A Guide for Applying PRC-019 to Synchronous Condensers

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***Abstract*—The intent of NERC standard PRC-019 is to ensure large or critical generating units and synchronous condensers have their controls, limiters, and protective functions set in a coordinated manner. Proper coordination allows the units to operate within their full capability ranges, provides adequate protection for the equipment, and prevents tripping events that could exacerbate system disturbances. Section G of the standard provides detailed example calculations and plots that are useful for applying PRC-019 to a synchronous generating facility; however, there are no detailed examples specific to synchronous condensers. Given the historical shift to flexible AC VAR compensation solutions (e.g., SVCs, STATCOMs), there may be less familiarity within the industry with the operating principles of synchronous condensers. Meanwhile, their installations are becoming more commonplace as penetration of inverter-based generating resources increases. This paper provides a primer on synchronous condenser basics and a guide on applying the PRC-019 standard to them.**

Keywords—synchronous condenser, fault current, system inertia, reactive power, PRC-019, excitation controls, protection

I. INTRODUCTION

Synchronous condensers have a long, but not widely known, history of providing support for electrical power systems. They provide a form of VAR compensation that can respond dynamically to help maintain system voltage health. Additionally, the inertia of their rotating mass can temporarily inject real power in the case of system underfrequency events [1] and prevent voltage collapse during faults by injecting VARS far above their nameplate rating. In the wake of widespread retirement of synchronous generation resources and the increase in low-inertia renewable generation replacing those resources, grid solutions beyond reactive compensation are needed to provide long-term grid resiliency. Synchronous condensers are a solution that provide both reactive compensation as well as system inertia during system transients.

Since 2012, the North American Electric Reliability Corporation (NERC) has enforced Protection Standard PRC-019, requiring owners of Bulk Electric System (BES) generation to confirm proper coordination of their generation control and protection functions on a recurring basis in an effort to increase grid reliability and stability. NERC PRC-019 applies not only to synchronous and inverter-based generation, but also to synchronous condensers. While the protection and control systems for synchronous condensers are similar to that of synchronous generators, there are enough differences to warrant special consideration. However, industry literature discussing protection and control of synchronous condensers as well as how to apply NERC PRC-019 is limited, thus we have compiled a brief application guide here with the goal of providing a useful companion to those applying NERC PRC-019 to a synchronous generation asset.

II. SYNCHRONOUS CONDENSERS

A. Functionality

A synchronous condenser is a large, free-spinning electric machine that can dynamically supply or absorb reactive power from its connected AC system. It's effectively an unloaded synchronous motor, providing VAR support through the control of the rotor DC excitation. There is no prime mover such as what drives a synchronous generator, as depicted in Figure 1 below, so a governor control system is not present. During steady-state operation VAR support capability of a synchronous generator can vary from its full MVA leading power factor rating (sourcing VARs) to 50% or more of its MVA lagging rating (sinking VARs) [2]. Overexcitation of the field circuit will source VARs to the grid, supporting low voltage situations, while underexcitation of the machine field circuit will cause it to absorb VARs aiding in overvoltage situations.

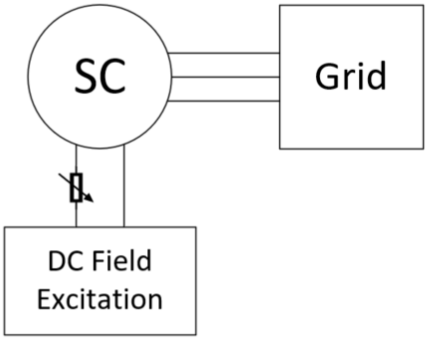

Figure 1 - Synchronous Condenser Connected to the Electrical Grid

Synchronous condensers do not produce real power under normal steady state operation making their capability curve appear very close to a vertical line moving up and down the Q axis on a P-Q diagram. The mass of the machine physically rotating provides a source of system inertia similar to synchronous generators. In the event of a frequency drop in the electrical system, the machine, which is now spinning faster than the rotating stator field due to its inertia, can provide temporary grid power and voltage support to help ride through the excursion. Depending on the excitation control system and rotor thermal capabilities, a condenser may provide VARs in excess of the machine MVA rating for a short duration by "field forcing". Additional mass in the form of spinning flywheels can be added to the machine rotor, providing even more inertia for the system. Synchronous condensers can source more real power than the machine MVA rating for a limited amount of time during a system disturbance. This inherent source of inertia can greatly improve system stability in weak systems.

Example capability "V" curve plots as provided by the manufacturer are shown in Figure 2. Note that unlike a synchronous generator, the condenser unit is capable of operating with no excitation current. A standard condenser application may not utilize this capability, but it is important to note the possibility as this requires special consideration in assessing the underexcitation limiter and protection functions should this operating function be implemented. This also highlights the importance of obtaining manufacturer data and documentation explaining the voltage control and protection settings for each unique synchronous condenser application as each will have capabilities and controls tailored to the specific needs of the grid where they are installed.

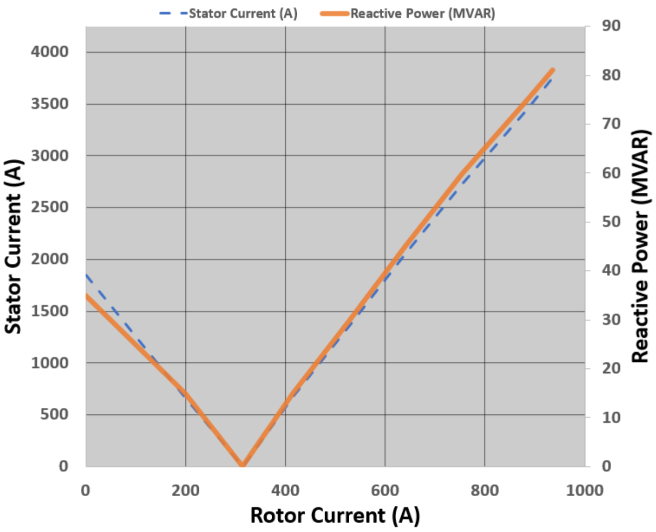

Figure 2 - Typical SC Capability "V" Curves depicting Reactive Power and Stator Current versus Rotor (Field) Current

B. Modern Power Grid Applications

While dramatic increases in renewables penetration in recent years is helping meet cleaner environmental standards, these changes to the grid come with a tradeoff in grid stability and resiliency.

During system faults, inverter-based resources do not contribute significantly more than their rated load as fault current and do not aid in stiffening the grid to counteract frequency excursions. As more coal burning synchronous machines are retired, grid inertia and short circuit capacity are decreasing. This makes electrical faults more difficult to detect and electrical systems less able to recover from voltage and/or frequency deviations.

Synchronous condensers are rotating machines; thus, they provide a source of inertia to improve gride resiliency while performing their primary function of reactive compensation. Other types of static flexible AC transmission system (FACTS) devices such as SVCs and STATCOMs provide faster VAR support response for less installed cost, making them more popular in recent decades. However, they do not provide the additional grid supporting inertia of a synchronous condenser. Condenser units also provide an advantage over static compensation devices, whose VAR output correlates to the square of the voltage, resulting in far reduced output during system undervoltage excursions.

Space constraints may also be a factor in selecting a synchronous condenser over other FACTS devices as condensers have a significantly smaller footprint. Additionally, as more fossil fuel-based synchronous generator units are seeing reduced utilization or being retired, opportunities have arisen to repurpose these units as synchronous condensers.

III. NERC PRC-019-2

A. Purpose

The intent of NERC standard PRC-019 is to ensure large or critical generating units and synchronous condensers connected as part of the Bulk Electric System (BES) have their controls, limiters, and protective functions set in a coordinated manner [3]. The "stiffness" or ability of a system to withstand a disturbance is directly a function of the short circuit capacity stored as inertia in rotating machines. Tripping synchronous machines unnecessarily during an external fault exacerbates the disturbance by removing a source of voltage and frequency support and can lead to cascading outages. PRC-019 looks to limit this effect by requiring machine owners to ensure their excitation control and protection functions are set to limit the machine's operation to within its capability region and only trip the machine when necessary to protect the equipment from damage. PRC-019 was developed directly in response to the multiple generation facility outages that occurred during the 2003 East Coast blackout due to protection system mis-coordination.

Generator and Transmission Owners are required to comply with the standard if they own any of the following applicable facilities connected to the BES:

- Individual generator over 20 MVA
- Synchronous condenser over 20 MVA
- Plant or facility with individual generating units aggregate over 75 MVA
- Black start units identified as part of a Transmission Owners

B. Requirements

To accomplish the goal of the standard, PRC-019 outlines two requirements. The first requirement (R1) requires that a coordination evaluation of voltage regulating system controls be performed every five (5) years. Specifically, Generator and Transmission Owners must perform the following:

1.1 Assuming the normal automatic voltage regulator control loop and steady-state system operating *conditions, verify the following coordination items for each applicable Facility:*

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

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

The second requirement (R2) requires that an R1 coordination evaluation shall occur within 90 days following the identification or implementation of system, equipment or setting changes that will affect coordination.

The details found in the standard outline acceptable forms of documentation for record keeping as well as application examples (including plots) that primarily apply to synchronous generators. Additional discussion and application examples can be found in the "PRC-019-2 Technical Reference Document" [4].

C. Challenges

One challenge to applying PRC-019 to synchronous condensers may be the lack of guidance found in industry literature that is specific to condensers rather than generators. This paper hopes to provide some support in this area. It is likely that situations will be found where sound engineering judgement and consideration of the intention behind NERC PRC-019 must be applied in place of finding direct guidance. For example, one may find that a programmed trip curve crosses a capability curve of the synchronous condenser. This may initially appear as a miscoordination, but upon further inspection one might realize that the capability curve is plotting in a region that should never be considered steady-state operation of a power system. In such cases, coordination between the limiter and protection function should be confirmed, and reasoning as to why the protection function crossing the capability curve at such a location is acceptable should be recorded in the PRC-019 study documentation.

Data collection can pose an additional challenge. An example process for completing a PRC-019 study for synchronous generators and distributed resources is detailed in a 2018 paper by M. Manley and T. Limon [5]. Many of the challenges identified for performing a study are shared by synchronous condensers, primarily in data collection, quality of the data received, and regulatory interpretations. The following data is needed to properly assess coordination of the protection and control functions of a condenser:

- Synchronous Condenser Data
  - Nameplate data (rated MVA and voltage)
  - Impedances (X_d, X_d', X_d'')
  - Rated MVAR range
  - Volts/Hertz Capability Curve
- Unit Transformer (GSU)
  - Nameplate data (rated MVA, voltage, impedance)
  - Volts/Hertz Capability Curve
- Excitation Control System
  - Under Excitation Limiter & Transfer Settings
  - Loss of Excitation Protection Settings
  - Over Excitation Limiter & Transfer Settings
  - Over Excitation Protection Settings
  - Volts/Hertz Limiter Settings
  - Excitation control system ratings
  - Brushless exciter ratings (if used)
  - Brushed static exciter ratings (if used)
  - System manuals that provide detailed limiter characteristic curves or equations, and translation to engineering units if settings are made in per-unit values
- Protection System
  - Settings for all relays protecting the generator, GSU transformer, and any Unit Auxiliary transformers
  - Manuals for all applied relays
- One-line diagrams
- Three-line diagrams
- An accurate short circuit model or system Thevenin impedance is to be used in calculation of the steady-state stability limit (SSSL) curve

Some of the challenge associated with gathering the data above can be mitigated through planning. Communicate early and often with plant managers, planning departments, and protection departments to begin having the data located when you know a PRC-019 assessment is upcoming. Require all newly set excitation controls and protective relays to be accompanied by detailed documentation that is easy to interpret later and have a standardized document management process to ensure the documentation is retained. Frequently in the past, original equipment manufacturers of installed units did not provide customers with detailed engineering guides to excitation control system settings, so these must be ordered prior to completing the study.

IV. APPLICATION OF PRC-019 TO SYNCHRONOUS CONDENSERS

A coordinated excitation and protection system will have limiter elements that are set within the operating bounds of the machine to detect an excursion and attempt to bring the machine back within a desired operating region. Outside of these bounds, protection elements will be set to trip the machine to prevent equipment damage. Both should be set such that they ride through brief external system disturbances. Some machines may include redundant excitation control systems with a primary controller and a hot standby. In these situations, a separate transfer control unit will have a set of transfer curves that will detect the machine approaching an out-of-bounds (trip) operating region and transfer to the hot standby first to confirm the issue is not with the controller itself. If a limit curve has been crossed, followed by the transfer curve, controls will transfer to the backup which will attempt to correct operation via limiters. If the controls are not successful, a protection element will most likely remove the machine from service. Time delays on elements should be set such that the machine rides through external disturbances but operate fast enough to limit damage to equipment. One can see that a properly coordinated system will function in the following order: limit, transfer (attempt backup limit), protect (trip).

Similar limit and protection functions are applied to synchronous condensers as are applied to synchronous generators, however, their appearance on P-Q and R-X diagrams will appear different due to the nature of synchronous condenser operation. Condensers are customized to the specific needs of each installation. Thus, some condenser control curves may not deviate greatly from a typical generator, while other times you may find something out of the ordinary. In these situations, manufacturer data becomes of particular importance. In this section, we present typical elements you will likely find set in machine controllers and protective relays, and what constitutes "coordinated".

A. Underexcitation Limiter / Loss of Field Protection

As shown in Figure 2, synchronous condensers are unique from generators in that they are capable of operating well into their underexcited region. In some applications, a condenser may even be configured to operate without excitation being applied, providing their full VAR sink capabilities spinning as an induction motor to help reduce system voltage. Applications which do not foresee the need to leverage the motoring functionality of a condenser may have underexcitation limiter and protection curves set in a manner similar to a synchronous generator.

In applications where the condenser installation is needed to consume significant VARs to correct system voltage issues, the underexcitation limiter may be disabled in the excitation controls altogether. If the excitation is lost due to an abnormal event or fault on the excitation circuit during an intentional motoring scenario, the condition cannot be directly detected via field current. More sophisticated excitation system installations can be configured to detect this condition via its voltage regulator. When the regulator does eventually attempt to push more current to increase VAR output, it will trigger an alarm state that trips after a set time delay. NERC compliance documentation should identify this type of protection if it exists.

Use of a loss of field (LOF) impedance element can also be used to detect faults on the excitation circuit. However, when applying this protection on a unit with the UEL disabled, it may be possible for the normal underexcitation conditions of the condenser to cross into the element operating region. It is thus recommended to supervise the element with an undervoltage relay, set at 90% to 95% of rated voltage, to prevent unwanted tripping during underexcited conditions [6]. This supervision leverages the fact that the conditions under which a controller would operate the synchronous condenser in an underexcited (VAR sinking) mode would be during a system overvoltage. If there is a true loss of field, there will not be a corresponding overvoltage.

A P-Q and R-X diagram plot of dual mho LOF protection plotted against the synchronous condenser capability curve is shown in Figure 3 and Figure 4, respectively. Note the cross-over of the condenser's underexcited region into the Zone 2 element. NERC compliance documentation should identify whether the element is secured by an undervoltage element in this scenario, satisfying Requirement R1.1.2. One or both plots should be kept as evidence for PRC-019 compliance.

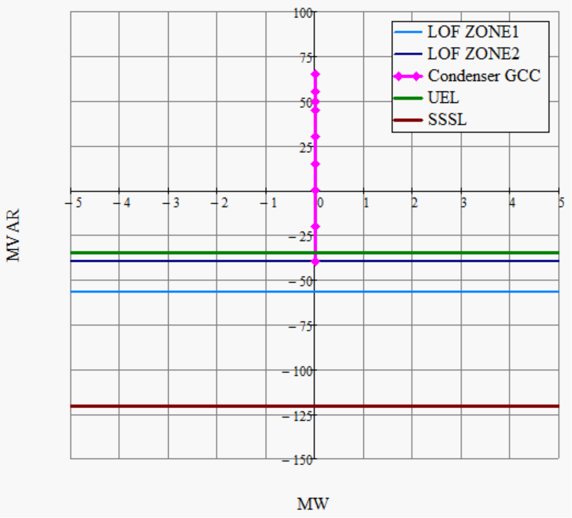

Figure 3 - P-Q Diagram for Capabilities, Limiters, and Protection

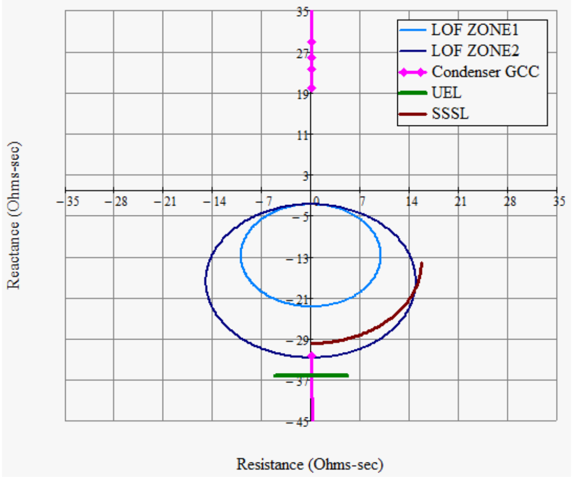

Figure 4 - R-X Diagram for Capabilities, Limiters, and Protection

The plots in Figure 3 and Figure 4 also depict the steady state stability limit (SSSL). SSSL is defined as the limit to synchronous stability and is characterized by a synchronous generator's direct axis (X_d) and the equivalent source's reactance (X_s) between the generator terminals and system, including the step-up transformer impedance. Fundamentally, if the power transfer between a generator and the system exceeds the maximum power transfer angle of 90°, the generator will slip a pole and risks going out-of-step with the system. An out-of-step condition can result in high currents and damage to the generating unit, as well as unwanted protection operations elsewhere in the system. Note that out-of-step conditions can also occur in synchronous motors if load torque requirements exceed available system power transfer.

Conversely, a synchronous condenser has no prime mover or load connected to its rotor. As such, there are no external forces to cause a pole slip as the machine free spins to follow the grid frequency. While synchronous condensers may not be completely immune to transient instability, they are significantly more resilient than synchronous generators. The traditional synchronous generator SSSL may not reflect the actual stability limit of a synchronous condenser, however, the PRC-019 standard does not currently make any distinction on what types of synchronous machines the SSSL applies to. Additionally, the PRC-019 technical reference does use the SSSL in their application examples. For these reasons, it is recommended to include it in coordination plots.

B. Field Overexcitation Limiter / Protection

To prevent thermal damage to the rotor field windings of a generator, the excitation system should have a field overexcitation limiter and protection setup that directly monitors the field current. IEEE Standard C50.13-2014 defines a minimum rotor thermal limit requirement for synchronous generators rated 10 MVA and above, defined in the equation below in percent of the machine rated current [7]. This limit has been traditionally used to coordinate against the limiter and protection as a conservative threshold.

$$I_{C50.13} = 100\sqrt{\frac{33.75}{t} + 1}, for\ t = 10 \dots 120\ s$$

Although synchronous condensers are not specifically mentioned in the standard, they are similarly constructed and are even included as part of its scope for the active IEEE C50.13 working group. NERC's PRC-019 technical reference also uses the same rotor thermal limit to show coordination with condenser overexcitation protection. For these reasons, it is recommended to use this thermal limit equation to demonstrate coordination in the absence of manufacturer specific data. Modern synchronous machine designs can be built with significant overload capabilities [8], so justification from the manufacturer should be included as evidence for PRC-019 if limiter or protection elements do not coordinate with the thermal limit curve.

Field excitation protection is typically set in the form of inverse-time overcurrent elements set in the excitation controls. To meet requirements of PRC-019, the overexcitation protection (trip) curve should be completely underneath the thermal limit curve when plotted on a time vs. current graph. The limiter curve should similarly be underneath the trip curve. If the excitation system includes a hot-backup field source and controller, it may have an additional overexcitation transfer curve. When this transfer curve is triggered, the field source and controller are switched to their backups. This action may prevent an unwanted protection trip operation if the primary field source or controller are failing to limit field current increases. The transfer curve should thus be above the limiter curve, allowing the primary controls a chance to reduce field current, and below the trip curve to potentially avoid condenser disconnect.

A plot depicting the above coordination is shown in Figure 5, which should be kept as evidence for PRC-019 compliance.

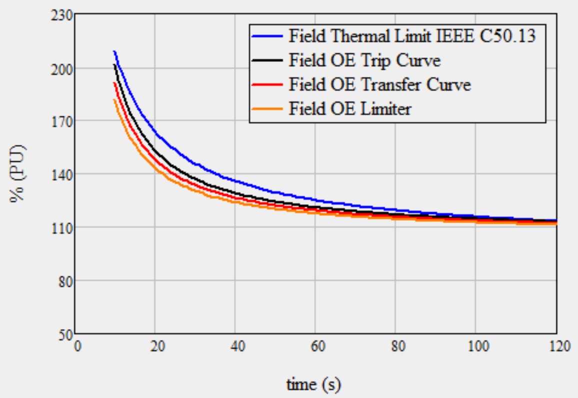

Figure 5 - Field Overexcitation Coordination Plot

C. Condenser Overexcitation Limiter / Protection

Overexcitation of a synchronous condenser occurs when the ratio of the voltage over frequency on the machine stator exceeds its capabilities. During this condition, stray flux generated may cause eddy currents in the machine laminations and overheating that can break down insulation. Volts per hertz (V/Hz) protection should be set in excitation controls and/or the protective relaying for the condenser to prevent this from occurring. The V/Hz capability curve of the condenser should be obtained from the Owner or the manufacturer to ensure proper coordination.

V/Hz protection is typically set in the form of inverse-time elements, definite-time elements, or combinations of the two. To meet requirements of PRC-019, the V/Hz protection (trip) curve should be completely underneath the V/Hz capability curve when plotted on a time vs percent V/Hz graph. The limiter curve should be underneath the trip curve. Like the field overexcitation protection, if the excitation system includes a hot-backup field source, it may have an additional V/Hz overexcitation transfer curve. The transfer curve should be above the limiter curve, allowing the primary controls a chance to reduce field current, and below the trip curve to potentially avoid condenser disconnect. Note that synchronous machines usually can operate continuously overexcited with a V/Hz of 1.05 PU, and if an overexcitation capability curve is not available, an existing installation may utilize a two-step definite V/Hz limiter and protection scheme for ease in setting. A more robust scheme is a combination of a short-time definite-time V/Hz element and a long-time inverse element which better utilizes the machine capability.

An example plot depicting the above coordination is shown in Figure 6, which should be kept as evidence for PRC-019 compliance.

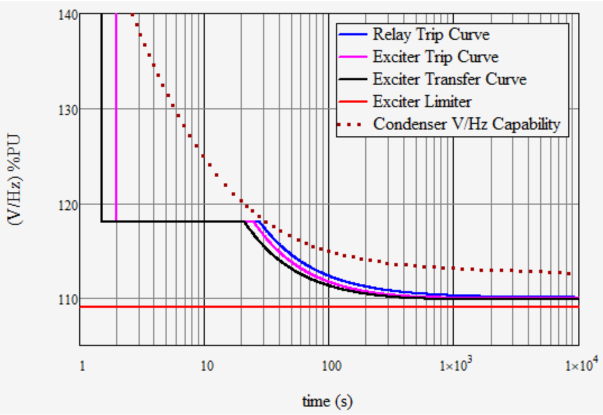

Figure 6 - Condenser Overexcitation Coordination Plot

D. GSU / UAT Overexcitation Protection

V/Hz overexcitation can also occur in the generator step-up (GSU) transformer and unit auxiliary transformer (UAT) associated with the condenser unit. V/Hz can similarly be set in the form of inverse-time or definite-time elements and should be coordinated to the V/Hz capability curve of the units. An example plot depicting this coordination for a GSU is shown in Figure 7, which should be kept as evidence for PRC-019 compliance.

Note that when reviewing this coordination, consideration should be taken of the plant or facility topology and tripping schemes. If operation of the GSU or UAT protection results in the unwanted disconnect of nearby condensers, generators, or critical system components in addition to the unit it is feeding, coordination with the condenser protection may be necessary. This can occur if multiple units share a single GSU, or if multiple GSUs share a high side bus without high side breakers available. Limiting the loss of additional units is in keeping with the spirit of NERC and its standards. Figure 7 includes the condenser V/Hz protection to demonstrate coordination for these cases, and should be noted in the PRC-019 documentation. It is common to combine this plot with the condenser V/Hz protection plot in Figure 6.

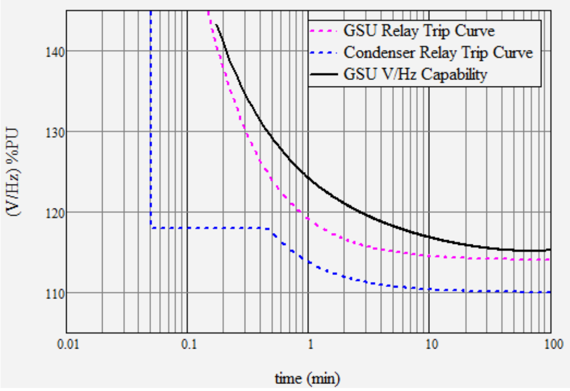

Figure 7 - GSU Overexcitation Coordination Plot

CONCLUSION

As the modern electric grid evolves with the increased penetration of renewables and inverter-based resources, along with the decline of fossil fuel-based generation, grid inertia is becoming less available. Synchronous condensers offer a unique solution, providing voltage regulation through dynamic VAR control with the added benefit of inertia inherent to a rotating machine to improve system stability. Condensers are similar to synchronous generators but have no prime mover and can operate well into their underexcited region. This presents some unique challenges for setting protection elements and demonstrating NERC PRC-019 standard compliance.

PRC-019 provides examples for demonstrating compliance for synchronous generators within the standard and some supplemental NERC literature touches on PRC-019's application to synchronous condensers. However, none of this documentation addresses atypical control curves you may find for tailored condenser applications and direct guidance on the coordination of synchronous condenser control and protection functions is not easy to find. This paper provides a guide for applying PRC-019 to condensers to meet compliance requirements. Proper coordination between the excitation system's limiter, transfer, and protection elements against the machine capabilities must be demonstrated and documented as evidence of compliance, and any manufacturer data discussing atypical capabilities and operating regions should be referenced and retained.

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BIOGRAPHIES

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