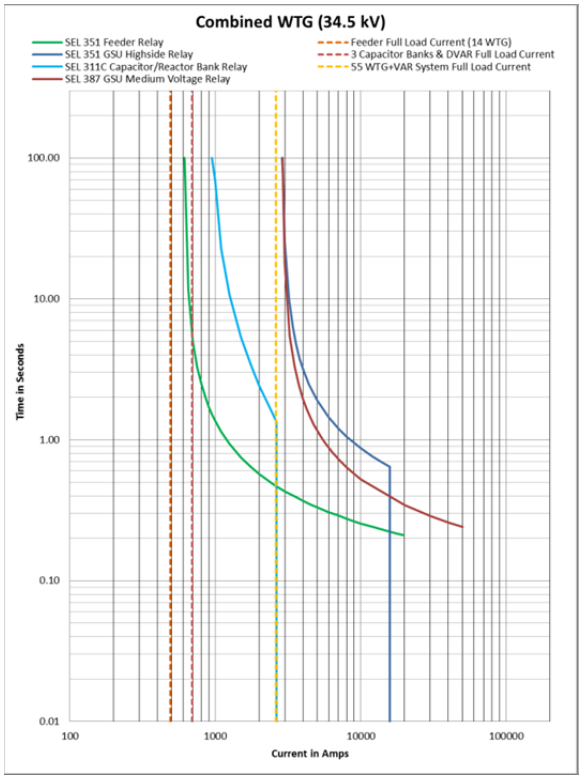

Figure 6 – Example Collector Substation

E. Plant Level Control Analysis

Plant level control can vary in complexity from a single relay switching in capacitor banks based on power flow to a DVAR system with communication to each individual turbine. Plant controllers typically operates in either voltage or power factor control modes. Voltage control mode usually maintains the voltage within a contracted range at the utility point of interconnection (POI). Power factor control mode usually measures current and voltage at the regulated POI, compares these values to a contracted power factor range, and then calculates what VAR compensation is needed to maintain the target power factor. Relay switching plant level control analysis is minimal; simply review capacitor bank relays for overcurrent settings that would trip the facility offline before the individual or combined WTG output limits are met. Advanced power factor or voltage regulating schemes require a more thorough analysis to both compare if control limits will curtail WTG output, but also that voltage regulating limits and protection are properly coordinated. Figure 7 shows a voltage coordination plot for a DVAR-STATCOM system regulating voltage at the 138kV collector bus.

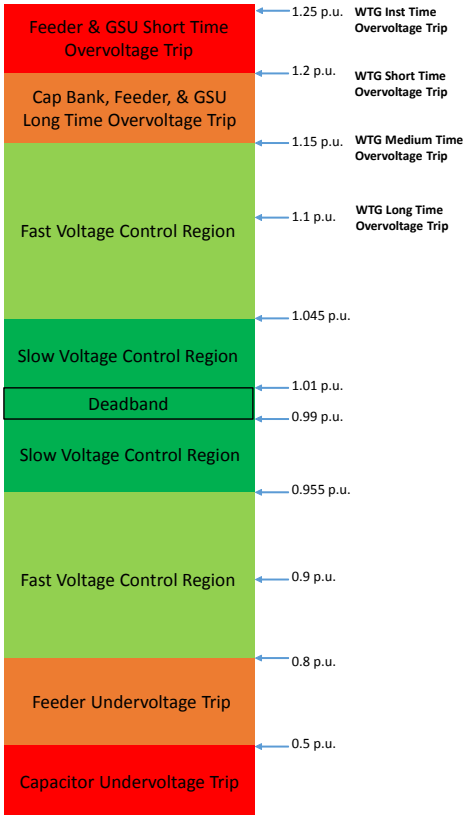

Figure 7 – Example Voltage Coordination Plot

Figure 7 was created to address wording in Requirement R1 that "Facilities shall coordinate the voltage regulating system controls, with applicable equipment capability and setting of the projection system devices and functions." [1] Both voltage limits and protection set points for the WTG, feeder, collector, and plant controller are shown to coordinated and therefore demonstrate compliance.

V. Challenges & Lessons Learned

A. Data Availability

As mentioned previously, the data used in PRC-019 studies is not typically used day to day and is often misplaced, of poor quality or the owner simply isn't familiar with what is being requested. For older installations with paper documentation, a site visit to review all available documentation is often required. For newer installations with O&Ms in PDF format or other electronic documentation, it is typical to request all documentation the owner has via email or FTP site and a site visit is not required.

It is not un-common to receive the exact data requested, only to find it un-useable. Paper drawings

that have been scanned may lack the resolution to pick up small text which tends to be the most pertinent text, particularly if they have been scanned multiple times. Nameplate photographs tend to be useless when the nameplate has been painted over during maintenance. Corroded nameplates for older units have also been an issue.

If data is un-available it may be re-created from equipment standards and reference texts in some cases. The P-Q Diagram in Figure 8 was calculated using equations from "Electric Machinery Fundamentals" [2]

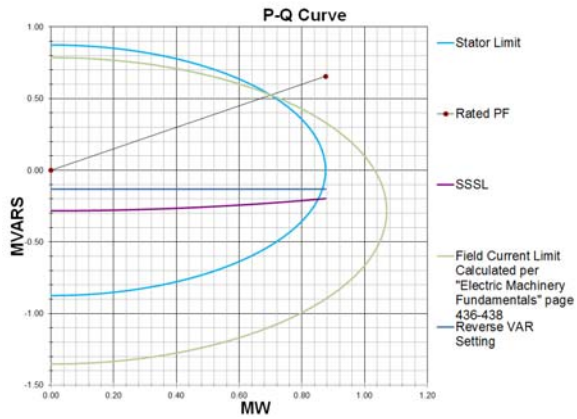

Figure 8 - Calculated Theoretical P-Q Diagram

Shortly after the P-Q Diagram in Figure 8 was developed, the manufacturer's P-Q Diagram for the generator was received. Figure 9 is a plot of the manufacturer's P-Q diagram for the generator.

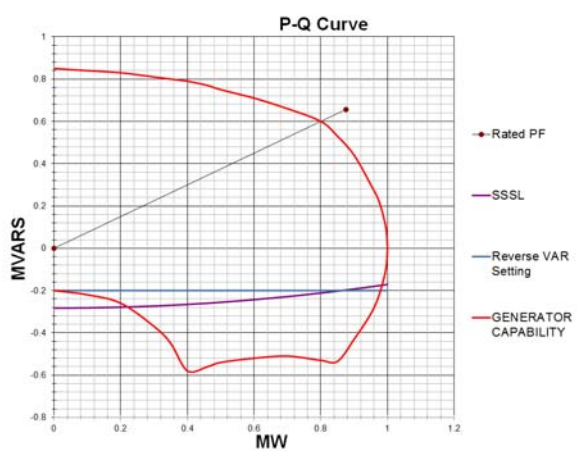

Figure 9 - Manufacturer's P-Q Diagram

It is apparent by observation that the theoretical plot in Figure 8 and the manufacturer's plot in Figure 9 are very similar in general shape. Although they are significantly different along the lower half of the MVARS axis, the general shape of the curves would both drive field current limiter and loss-of-excitation settings to very similar values. When machine capacity plots are not available, such as for a hydro-turbine generator that may be over 90 years old, it is acceptable to recreate this information using standard methods described in engineering texts.

B. <u>Atypical Data</u>

Data sometimes comes in formats that don't fit typical reporting diagrams. Figure 10 shows a sample of a Volts-per-Hertz capability plot from a generator manufacturer that was given simply in terms of voltage and frequency per unit values, rather than a time based withstand curve.

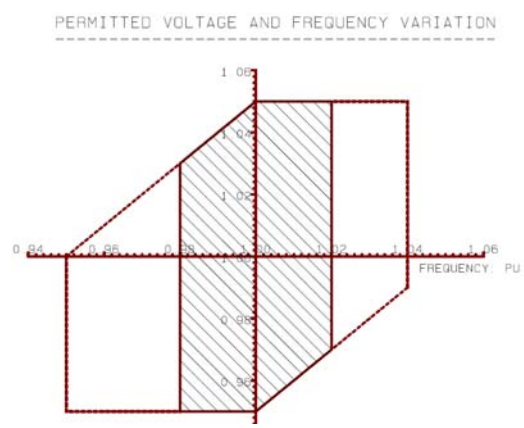

Figure 10 - Atypical Data Format

In this case, protective settings were interpreted to fit the withstand curve in the format it was provided in. Figure 11 shows the resulting plot.

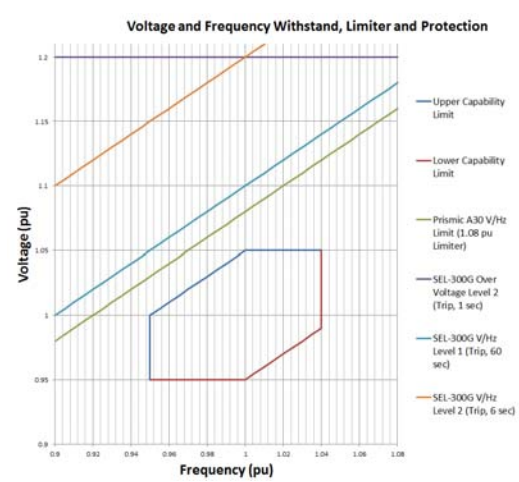

Figure 11 - Atypical Voltage/Frequency Plot

It is clear by observation that the applicable limiter is coordinated with the applicable protection elements. Although the plot is not in a typical format, it does show that the limiters and protection on that generator are compliant with PRC-019.

C. Manufacturer Data

Contacting manufacturer's directly has been a successful step in receiving any outstanding information for generators of all types. Typically supplying a model and serial number for the generator is required to receive useful data. In some instances the manufacturer has required the data request come from the generator owner directly, in others the manufacturer has provided it to a third party. In a few instances data requests have been denied based on the claim that the requested information is proprietary, an unfortunate situation with many DER OEMs. With manufactures that have reservations about sharing certain information, many times holding a teleconference with the manufacture, generation owner, and the third party performing the study can help assure only the minimum amount information required to successfully complete the study is being asked for.

D. Regulatory Interpretation

PRC-019-2 was clearly written with classic synchronous generators and condensers in mind. To apply PRC-019 to asynchronous generators requires meeting the intent of the standard rather than creating a plot explicitly given in the standard. It is important to keep in mind that the most important audience of a PRC-019 study is the reliability coordinator for the North American region where the generation facility is located. It is critically important to provide adequate information and thoroughly justify your interpretations of the standard to help step a compliance auditor through the study process and come to the same conclusion. The complete study must assure a compliance auditor that the generator or condenser facility will operate as intended by the requirements of PRC-019.

VI. Conclusions

As the bulk electric system evolves it is becoming increasingly intricate which creates new reliability challenges. Unforeseen BES events are going to occur and NERC will respond with revised reliability standards in an attempt to prevent those events from happening. As standards are revised, gaps in supporting documentation for what demonstrates compliance may require an interpretation of the standard for certain facilities until more prescriptive requirements are developed.

The task of NERC PRC-019 compliance may seem cumbersome considering the amount of non-typical information required and the lack of guidance in the standard for what is expected to show compliance for DER facilities. Through those difficulties, a PRC-019 study can provide an opportunity to document facility information for a generating facility which would otherwise not be available for future use.

VII. References

[1] "*NERC PRC-019-2 Coordination of Generating Unit or Plant Capabilities, Voltage Regulating Controls, and Protection"*, National Electric Reliability Council, Version 2 May 29, 2015

[2] "Electric Machinery Fundamentals", Stephen Chapman, 2011

[3] "*NERC Considerations for Power Plant and Transmission System Protection Coordination"*, National Electrical Reliability Council, July 2015

[4] "IEEE C37.102-2006 IEEE Guide for AC Generator Protection"

VIII. Biographies

Matthew Manley joined POWER Engineers in 2015. He is a member of the SCADA and Analytical Services group where he performs a variety of electrical system studies for transmission, substation, and generation projects. He has a background in protective relaying, transmission system coordination, NERC reliability standards, and soil resistivity testing and grounding grid analysis. Matt received his B.S. in electrical engineering from Texas A&M University.

Tony Limon joined POWER Engineers in 2015. He is a member of the SCADA and Analytical Services group where he performs a variety of electrical system studies for transmission, generation, and distribution projects. He has a background in power system analysis, protective relaying, and arc flash studies. Tony holds a B.S. in electrical engineering from Washington State University.