Integrating Inverter-Based Resources into Low Short Circuit Strength Systems

Reliability Guideline

December 2017

RELIABILITY | ACCOUNTABILITY

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Preface

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

The North American BPS is divided into eight Regional Entity (RE) boundaries as shown in the map and corresponding table below.
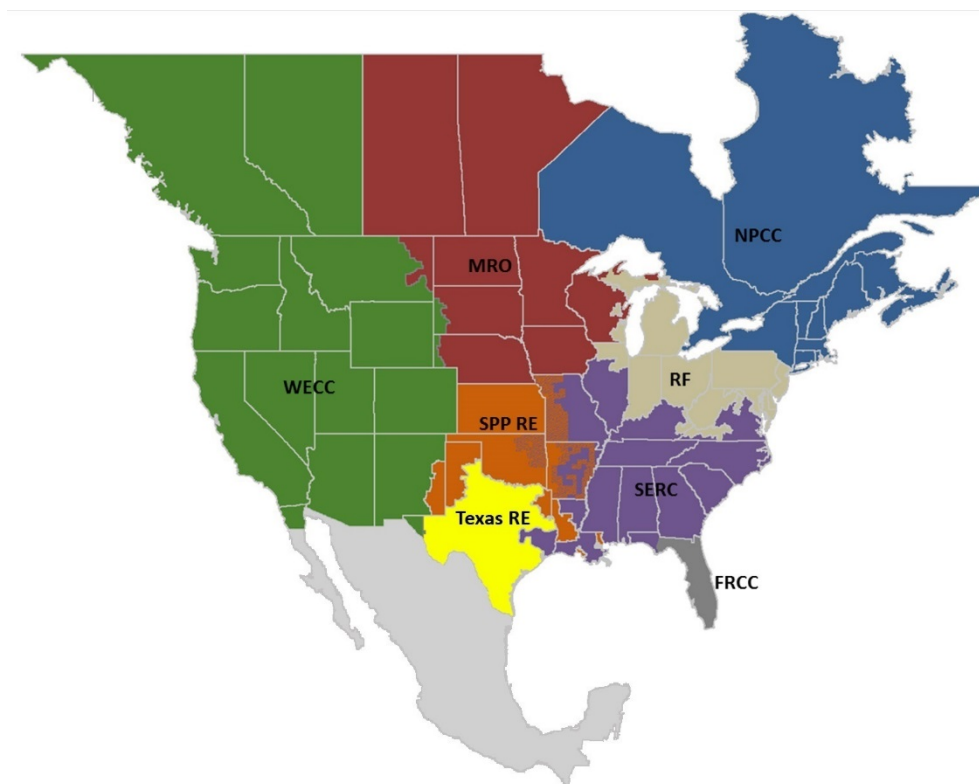
The North American BPS is divided into eight RE boundaries. The highlighted areas denote overlap as some load-serving entities participate in one Region while associated transmission owners/operators participate in another.

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

Preamble

NERC, as the FERC-certified Electric Reliability Organization (ERO),[1] is responsible for the reliability of the Bulk Electric System (BES) and has a suite of tools to accomplish this responsibility, including but not limited to the following: lessons learned, reliability and security guidelines, assessments and reports, the Event Analysis program, the Compliance Monitoring and Enforcement Program, and Reliability Standards. Each entity, as registered in the NERC compliance registry, is responsible and accountable for maintaining reliability and compliance with the Reliability Standards to maintain the reliability of their portions of the BES.

It is in the public interest for NERC to develop guidelines that are useful for maintaining or enhancing the reliability of the BES. The NERC Technical Committees—the Operating Committee (OC), the Planning Committee (PC), and the Critical Infrastructure Protection Committee (CIPC)—are authorized by the NERC Board of Trustees (Board) to develop Reliability (OC and PC) and Security (CIPC) Guidelines per their charters.[2] These guidelines establish voluntary recommendations, considerations, and industry best practices on particular topics for use by users, owners, and operators of the BES to help assess and ensure BES reliability. These guidelines are prepared in coordination between NERC Staff and the NERC Technical Committees. As a result, these guidelines represent the collective experience, expertise, and judgment of the industry.

The objective of each reliability guideline is to distribute key practices and information on specific issues to support high levels of BES reliability. Reliability guidelines do not provide binding norms and are not subject to compliance and enforcement (unlike Reliability Standards that are monitored and subject to enforcement). Guidelines are strictly voluntary and are designed to assist in reviewing, revising, or developing individual entity practices to support reliability for the BES. Further, guidelines are not intended to take precedence over Reliability Standards, regional procedures, or regional requirements. Entities should review this guideline in conjunction with Reliability Standards and periodic review of their internal processes and procedures, and make any needed changes based on their system design, configuration, and business practices.

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[1] http://www.ferc.gov/whats-new/comm-meet/072006/E-5.pdf
[2] http://www.nerc.com/comm/OC/Related%20Files%20DL/OC%20Charter%2020131011%20(Clean).pdf
  http://www.nerc.com/comm/CIPC/Related%20Files%20DL/CIPC%20Charter%20(2)%20with%20BOT%20approval%20footer.pdf
 http://www.nerc.com/comm/PC/Related%20Files%202013/PC%20Charter%20-%20Board%20Approved%20November%202013.pdf

Acknowledgements

Executive Summary

The electric utility industry is undergoing a rapid change in the way the bulk power system (BPS) is planned and operated, predominantly driven by a changing resource mix and increasing penetration of renewable energy resources such as wind and solar. One aspect of this change is the growing use of newer technologies, such as wind plants, solar photovoltaic solar plants, and battery energy storage systems that are asynchronously connected to the grid through a power electronic interface. As a group, these types of resources are commonly referred to as inverter-based resources or non-synchronous resources. The changing resource mix not only affects dispatch and essential reliability services such as voltage control, frequency response, and ramping, but also affects grid dynamics and controls. Grid planners and operators are faced with addressing these engineering issues as more of these resources connect to the grid.

Grid strength is a commonly used term to describe how "stiff" the grid is in response to small perturbations such as changes in load or switching of equipment. While strong grids provide a stable reference source for resources, weak grids can pose challenges for connecting new resources and particularly for connecting inverter-based resources. These resources rely on an adequate grid strength (relative to the size of the resource) for synchronizing the power electronics. In addition, inverter-based resources do not provide significant levels of fault current. While these issues alone do not pose a reliability risk, existing control, and protection paradigms need to be adapted to accommodate these changing characteristics from the generation fleet.

This guideline provides the electric utility industry with background and useful reference information pertaining to the topics of identifying weak grid conditions and potential issues that may arise from weak grids when connecting or operating inverter-based resources. The goal of this guideline is to proactively provide the industry with information to consider as these types of issues emerge for increased penetrations of inverter-based resources.

Key takeaways discussed throughout this guideline include:

- **Increasing Penetration of Inverter-Based Resources and "Weak Grid" Conditions:** Inverter-based resources (e.g., wind and solar) continue to be a significant component of new generating resource additions. As the resource mix and technologies interconnecting to the BPS continue to evolve, the electric power grid will undergo changes. Utility-scale, inverter-based resources are often located in areas of the BPS with relatively sparse transmission and few synchronous generating resources; and are generally considered "weak" parts of the system due to their low short circuit strength relative to the size of the interconnected inverter-based resources.

- **Need for Enhanced Coordination and Communication:** The most important aspect of identifying and mitigating issues with inverter-based resources in a weak grid is coordination and communication between the Transmission Planner (TP), Generator Owner (GO), and manufacturer of the inverter-based resource. Increased coordination between these entities will help ensure any weak grid issues that may arise can be addressed and mitigated effectively.

- **Inverter Controls Affected:** The control systems of a vast majority of inverter-based resources rely on the voltage magnitude and angle at their terminals to not be largely affected by the current injection of the resource for stable operation. In this context, electrical system strength refers to the sensitivity of the resource's terminal voltage to variations of current injections. In a "strong" system, voltage and angle are relatively insensitive to changes in current injection from the inverter-based resource, while this sensitivity is higher in a "weak" system.

- **Short Circuit Ratio (SCR) Based Metrics:** The SCR metric is most appropriate when considering a single inverter-based resource interconnecting to the BPS. It does not account for the presence of other inverter-based resources or power electronic-based equipment. Additional SCR-based metrics have been developed

by industry to address the presence of multiple inverter-based resources, and should be considered accordingly for each system being studied. Each SCR-based metric has potential benefits and drawbacks in its application that are discussed herein. In general, SCR-based metrics should be used by planners, manufacturers, and developers to obtain a high level understanding of area system strength. The relative impact the inverter-based resource (s) will have on the larger power system is assessed with more detailed studies using specific knowledge of the equipment (from the manufacturers and developers) and the network (from the planners) to confirm whether the plant will work correctly.

- **Weak Grid Issues:** A number of issues may manifest under weak grid conditions. These issues may include anything from classical voltage instability to control instability and control interactions. Examples of these types of issues are provided in this guideline to raise industry awareness of the issues and means by which to study these issues. The most important aspect of identifying and mitigating these issues is coordination and communication between the TP, GO, and manufacturer of the inverter-based equipment.

- **Planning Considerations:** TPs need to ensure accurate and representative models are available to perform grid reliability studies, including inverter-based resources. Planners are recommended to use the screening methods outlined in this guideline to identify areas where weak grid conditions may be a concern. Once these areas are understood, modeling requirements should be put in place that clearly define the types of models, list of acceptable models, and intended use of these models. Transient stability models may have limitations to model detailed inverter-response, particularly under weak grid conditions. Detailed electromagnetic transient (EMT) models may be needed to identify any weak grid issues that could arise.

- **Solution Strategies:** The TP, GO, and manufacturer have a number of exploratory solution options to mitigate potential weak grid issues that may arise for interconnecting inverter-based resources. These range from reinforcements or equipment that improve grid strength directly to enhancing inverter-based resource controls to enable more reliable operation under weak grid conditions.

Introduction

Inverter-based resources such as variable energy resources (VER) like wind and solar continue to be a significant component of new capacity additions. The cumulative additions of these utility-level resources to the North American power system surpassed 100 GW in 2016 (Figure 1.1). While wind has been the predominant renewable resource, solar capacity additions are rapidly growing in many areas of the BPS. As the resource mix and technologies interconnecting to the BPS continue to evolve, the electric power grid will undergo changes. Many of the large utility-scale renewable generating resources are not located near major load centers. These resources are often in areas of the grid with sparse extra high voltage (EHV) transmission backbone and few synchronous generating resources to provide short circuit current and grid strength. These parts of the grid are generally considered "weak" parts of the system for these reasons.
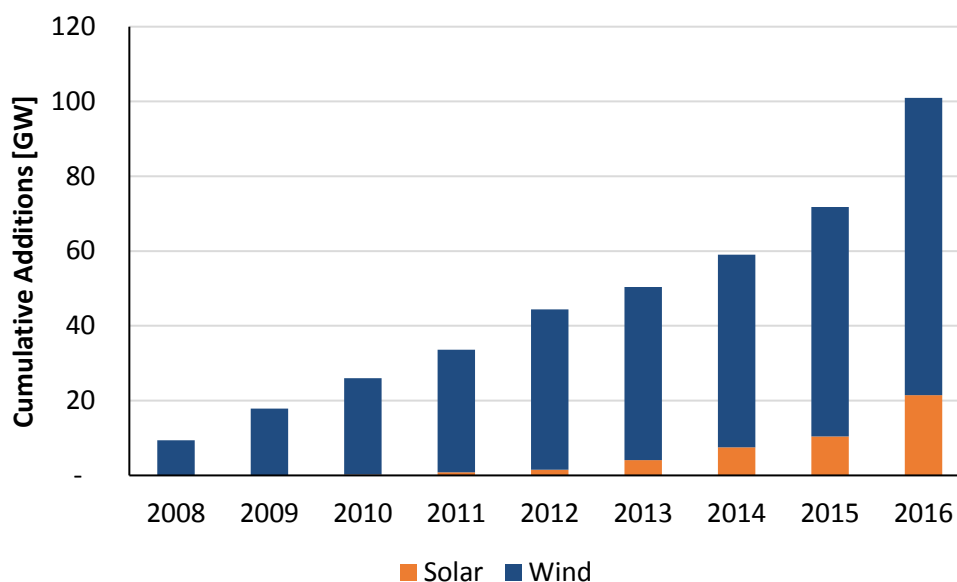
Figure 1.1: Cumulative Wind and Solar Additions (2008-2016)

There are engineering challenges when integrating inverter-based resources into weak electric systems. More common challenges that planners and operators have had to face include:

- **Transmission overloading:** need for higher capacity transmission in the local area to accommodate higher penetrations of inverter-based resources

- **Voltage profile or voltage deviation challenges:** additional reactive power compensation or inverter-based controls to ensure acceptable voltage profiles across the system and sufficient reactive power available following major grid events

- **Low short circuit ratio (SCR):** no significant short circuit sources driving need to ensure sufficient levels of current for fault clearing and generator protection

There are additional challenges that can occur when interconnecting inverter-based resources to weak parts of the BPS that are typically more complex and involve more advanced engineering analysis. A technical brochure was recently published by CIGRE WG B4.62, titled *Connection of Wind Farms to Weak AC Networks*, which describes some of these more advanced issues related to interconnecting wind power plants (WPPs). The purpose of this guideline is to highlight some of the key takeaways from the CIGRE technical brochure, in coordination with CIGRE and the subject

matter expertise that helped contribute to the brochure, and introduce some additional points that are relevant for the North American BPS. The focus is to provide utility planners, modelers, generation developers and owners, and operations engineers with useful experience-based information, tools, techniques, and recommendations around identifying weak grids and mitigating potential issues that could arise in weak grid conditions.

Qualitative Description of System Strength

Most inverter-based resources are interfaced with the BPS using power electronic converters. Examples include wind turbine generators (WTGs) with full converter technology (Type 4 WTGs), doubly-fed induction generators (Type 3 WTGs), and solar PV inverters. The vast majority of control systems for these resources rely on the voltage magnitude and angle at their terminals to not be largely affected by the current injection for stable operation. In this context, electrical system strength refers to the sensitivity of the inverter-based resource terminal voltage to variations of its current injection. In a "strong" system, this sensitivity is low; in a "weak" system, this sensitivity is higher.

> **Key Takeaway:**
> The control systems of a vast majority of inverter-based resources rely on the voltage magnitude and angle at their terminals to not be largely affected by the current injection of the resource for stable operation. In this context, electrical system strength refers to the sensitivity of the resource's terminal voltage to variations of current injections. In a "strong", voltage and angle are relatively insensitive to changes in current injection from the inverter-based resource, while this sensitivity is higher in a "weak" system.

Inverter-based resources connecting to a portion of the BPS with synchronous generation that is electrically close or relatively large is likely to be connecting to a strong system. If the size (rating) of resource connecting to this system increases or the electrical distance to the synchronous generation increases, then relative system strength becomes weaker. Technology and control advances in recent years has enabled certain inverter-based technologies to perform satisfactorily in these weaker systems. Regardless, system strength continues to be a useful and simple indication to anticipate potential performance issues and facilitate discussions with inverter-based resource developers and manufacturers regarding any identified issues.

A different definition of system strength is occasionally used to characterize the tolerance of system frequency to active power unbalances. While that aspect is relevant to BPS reliability, and is also an issue that will grow with increased penetration of inverter-based resources, it is not related to the subjects discussed in this guideline.

Variable Energy Resources

The predominant reason the issues highlighted throughout this guideline are more prevalent with variable energy resources is that these resources are connected to the grid through power electronic controls. Inverter-based resources offer faster, more advanced controls than synchronous machines, but the additional flexibility also adds a layer of complexity when it comes to ensuring their reliable operation when interconnected to the BPS. This section provides a high-level overview of the types of inverter-based resources[3] described throughout this guideline; in particular, Type 3 and Type 4 wind turbine generating plants and solar photovoltaic plants.

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[3] Battery energy storage systems are also inverter-based resources with full converter controls that are essentially the same as those in solar PV plants. These resources are not covered in detail in this guideline since the penetration of these resources on the BPS is relatively low (although growing).

Wind Turbine Generator Technologies

WPPs consist of many individual WTGs connected through a collector system to a WPP collector substation where the voltage is typically stepped up to same voltage as the BPS voltage in which it is connected to. The individual WTG ratings are usually in the range of 1 to 5 MVA, and are one of the four major technology types (Figure 1.2):

- Type 1: Fixed speed induction generator

- Type 2: Variable slip induction generator with variable rotor resistance

- Type 3: Variable speed doubly-fed induction generator

- Type 4: Variable speed full converter interface
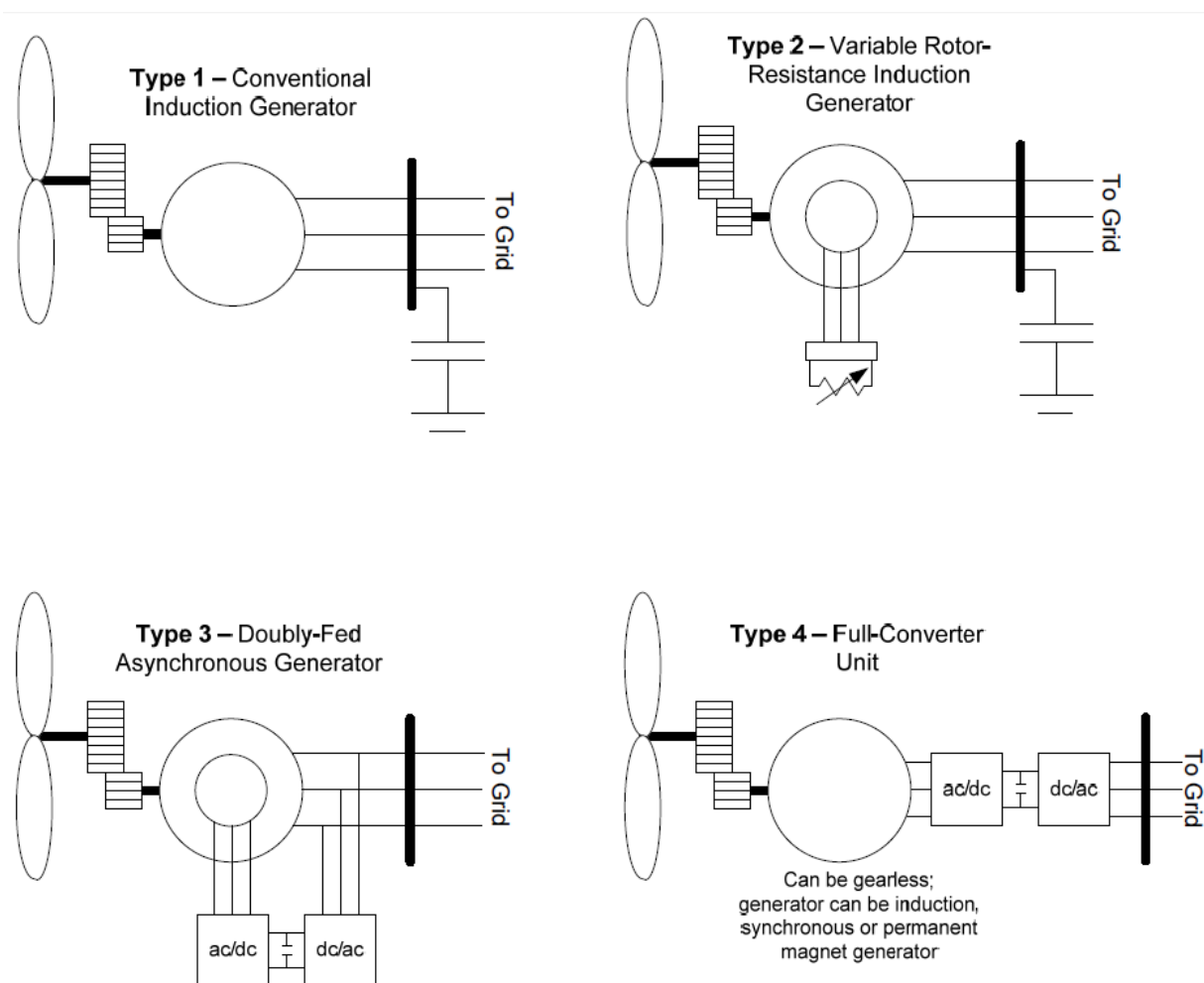
Figure 1.2: WTG Technologies and Grid Interfaces [Source: WECC[4]]

Type 1 and 2 WTGs are induction generators directly connected to the electric power system. Type 1 WTGs are induction generators with simple controls and a steep torque-speed characteristic so they operate at nearly constant speed and larger units use (relatively slow) blade pitch controls to aid in speed control. Type 2 WTGs vary the rotor resistance using power electronics. The (fast) rotor resistance control works with the blade pitch control to control speed, improve stability following disturbances, and reduce mechanical stress. It also helps smooth out voltage flicker caused by variable output, improving power quality. As induction generators, these WTGs consume reactive power

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[4] https://www.wecc.biz/Reliability/WECC-Second-Generation-Wind-Turbine-Models-012314.pdf

and require shunt compensation to meet power factor requirements at the point of interconnection (POI). While these technologies may still exist, they are relatively older technologies and are not typically being installed in the North American market.

Type 3 and 4 WTGs are connected to the grid through some form of power electronic interface that includes an AC-DC-AC conversion. This inverter interface and fast electronics allow for a much more flexible control of speed vs. torque, enables independent control of active and reactive power, provides more efficient conversion of kinetic energy to electrical energy, and enables these resources to support steady-state and dynamic voltage control. The stator of a Type 3 WTG is directly interfaced with the electric power system while the rotor is connected through a power electronic interface allowing for variable speed of the machine and fast control response. Type 4 WTGs are connected through a full AC-DC-AC interface, asynchronously isolating the WTG from the system. This requires the converter to be fully sized to the rating of the WTG the electric machine which may be an induction generation, synchronous generator, or permanent magnet generator that operates at variable speeds.

WPPs, particularly WPPs with Type 3 and 4 WTGs, typically have a plant level control strategy where each individual WTG has its own controls to ensure some level of speed-torque, aerodynamic, pitch, and converter controls, and an overall plant controller coordinates these turbine level controls to ensure overall stable operation of the entire fleet of WTGs. The plant level controls generally use a voltage or MW/MVAR reference and distribute active and reactive power set points to each individual WTG, allowing the entire plant to operate with the grid in a coherent way. Figure 1.3 shows a block diagram of the overall wind plant control functions and how they operate together.
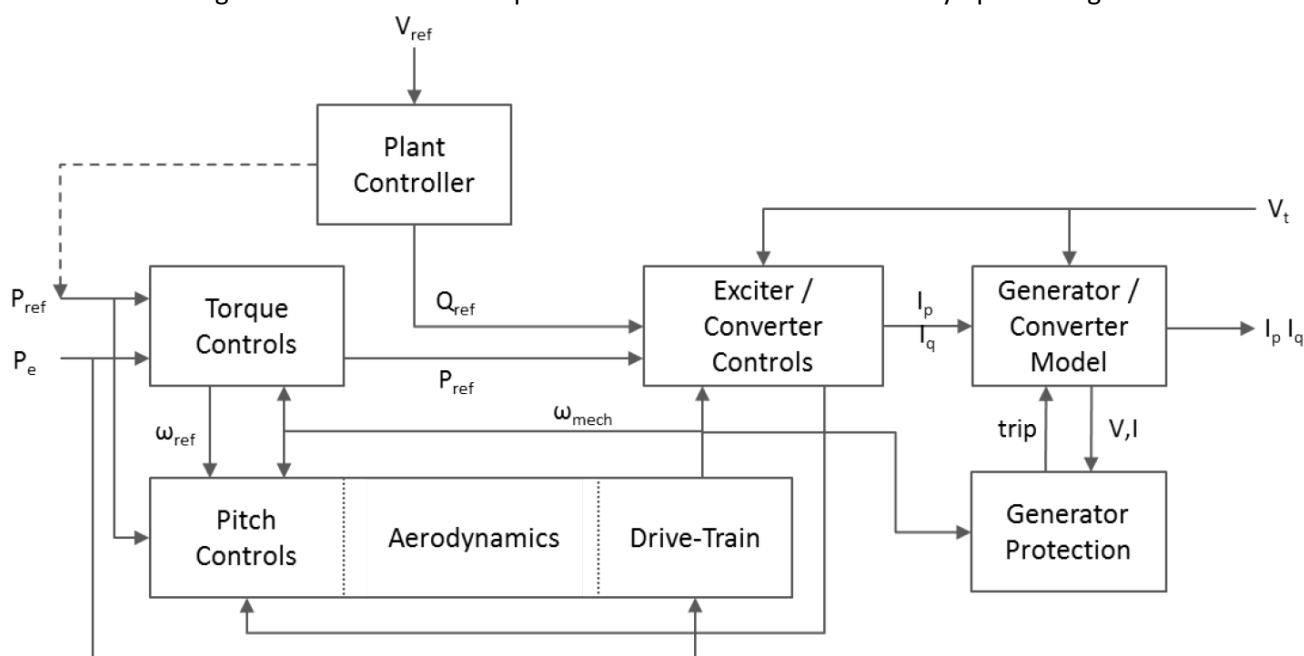
Figure 1.3: Wind Plant Controller Block Diagram [Source: WECC[5]]

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[5] https://www.wecc.biz/Reliability/WECC%20Wind%20Plant%20Dynamic%20Modeling%20Guidelines.pdf

Solar Photovoltaic Generator Technologies

Utility-scale solar PV plants are built and designed in a similar fashion to Type 3 and 4 WPPs in that they consist of many individual inverter-based resources aggregated up to a central plant-level control system. The PV arrays are connected to the grid by a DC bus connected through power electronics and an isolation transformer (Figure 1.4). Being fully electronic, these resources have significant control flexibility as a result of the capabilities of the power electronics driving the inverters. Similarly, solar PV technology does not involve rotating mechanical parts so any mechanical limitations of WPPs that may hinder their control capabilities are not present with solar PV resources. Plant-level controls operate in much the same fashion as a wind plant in sharing controls amongst the PV panels based on inverter capability, available irradiance, panel status, and grid operating conditions.
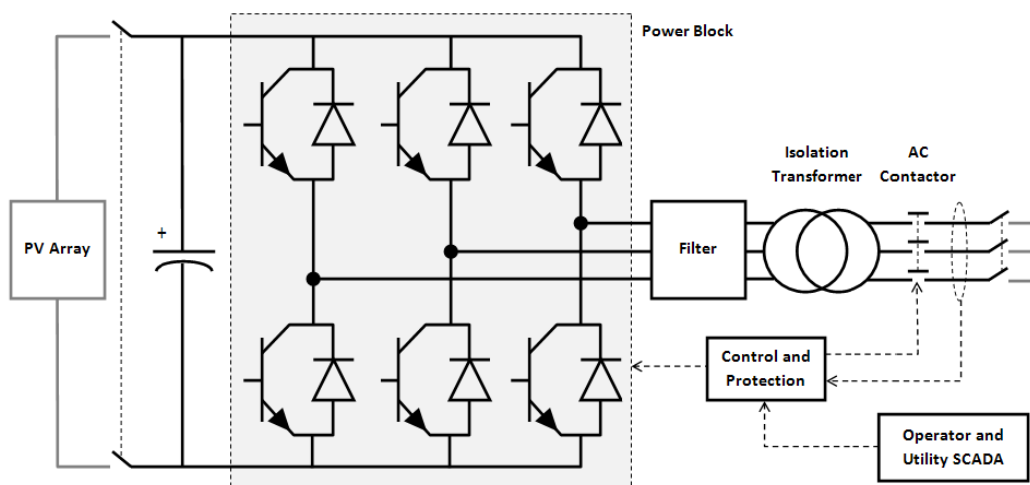
Figure 1.4: One Line Diagram of a Solar PV Plant [Source: WECC[6]]

Inverter-based resources are particularly susceptible to weak grid conditions for several reasons. First, they have little or no inertia in their mechanical systems to provide the synchronizing power inherent in more traditional generation forms. Their ability to provide expected real and reactive power is dependent on the electronic controls which separate the power source from the grid. These controls in turn depend on a stable voltage reference from the grid. As the system is weakened, the voltage reference becomes less stable, and control dynamics and tuning become increasingly influential on overall system behavior. The specifics of some of the issues that may be encountered and the reasons for them will be covered later in this guideline.

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[6] https://www.wecc.biz/Reliability/WECC%20Solar%20Plant%20Dynamic%20Modeling%20Guidelines.pdf

Chapter 1: Qualifying a Weak power System

The ability to identify "weak" systems helps to reliably plan and operate the BPS by understanding potential areas where weak grid issues could arise. Weak grids and the challenges associated with them are usually system-specific, making blanket interconnection standards or requirements often difficult to apply in a reasonable and fair manner. Therefore, it is often more appropriate for planners to use tools, techniques, and approaches to identify weak grid and determine if more detailed analyses are required for each interconnection or areas where weak grid issues and high penetration of inverter-based resources may occur. Similarly, it is important to understand, where applicable, the types of credible system conditions that could drive the grid into a weak condition and result in weak grid issues.

There are a number of different methods in which system strength can be quantified. Each method has its benefits and drawbacks, which are described briefly in the following sections. However, some of these metrics are useful screening tools to determine potential weak grid conditions or areas.

As described before, the strength of a system is associated to the sensitivity of the inverter-based resource terminal voltage to its current injection changes. Hence, the quantification of system strength is related to the equivalent impedance seen from resource's terminals into the BPS for small voltage variations during normal or contingency conditions. The indices described in this section can be calculated using short circuit programs to estimate these equivalent impedance values. It should be noted that these estimations are not related to the operation of the system during any particular short circuit condition.

Short Circuit Ratio (SCR)

The most basic and easily applied metric to determine the relative strength of a power system is short circuit ratio (SCR). SCR is defined as the ratio between short circuit apparent power (SCMVA) from a 3LG fault at a given location in the power system to the rating of the inverter-based resource connected to that location. Since the numerator of the SCR metric is dependent on the specific measurement location, this location is usually stated along with the SCR number.

$$SCR_{POI} = \frac{SCMVA_{POI}}{MW_{VER}}$$

Where $SCMVA_{POI}$ is the short circuit MVA level at the POI without the current contribution of the inverter-based resource, and MW_{VER} is the nominal power rating of the inverter-based resource being connected at the POI. This metric was developed as an aid in classical line-commutated converter (LCC) HVDC design, and is commonly used by the utility industry to quantify system strength. A low SCR area ("weak system") indicates high sensitivity of voltage (magnitude and phase angle) to changes in active and reactive power injections or consumptions. High SCR ("stiff") systems have a low sensitivity and are predominantly unaffected by changes in active and reactive power injection. The SCR metric is most appropriate when considering a single inverter-based resource operating into a relatively conventional power system (does not account for the presence of other inverter-based resources or power electronic-based equipment electrically close to the POI under study (e.g., other WPPs nearby)).

> **Key Takeaway:**
> The SCR metric is most appropriate when considering a single inverter-based resource interconnecting to a power system. It does not account for the presence of other inverter-based resource or power electronic equipment.

Other SCR-Based Metrics

SCR, as defined above, cannot be easily applied to understand the strength of a grid when multiple inverter-based resources are connected electrically close. More specifically, the use of SCR to estimate system strength for an inverter-based resource connected close to other inverter-based resources can lead to overly optimistic results. Several methods have been proposed to estimate system strength for groups of inverter-based resources connected electrically close. These are described briefly below for reference. Refer to the CIGRE technical brochure for more detailed examples.

Weighted Short Circuit Ratio[7] (WSCR)

The weighted short circuit ratio (WSCR) has been recently applied in Texas to assist in defining operational limits for total transmission of power from inverter-based resources across key power system interfaces. WSCR is defined as:

$$WSCR = \frac{\sum_i^N SCMVA_i * P_{RMW_i}}{\left(\sum_i^N P_{RMW_i}\right)^2}$$

where SCMVA$_i$ is the short circuit capacity at bus *i* without current contribution from non-synchronous generation and P$_{RMWi}$ is the MW output of non-synchronous generation to be connected at bus *i*. N is the number of wind plants fully interacting with each other and *i* is the wind plant index.

Composite Short Circuit Ratio (CSCR)

Composite short circuit ratio (CSCR) estimates the equivalent system impedance seen by multiple inverter-based resources by creating a common medium voltage bus and tying all inverter-based resources of interest together at that common bus[8]. The composite short circuit MVA at the common bus without current contribution from the inverter-based resources, CSC$_{MVA}$, is then calculated. CSCR can then be calculated as

$$CSCR = \frac{CSC_{MVA}}{MW_{VER}}$$

where MW_{VER} is the sum of the nominal power rating of all inverter-based resources considered. This method calculates an aggregate SCR for multiple inverter-based resources, rather than each resource like the conventional SCR approach.

Both the CSCR and the WSCR calculation methods are based on the assumption of strong electrical coupling between non-synchronous generation plants. This is equivalent to assuming that all non-synchronous generation plants are connected to a virtual POI. In practice, there is usually some electrical distance between each non-synchronous generation plant's POI, and the non-synchronous generation plants will not fully interact with each other. The CSCR and WSCR values obtained with this method will typically give a more accurate estimate of the system strength compared to SCR values when more than one inverter-based resource is present.

Short Circuit Ratio with Interaction Factors (SCRIF)[9]

Other methods have been proposed which more directly account for impedances between the considered plants. This is done either through impedance matrix manipulation, or calculated changes in voltage at all other locations when reactive power is injected at each location. Although this method is more rigorous and allows consideration of

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[7] Y. Zhang, S. H. F. Huang, J. Schmall, J. Conto, J. Billo and E. Rehman, "Evaluating system strength for large-scale wind plant integration," 2014 IEEE PES General Meeting, National Harbor, MD, 2014, pp. 1-5.

[8] Details related to connection of medium voltage buses of different voltages and specifics of using short circuit programs for these estimations are described in: *Report to NERC ERSTF for Composite Short Circuit Ratio (CSCR) Estimation Guideline*, GE Energy Consulting: Fernandes, R., Achilles, S., MacDowell, J., January 2015.

[9] This metric is titled "Equivalent SCR" in the Cigre brochure, which is distinct from the classical "Effective SCR" used in LCC HVDC design.

each individual wind plant in the presence of the others, it is more difficult to apply as a screening method (for example, on the back of an envelope), and may be more difficult to determine what actions should be taken when used as an area wide operating screening tool.

SCR with Interaction Factors (SCRIF) has been proposed to capture the change in bus voltage at one bus corresponding resulting from a change in bus voltage at another bus. Electrically close inverter-based resource buses will have a relatively higher Interaction Factor (IF) than inverter-based resource buses that are electrically separated. When multiple inverter-based resources are located very close to each other, they share the grid strength and short circuit level; hence, the grid strength is actually much lower than the overall short circuit level calculated at that bus or buses. SCRIF captures the voltage sensitivity between inverter-based resources as a screening tool for potential controls issues by using inverter-based resource interaction factors, as follows:

$$SCRIF_i = \frac{S_i}{P_i + \sum_j (IF_{ji} * P_j)}$$

Where IF is the change in bus voltage at bus i (ΔV_i) for a change in bus voltage at bus j (ΔV_j), as follows:

$$IF_{ij} = \frac{\Delta V_i}{\Delta V_j}$$

An advantage of the use of SCRIF is that it can be readily amended to cater for any conceivable configuration for connection of multiple inverter-based resources.

Application of Metrics using MW vs. MVA

SCR, WSCR, CSCR, and similar metrics should be carefully applied, understanding the assumptions and limits of each metric. For example, if a system is determined to be extremely weak, such that the inverter-based resource is likely to have a problem, the equation for SCR immediately presents several mitigation solutions. Increasing the SCMVA at the interconnection (increasing the numerator) directly increases SCR. Synchronous condensers, lower impedance transformers, and additional interconnecting transmission all increase the short circuit level and generally improve weak system behavior. Conversely, decreasing inverter-based resource output (decreasing the denominator) also directly increases SCR, and is also effective to improve weak system behavior.

However, in both cases care is needed. Adding synchronous condensers can introduce new modes of angular instability, and may also introduce protection and maintenance challenges. Reduction in active power from the wind plant (through curtailment) relieves stress on loaded lines and generally improves stability, but can leave a fully rated inverter (with associated voltage controls etc.) still actively connected to the same grid. Since SCR generally does not consider inverter capacity, but MW output, other inverter-based equipment such as static var compensators (SVCs) or flexible AC transmission system (FACTS) devices are generally ignored in these calculations, even though they also require a stable voltage for their own power electronic controls.

It is clear that disconnecting half of the units in an inverter-based resource plant may result in the same SCR increase as 50% active curtailment, the resulting electrical system is not the same and may respond differently in a weakened condition.

Key Takeaway:
The equations for SCR and other SCR-based metrics help illustrate why curtailment of inverter-based resources under weak grid conditions can be used as a mitigation strategy, particularly for temporary outage conditions. As the active power injection (or capacity) to the system increases, SCR and other metrics are reduced. By limiting the injection (or capacity) into the system, this may help increase SCR.

If applying such a metric as a generic operating procedure (for example, WSCR should stay above a given threshold), the threshold for WSCR calculated using MVA could be different from WSCR calculated using MW. In this case, the WSCR metric could be applied both in terms of MW and MVA, as expressed below.

$$WSCR_{MW} = \frac{\sum_i^N SCMVA_i * P_{RMW_i}}{\left(\sum_i^N P_{RMW_i}\right)^2}$$

$$WSCR_{MVA} = \frac{\sum_i^N SCMVA_i * P_{RMVA_i}}{\left(\sum_i^N P_{RMVA_i}\right)^2}$$

Comparison of SCR Methods

Each of the methods described in the preceding sections has benefits and drawbacks as a screening tool to identify weak grid conditions and potential issues with inverter-based resources. Table 2.1 provides an illustrative description of the similarities, differences, benefits, and drawbacks of these metrics[10]. The red 'X' represents that the metric cannot be applied for the described purpose. One star represents that the metric can be applied with some additional effort or processing, or can be applied to a limited extent, and two stars represents that the metric is easily or directly applied for these purposes.

Table 2.1: Comparison of SCR Methods							
Metric		Simple calculation using short circuit program	Accounts for nearby inverter based equipment	Provides common metric across a larger group of VER	Accounts for weak electrical coupling between plants within larger group	Considers non-active power inverter capacity*	Able to consider individual sub-plants within larger group
SCR	Short Circuit Ratio	★★	X	X	X	X	X
CSCR	Composite SCR	★	★★	★★	X	X	X
WSCR-MW	Weighted SCR using MW	★	★★	★★	★	X	X
WSCR-MVA	Weighted SCR using MVA	★	★★	★★	★	★★	X
SCRIF	Multi-Infeed SCR	X	★★	X	★★	★★	★★

* e.g., STATCOMs or partial power inverter-based resources

Each metric has benefits and drawbacks in its application for assessing system strength and potential weak grid issues. These may include:

- **Simple calculation using short circuit programs:** Metric utilizes positive sequence short circuit program for primary results. Some simple additional manipulation or post-processing may be required.

- **Accounting for nearby inverter-based equipment:** Metric inherently considers the presence of nearby inverter-based equipment, particularly if the equipment is very close.

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[10] Note that WSCR-MW and WSCR-MVA are separated here to illustrate that consideration of MW vs. MVA rated metrics may have different benefits; however, this concept applies to all the metrics listed below.

- **Common metric across large group of inverter-based resources:** Metric provides a single consolidated value for all the plants within the selected group.

- **Accounts for weak coupling between plants within larger group:** Metric is able to consider the isolating effect of impedance between inverter-based resource plants, or to consider that each plant may be obtaining system strength from different sources. (As opposed to assuming plants are perfectly coupled - essentially a single plant).

- **Considers non-active power inverter capacity:** Metric accounts for capacity of inverters nearby which may require a strong system, but do not generate active power. Examples could be curtailed wind plants, static compensators (STATCOMs), or SVCs.

- **Considers individual sub-plants within larger group:** Metric provides a system strength value at any number of individual buses within a group, accounting for the presence of the others.

Limitations of Screening Metrics

There are some critical limitations when SCR-based screening tools are used in power systems planning. First among these is the wide variety of problems which may be encountered under weak conditions. When the system is generally unable to support stable operation as well, the specific limits which will be encountered are very dependent on the precise nature of the interconnection. Specific control revisions within a vendor family of controls, specific system and outage conditions, and the precise nature of nearby equipment can all determine whether there will be a problem at a given SCR or not. The temptation for planners is to apply screening metrics in a general way to determine whether their system will operate correctly, while the reality is that weak system issues are usually not general but specific. Lower SCR typically increases the likelihood of issues, but often doesn't predict the exact mode of failure or the precise point at which system stability will be compromised. This uncertainty means that usually SCR-based metrics should be relegated to a high level of screening, and if specific knowledge is required regarding whether a given system will operate as expected, more rigorous study is required, often entailing EMT study tools.

Even when used purely as screening metrics, there is a temptation for planners to use SCR-based tools to set "minimum system strength" criteria. The danger with this is that as equipment and control technology evolves, or as different types of equipment are mixed, the appropriate threshold becomes perilously difficult to set correctly. What is "weak" for one manufacturer may not be a problem for another. What was "weak" for one manufacturer two years ago may no longer be difficult to achieve. The addition of a new piece of equipment may (through poor controls, for example) suddenly destabilize otherwise very well controlled existing equipment.

> **Key Takeaway:**
> While lower SCR typically increases the likelihood of potential issues with inverter-based resources, these methods should be used as a screening tool. Weak grid issues are system- and equipment-specific and it is difficult to define a "minimum system strength" criteria that can be applied uniformly. The equipment manufacturer should also be apprised of which SCR-based metric was used by the planning engineer.

Appropriate use of SCR-based metrics

In general, SCR-based metrics should be used by planners, manufacturers, and developers to obtain a high level understanding of the relative impact the interconnecting generator(s) will have on the larger power system. Based on that information, and combined with specific knowledge of the equipment (from the manufacturers and developers), and specific knowledge of the network (from the planners), further studies may be required to confirm whether the plant will operate correctly.

Chapter 2: Issues Associated with Weak Systems

A number of issues can occur under weak grid conditions. Once these potential conditions have been identified, it is useful to understand the different types of issues that have been observed and how these issues may be mitigated. All issues should be addressed in close coordination between the TP, Planning Coordinator (PC), GO, and manufacturer of the generating resources under consideration. These issues are relatively complex and this close coordination helps ensure all entities develop the most effective and efficient solution to the problem(s). This chapter provides an overview of some of the issues that may be encountered under weak grid conditions, particularly for inverter-based resources. Appendix B provides some illustrative examples of actual weak grid interconnection issues.

Classical Voltage Stability in Weak Grids

Weak grid issues have been addressed by transmission planning engineers in different aspects for many years. One relatively well understood aspect of weak grids is steady-state voltage stability, which relates to how much the system voltage changes (dV) relative to changes in real or reactive power flow (dP or dQ) across the network. The change in system voltage compared to real or reactive power flow (dV/dP or dV/dQ) are well known measures quantifying grid voltage stability. The amount of reactive loss in the network is proportional to the square of the current (I^2). The amount of voltage drop across the network is also based on the magnitude of current flowing through it. Network elements (e.g., transmission lines, transformers, and cables) are inherently lossy during periods of high power transfer due to their relatively high leakage and series reactance properties, ultimately lowering system voltage. During periods of lower demand, transmission line or cable shunt susceptance (also known as line charging) dominates and adds to the overall system reactive power supply, raising the voltage.[11]

When the grid is strong, there are a relatively large number of online synchronous machines providing a substantial amount of available short circuit current and reactive support to the network. In a strong grid, the system series impedance is relatively low and the voltage is relatively constant vs. load level. That is, as power flow increases in a strong grid, dV/dP and dV/dQ is small. However, a weak grid has a comparably small availability of short circuit current (either due to fewer online synchronous machines or a higher network impedance due to long transmission lines and multiple voltage transformations). This low short circuit availability causes higher dV/dP and dV/dQ sensitivity, and these sensitivities increase as the electrical network becomes weaker (i.e., higher risk of voltage collapse).

The increased active power variability of inverter-based resources, their connection to weak grid locations, and the nature of their inverter controls can result in potential weak grid issues that may not generally be studied (or as closely considered) as synchronous resources. Figure 3.1 shows two illustrations of grid strength and control modes and how they may impact voltage stability.

- The left figure illustrates the impact that control modes can have on grid performance in a relatively strong grid. For a given installed rating of the generating resource, the constant power factor (unity power factor in this example) is unable to maintain voltage as strongly as the same resource in voltage control mode. While this is expected, this is an important concept and similar to the requirements put forth in FERC Order 827[12]. In both cases, the voltage does not sag all that much in the strong grid case as load level is increased, but closed-loop dynamic voltage control of the POI and supply of reactive power to maintain voltages does a better job of supporting grid voltage during steady state operation. For inverter-based resource plants (as with any new generator following FERC Order 827[13]), closed-loop voltage regulation is an essential reliability service for the BPS.

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[11] Overvoltage issues at weak points of interconnection are often easily overlooked, in part because planning cases often do not represent actual light load conditions. Also, actual system voltage measurements may not be available until after a POI substation is constructed (for example looping a new POI substation into the middle of a long transmission circuit).

[12] See FERC Order 827 "Reactive Power Requirements for Non-Synchronous Generation", Docket No. RM16-1-000, June 16, 2016.

[13] Federal Energy Regulatory Commission, Order No. 872, 16 June 2016. Available: http://www.ferc.gov/whats-new/comm-meet/2016/061616/E-1.pdf

- The right figure illustrates the impact of power transfer on voltage in weak grids and how the different control points enable more active power transfer and a more stable local power system. The plot shows the PV curves under voltage control mode (green) and power factor control mode with various set points. As more power is transferred across the system in this weak grid scenario, dV/dP becomes larger. To support the grid voltage in these cases, shunt capacitor banks are switched on to discretely add reactive power and extend the power transfer capability, hence the spikes in the plots. Voltage control mode is able to stably support the most active power transfer across the system and also maintains a steady system voltage at higher power transfers. Conversely, power factor control mode at unity causes a quick degradation in system voltage for increased power transfer since the system requires an exponentially higher amount of reactive power for this case. Decreasing power factor levels (i.e., pf = 0.99, 0.98, 0.97) delivers more reactive power to the grid and result in high voltage conditions since the system is unable to accommodate the increasing reactive output at higher active power levels. In all power factor modes, the steepness of the PV curve and instability points are at relatively higher voltages than the voltage control mode.
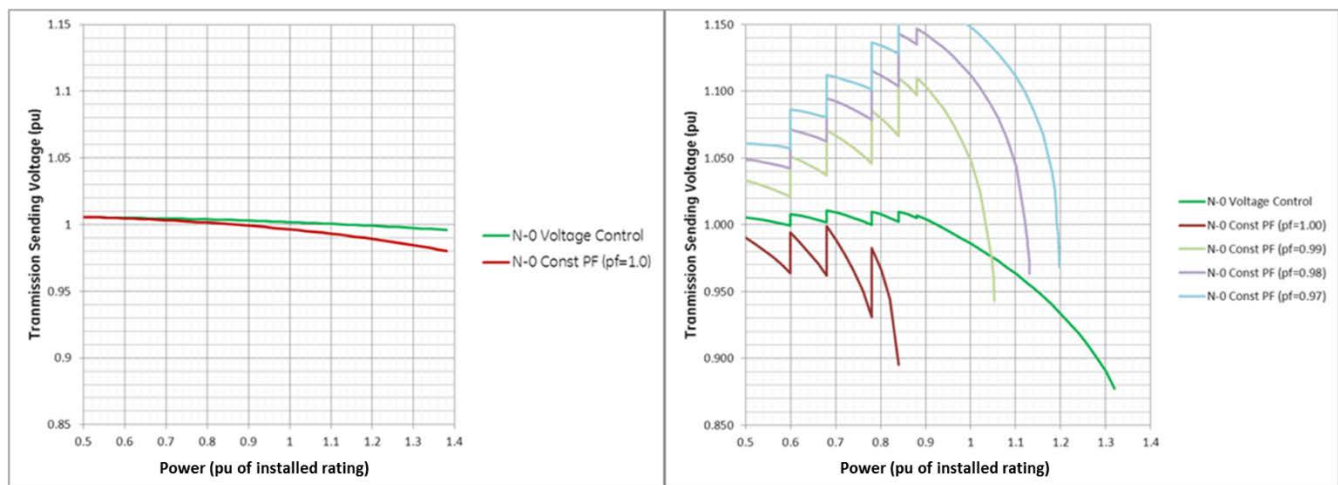
**Figure 3.1: Illustration of Grid Strength, Voltage Stability, and Wind Plant Control
[Source: GE]**

With inverter-based resources, output variability (e.g., changes in cloud cover or wind speed) may illuminate potential voltage issues that could arise in a classical voltage stability sense. Synchronous generation is typically held at constant active power output and ramped relatively slowly. Daily load changes can drive some instability issues, and those can be dealt with accordingly on a relatively slow basis. Individual inverter-based resources, on the other hand, can ramp output very quickly depending on available input power. This variability, coupled with the load profile, can exacerbate voltage stability risks. This can be further complicated by network topology changes, planned or forced outages, etc. While the system is planned for N-1 security, weak grid issues can materialize under a wide range of conditions, particularly under outage conditions. It is critical to have closed-loop voltage control for all grid-connected inverter-based resources, particularly in weak areas of the grid.

This issue of classical voltage stability is relevant and important to consider regardless of the source technology. However, it is not the only issue to be resolved. Separately, control stability is also an important issue to resolve in weak grids that have power electronic sources.

Control Interactions and Control Instability
Control interaction refers to any interaction of control systems between elements on the BPS. This term is typically associated with power electronic-based generation interacting with other power electronic resources such as generators and FACTS devices, but also conventional generation and non-power electronic-based devices such as

series capacitors or switched shunt devices. Control interaction is more prominent in weak grid areas because each device attempting to control a specific electrical quantity or point on the BPS has more impact on other devices. Conversely, in strong ("stiff") parts of the system, each device has little overall impact in changing that quantity and therefore little impact on other devices.
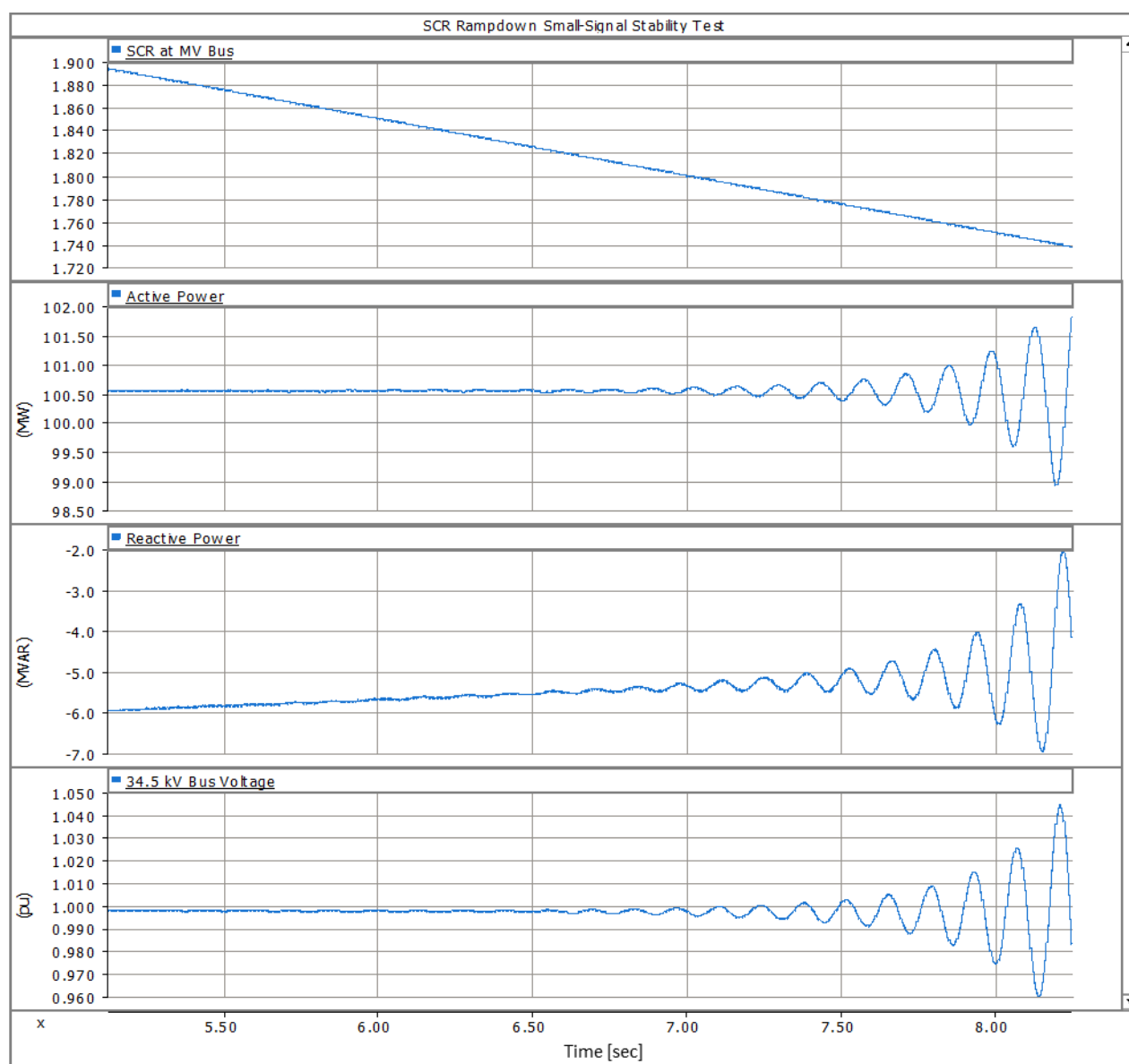
Control Instability

"Control instability" encompasses a broad spectrum of phenomena when applied in power systems, but one of the important modes of instability in weak systems relates to interactions between fast, high gain controllers of power electronic resources such as wind (Type 3 and Type 4) or solar plants and relatively high impedances connecting the resources to the power system. In general, the open loop gain as experienced by the interacting controllers is higher when they are connected and operated in weak AC systems, making them more susceptible to control instability (sometimes referred to as "small signal[14]" instability). These instabilities may result in growing or erratic oscillations that have negative consequences to grid reliability such as unit tripping, flicker or power quality concerns, and ultimately potential human safety concerns or damage to equipment. Small signal stability concerns such as these are usually functions of the linear control regions and the network impedance, and are often characterized by oscillations occurring in the absence of any disturbance.

Figure 3.2 shows an example of a wind turbine connected to a test system where the SCR is gradually decreased by increasing the impedance between the WPP and the simulated bulk system. At some point, every conventionally controlled wind plant will reach a minimum SCR, below which its controls will experience instability.

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[14] "Small signal stability" term is often used to describe electromechanical oscillations that occur between synchronous machines or groups of synchronous machines in the BPS. In this guideline, "small signal stability" is used differently and refers to instabilities or oscillatory behavior of fast controls in PV converters, WTGs, plant controls, or dynamic compensation equipment. In this case, the instability is triggered by small perturbations associated with normal operation of the BPS (line switching, capacitor/reactor operation, etc.).
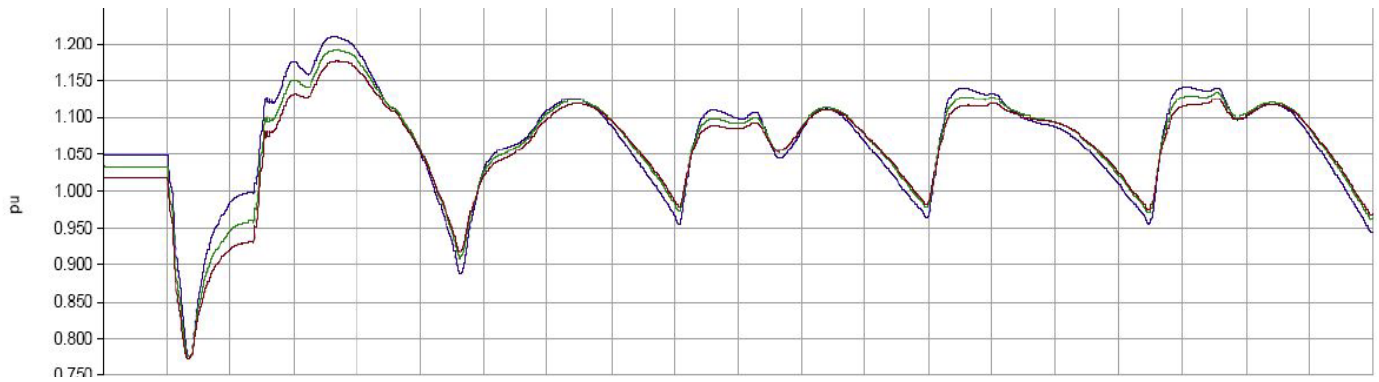
Figure 3.2: WPP Control Instability Example for Weak Grid
[Source: Electranix]

Other Modes of Control Instability

Other modes of instability become more common as the system is weakened, depending on specific control and protection configurations of individual plants. These can include non-linear controls or control-mode changes which activate during system disturbances or external events.

Figure 3.3 shows an example of control instability at a wind plant connected to a weak grid. Following a fault, the plant enters a separate ride-through control mode, where active power is reduced and quickly ramped back up following fault clearing. However, as the active power ramps, the reactive support available from the inverter is unable to support the voltage due to the high impedance between the plant and the larger grid, and voltage collapses. This causes the plant to re-enter ride-through mode and reduce its active power, which in turn allows the voltage to recover, and the cycle repeats, causing severe voltage oscillations to propagate through the system.

Figure 3.3: Example of Control Instability (Mode Cycling) at Wind Plant Connected to Weak Grid [Source: Electranix]
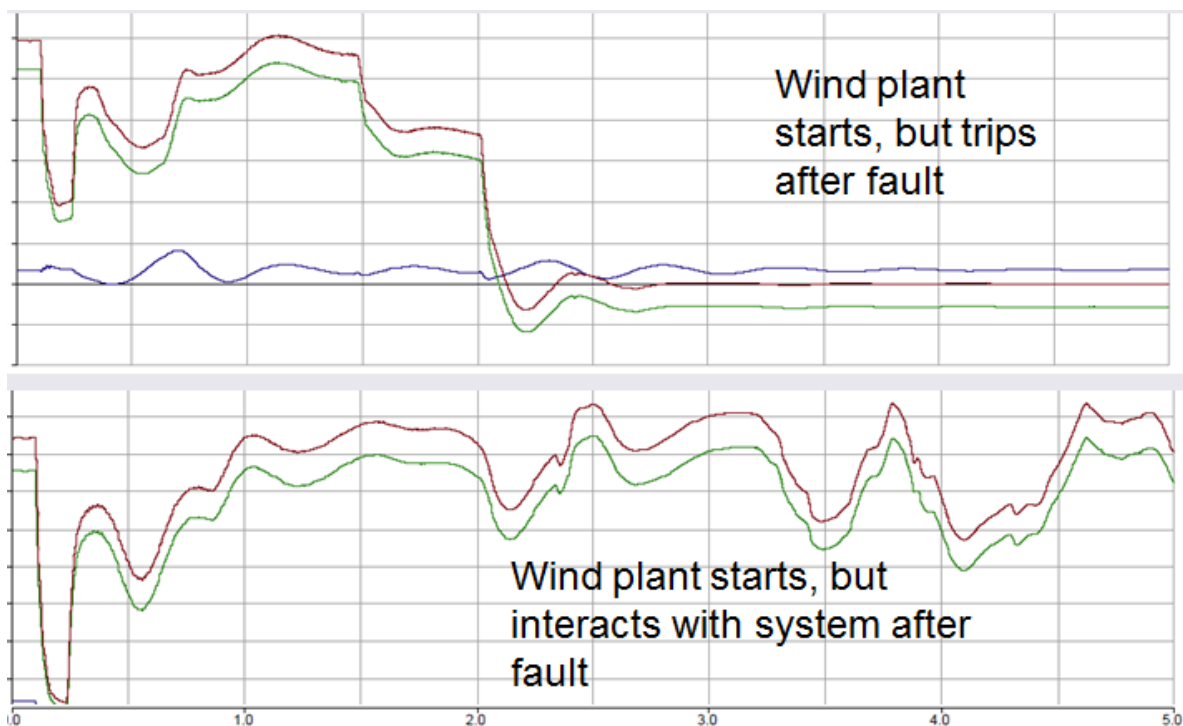
Figure 3.4 shows an example of control instability at a wind plant connected to a weak grid. Following a fault, the plant enters a separate ride-through control mode, where active power is reduced and quickly ramped back up following fault clearing, as in the prior example. However, the plant is unable to find a stable post fault operating point in the weakened system, and following several severe oscillations, the plant trips.

Figure 3.4: Example of Control Instability at Wind Plant Connected to Weak Grid [Source: Electranix]

These types of control interactions and instabilities are often not detectable using positive sequence simulation tools since these models usually do not represent the fast inner controllers that are responsible for the unstable modes. More complex studies using EMT tools may be required to identify control interactions or control instability for power electronic resources connected to weak grids. Furthermore, utilities with power electronic resources connected to weaker parts of the grid should be aware of these types of control interactions and should be proactive in identifying and mitigating these types of issues so as to ensure reliable operation of the BPS and avoid any unnecessary oscillatory behavior and/or plant tripping.

Disturbance Ride-Through Capability

Ensuring ride-through capability and coordinated controls during abnormal grid conditions is essential for effectively integrating inverter-based resources into weak grids. Two aspects related to ride-through include meeting Reliability Standard requirements related to voltage and frequency protective relays, as well as stability of the phase lock loop (PLL) and inverter-based resource response to any PLL issues.

Ride-Through Requirements

NERC Reliability Standard PRC-024-2 describes how generator protective relays should be set such that generating units remain connected during frequency and voltage excursions (see Figures 3.5 and 3.6). The curves specify a "No Trip Zone" where the BES resources should not trip within the specified time durations. Outside this specified region, BES resources may remain online to support grid reliability to the best extent possible. There is no explicit requirement for BES resource to trip; this is driven by plant protection requirements and local grid reliability issues.

Within the "No Trip Zone", resources are not permitted to "trip" or disconnect from the grid. Inverter-based resources typically incorporate a Momentary Cessation ("block") mode where they cease to supply current to the grid. Inverter-based resources should support the grid during fault conditions by supplying active and reactive current to the best extent possible within their inverter capability. Momentary cessation should be used as sparingly as possible, and current injection should resume immediately following fault clearing in most cases. The concept of momentary cessation contradicts the general intent of PRC-024-2 to ride through abnormal conditions to continue operation and injection of active and reactive power (according to grid conditions and unit capabilities). The misinterpretation of PRC-024-2 standard requirements by asynchronous resources warrants a revisiting of PRC-024-2 to clarify these issues[15].

Balancing the contribution of active and reactive current with the grid needs of voltage and frequency response may require detailed studies of inverter capability and coordination with the inverter-based resource manufacturer. While, in general, priority should be given to reactive current to ensure local voltage stability and maintaining voltages within acceptable limits during the transient timeframe and post-contingency steady-state, this should be coordinated between the TP, PC, GO, and manufacturer. Any inverter momentary cessation should be reserved for severe fault (zero voltage) conditions, and inverters should be capable of fast resumption of active and reactive power control once the fault condition has been cleared, depending on the energy and frequency requirements for the area. Manufactures should design their equipment such that it reliably supplies current to the grid within the "No Trip Zone" of the PRC-024-2 ride-through curves. Any local interconnection requirements should be met in addition to the PRC-024-2 requirements.

Voltage and frequency ride-through is critical under weak grid conditions for the following reasons:

- Weak grids experience a high sensitivity of voltage to changes in power (i.e., higher dV/dP, dV/dQ), and are more prone to potential voltage collapse conditions. Attempting to push active current during low voltage conditions could further degrade system voltage and result in collapse. Reactive current should be given priority during fault conditions in these weak grid conditions; however, studies should ensure that reactive current contribution during fault conditions does not cause voltage overshoot or other problems that could trip the inverters.
- Weak grids are indicative of a lack of synchronous generators or transmission in the local area. Tripping of inverter-based resources during abnormal voltage and frequency excursions would further exacerbate issues of grid support.

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[15] See the Disturbance Report developed by a NERC/WECC task force to explore fault-induced solar loss events. Available: http://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf.

- Tripping of inverter-based resources could result in high voltage conditions due to loss of power transfer, which could result in cascading outage of inverter-based resources and further voltage rise.
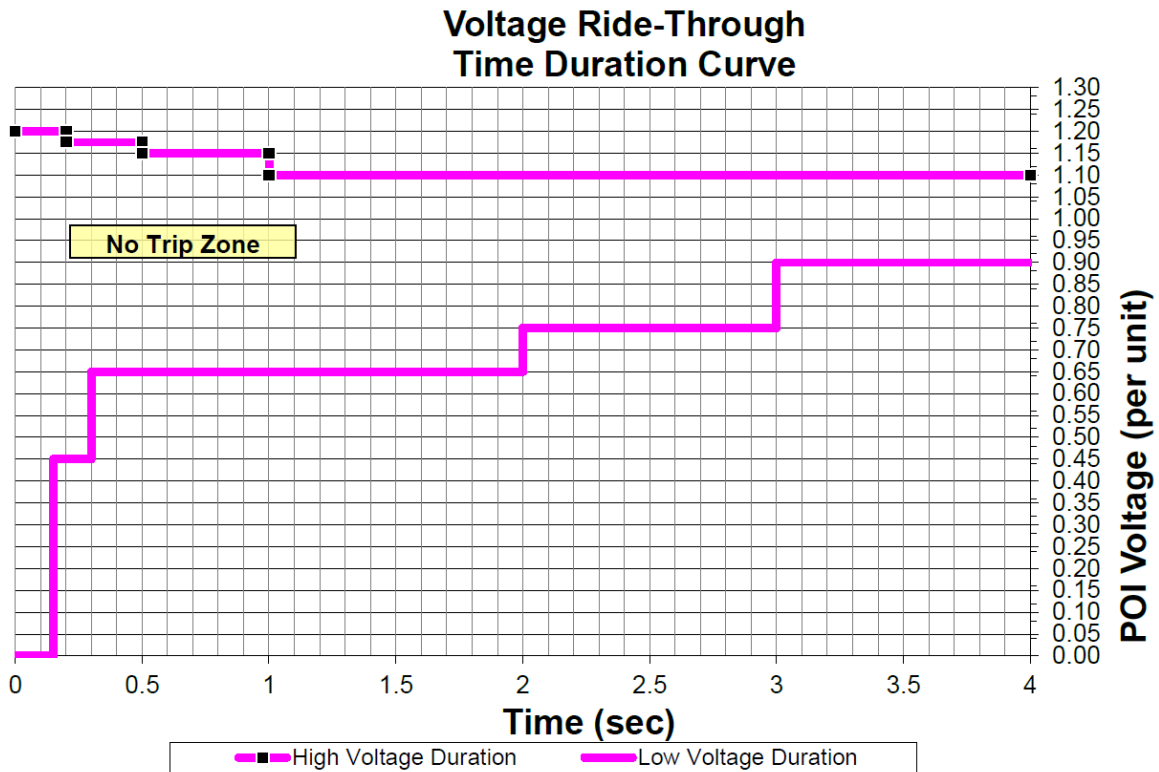

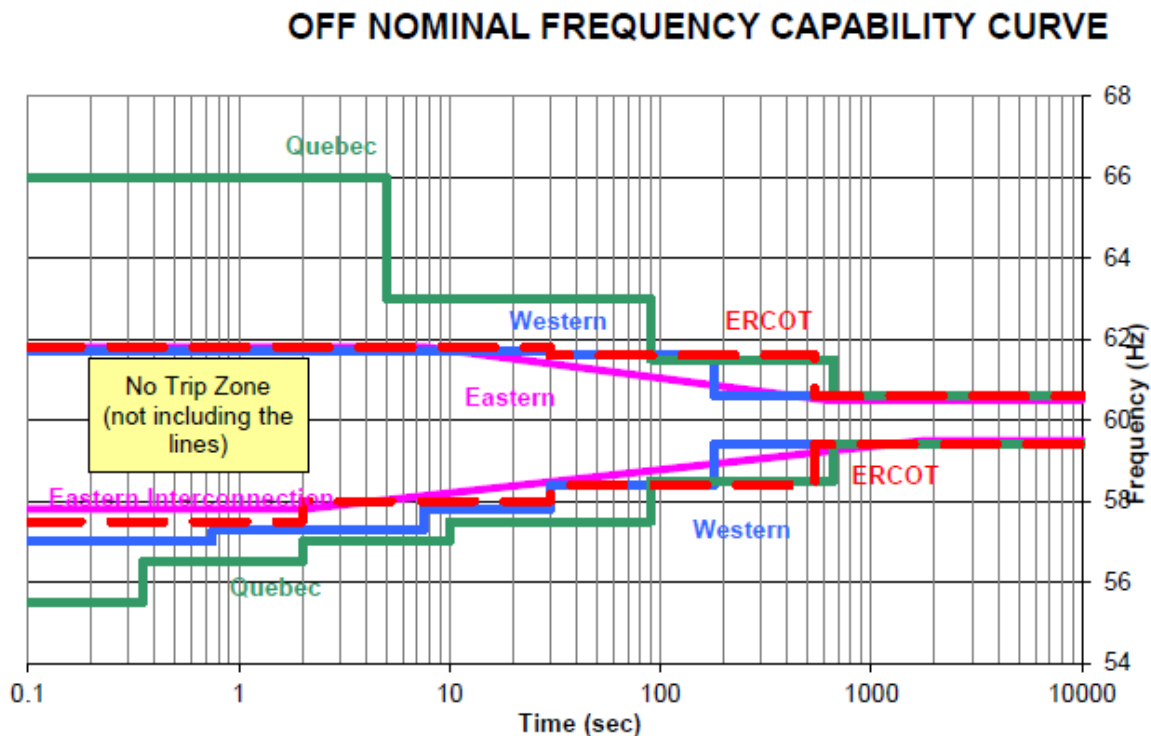**Figure 3.5: PRC-024-2 Voltage Ride-Through Curve**

Figure 3.6: PRC-024-2 Frequency Ride-Through Curve

Phase Lock Loop Stability

The majority of inverter-based resources use a PLL to synchronize to the grid. Figure 3.7 shows a generic inverter schematic and how the PLL is a key component of the overall control system between the network and the inverter. The inverter operates in a "grid following" fashion by deriving the grid phase and frequency using a closed loop control system (Figure 3.8). The PLL voltage phase estimation is used to derive the d- and q-axis voltages and currents that are fed to the control algorithms. Similarly, the PLL voltage phase estimation is used to convert the control action (i.e., converter modulation) from d-q to phase quantities. Inaccurate PLL system voltage phase angle results in inaccurate control of the inverter-based resource active and reactive power. Following clearing of a fault, the PLL should regain synchronism sufficiently fast in order to control reactive power to maintain system voltage. In the short period (1-2 cycles following a fault), this critical PLL function becomes even more difficult in weak systems, as the phase angle may have shifted drastically, and the post fault voltages may be especially noisy. Inverter manufacturers should ensure PLL stability and the ability to withstand large changes in phase that are typically experienced under EHV fault conditions. Actual PLL functionality is often considered by manufacturers to be proprietary information, supported by internal research. However, this consideration should also be balanced against the requirement for TPs to understand the characteristics of the resources connected to the BPS. Transient stability models do not represent the PLL in detail, and this is a major limitation for studying integration of inverter-based resources in weak systems. This issue supports the need for appropriate models to perform detailed EMT studies for weak grid conditions.

> **Key Takeaway:**
> The PLL is used to synchronize to the grid using a fast closed loop control system. The PLL estimates voltage phase and derives d- and q-axis voltages and currents fed to the control algorithm. These controls are typically not modeled in the generic positive sequence models used for bulk grid studies. However, some detailed positive sequence models may include a PLL control system representation. Future work may explore incorporating some form of PLL logic into the generic models. EMT modeling can capture PLL dynamics in much more detail.
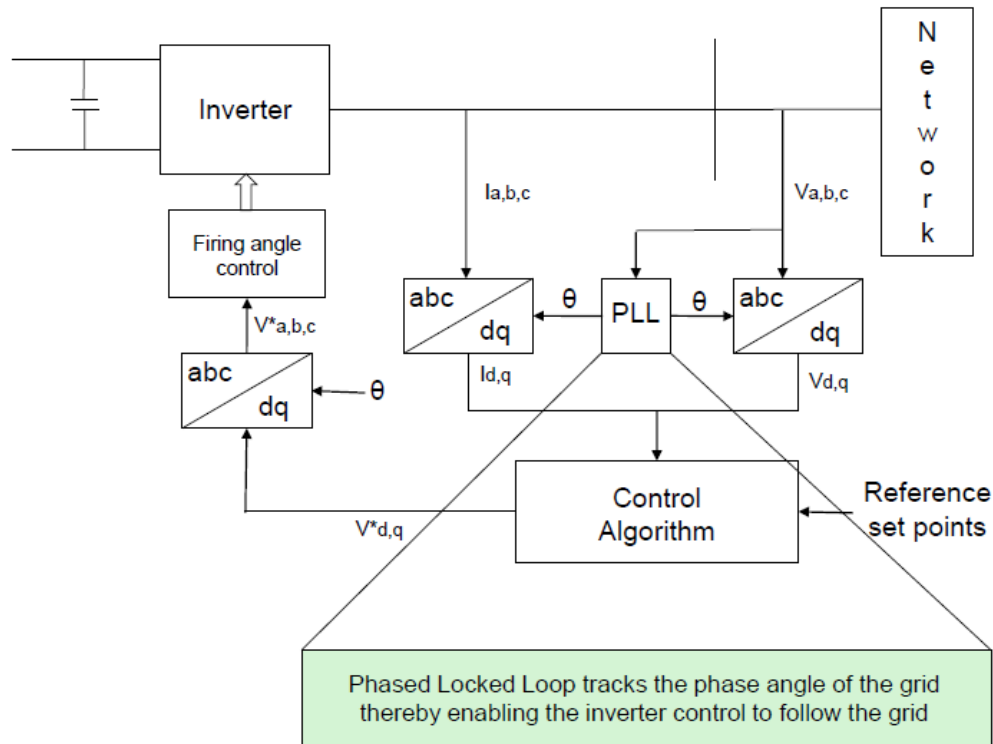

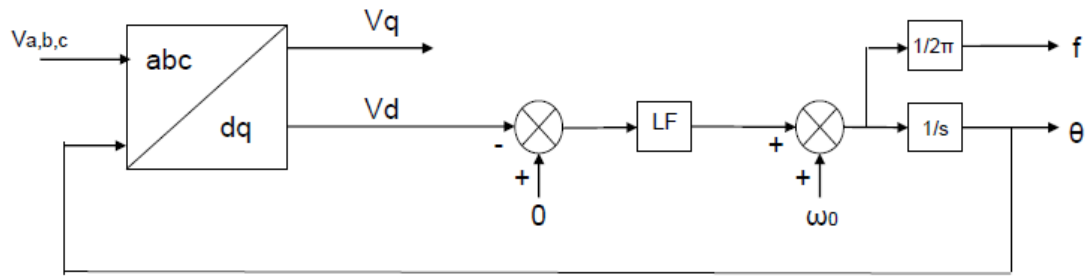**Figure 3.7: Generic Inverter Control Schematic [Source: EPRI]**

Figure 3.8: Common PLL Structure – Synchronous Frame [Source: EPRI]

Chapter 3: Planning Study Considerations

The following sections describe useful considerations that TPs and PCs should make when studying integration of inverter-based resources to the BPS.

Transient Stability Limitations

Transient stability simulation tools are widely used in planning applications to evaluate stability of the BPS. These tools are effective in predicting disturbance response, generator stability, voltage stability, load dynamics, and many other phenomenon for most applications. However, as the penetration of inverter-based resources grows and the prevalence of weak grid interconnections becomes more important, these tools may encounter limitations which should be well understood by those who use them. Some considerations that should be made with respect to weak grids studies using transient stability tools include:

- **Validity for Phenomena Slower than 5 Hz:** "Transient stability programs use simplified generator models ignoring the dynamics of stator flux. In addition, the transmission network is modeled using a constant bus admittance matrix calculated for the power frequency. Due to these simplifications, any oscillations above the range of electromechanical oscillations (up to 5 Hz) produced by a transient stability program are not reliable."[16] Subsynchronous phenomena or harmonic effects due to switching or controls are not accurately represented using these models.

- **Positive Sequence-based:** Positive sequence RMS quantities are typically calculated in these tools. The effect of DC current components, as well as zero and negative sequence components are usually neglected in these calculations. Some of the limitations of these approximations are commonly understood for unbalanced conditions (for example, the negative sequence aspects may become relevant for evaluating limitation of overvoltages in unfaulted phases during unbalanced faults). Zero sequence aspects may not be critical because the transformer connection group in the inverter-based systems often isolates the zero sequence system in the inverter-based resource from the BPS, but this may require additional review.

- **RMS-based:** Phasor-based tools require that the power system electrical quantities be represented as 3-phase rms quantities. The operation of protection systems is highly dependent on how measurement is modeled; there may be limitations in transient stability tools on measurement delays. Measurement, in general, must be approximated in these models, as the rms quantities are inherent to the transient stability tools (instantly available), while in the real controls they must be calculated from phase quantities. Additionally, the unique individual phase dynamics implicit in a severe contingency event such as a fault may not be captured, and this can result in different behavior from control elements which use these phase quantities, such as instantaneous phase-based protection circuits and synchronization controls (PLL details).

- **Large simulation time step:** A typical power electronic converter contains control loops and algorithms with very fast response times – faster than can be represented with the relatively large simulation time steps used in transient stability programs. These control loops include PLL controllers and inner current loop controllers, are often key drivers of instability modes in weak systems (such as small signal instability modes), and govern the ability of the plant to maintain synchronism and quickly provide grid support. If a smaller time step in the transient stability tools can more accurately represent the controller, then the time step may be reduced for the simulation; however, this may cause numerical issues with the simulation and the time step often cannot be reduced to a sufficiently small interval to capture the dynamics necessary for weak grid stability studies.

- **Convergence issues:** The iterative nature of the transient stability and powerflow calculations can be challenging in weak systems, manifesting in convergence problems as the system becomes very weak. This

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[16] WG B4.62, "Connection of Wind Farms to Weak AC Networks," Cigré Technical Brochure 671, December 2016.

aspect in some cases is driven by limitations of specific models and not the tool itself, but can prevent proper analysis.

- **Limited converter electrical representation:** Depending on the sophistication of the model, internal converter electrical representation is simplified. For example, the converter DC bus (including associated bus voltage protections, choppers, and controls) may be assumed to be infinitely strong. Likewise, interfaces and controls relating to the inverter-based resource energy source are often approximated or ignored, where these elements can in some circumstances influence the converter behavior.
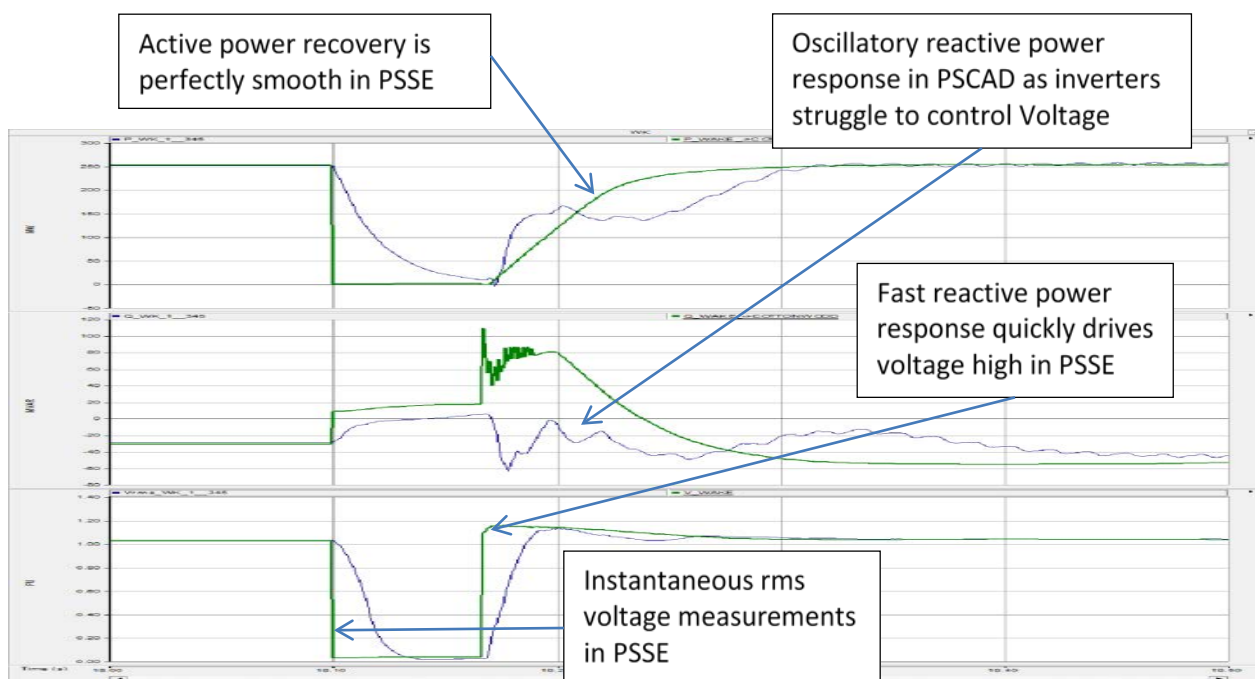
Figure 4.1: Comparison of Fault Response between Transient Stability and EMT Models (Modified from public ERCOT Panhandle Study Report) [Source: Electranix, ERCOT]

Key Takeaway:
The above approximations typically result in increasing differences between the positive sequence, phasor-based simulation methods, and the EMT simulations as the system strength becomes lower. This can lead to misrepresentation of ride-through performance, false stability evaluations, or failure to predict control interactions.

Manufacturers of modern inverter-based equipment have in some cases gone to considerable lengths to overcome some of the above limitations and often use creative approximations to provide the best possible representation of their specific equipment using user-defined models. However, for some phenomena these tools are not appropriate, and as interconnecting systems become very weak, most manufacturers will recommend using EMT tools to confirm equipment behavior or validate the transient stability results.

Electromagnetic Transient Models

In very weak system interconnections, planners and manufacturers may deem more detailed analysis to be necessary using EMT simulation tools. EMT simulation programs have in common a key distinction from phasor-based transient stability models. Power-flow and transient stability programs iteratively solve a system of equations to satisfy a set of constraints in the phase domain. EMT software solves systems of differential equations which describe the three-phase electrical network in the time domain, allowing unbalanced faults, harmonics, fast transients, and other effects to be modeled. In addition, extremely high levels of detail may be used in modeling the fast controllers which are

used in real equipment converters, capable of capturing the very fast time constants used in current controls and switching algorithms. In many cases, the actual firmware code used in the power electronic devices may be inserted as-is into the model, eliminating most modelling approximations and approaching perfectly accurate control representation under transient conditions.

If it is determined that EMT studies are required, this very high level of detail is necessary, as the control modes which lead to the weak system issues described above are critically dependent on the specific control implementation (including PLL, inner current controls, specific protection implementation, etc.). Use of "generic" or "typical" EMT models is usually not recommended, as they cannot predict with accuracy the specific issues which may be encountered. If conventional transient stability models are not sufficiently accurate, detailed EMT models are required.

> **Key Takeaway:**
> Use of "generic" or "typical" EMT models is usually not recommended, as they cannot predict with accuracy the specific issues which may be encountered. If conventional transient stability models are not sufficiently accurate, detailed EMT models are required.

In some cases, it is useful to validate transient stability models using detailed EMT models (particularly in systems which are "marginally weak"), to provide justification to the planners that their standard transient stability models and studies are accurately predicting performance.

An example set of requirements for EMT models is shown in Appendix A.

Study Model Recommendations

The increasing penetration of inverter-based resources and potential weak grid issues drives the need for TPs to understand where weak grid conditions may be a concern and ensure accurate and representative models are available to study the impacts inverter-based resources may have on grid reliability, and vice versa. Planners are recommended to use the screening methods outlined in this guideline to identify areas where weak grid conditions may be a concern. Once these areas are understood, modeling requirements should be put in place that clearly define the types of models, list of acceptable models, and intended use of these models. The following concepts should be considered when developing these requirements:

- **Generic Positive Sequence Stability Model:** A generic model used for interconnection-wide modeling should be required for every resource seeking interconnection to the BES. Generic models are expected to accurately represent the general dynamic behavior of the inverter-based resources, and should be benchmarked to more detailed models by the manufacturer, to the best extent possible. These generic models should be part of the standard model library within the commercial software platforms, and should also conform to the data requirements specified by the TP and PC under NERC Reliability Standard MOD-032-1.

- **Detailed Positive Sequence Stability Model:** Interconnection stability studies (e.g., System Impact Studies) should use the most detailed model available for the study being performed. These studies are often positive sequence transient stability analyses. Detailed models from the inverter-based resource manufacturer should be provided for these studies to ensure stability and security of the BES prior to connection of these resources. It is very important that these models be developed to a sufficient quality, with appropriate documentation, to allow for dependable use in system studies.

- **Electromagnetic Transient Model:** In the event that a weak grid condition has been identified, or a possible weak grid condition may occur in the future, EMT models should also be required from the GO. The EMT models should follow the considerations listed in Appendix A.

Sharing EMT models usually requires confidentiality agreements between the manufacturer and data owners and users. These types of models are used for detailed local studies; however, the data sharing and software support for these models create challenges from an interconnection-wide modeling perspective. Transient stability models

typically do not have the same degree of confidentiality restrictions (i.e., user-defined transient stability models may still require a confidentiality agreement). Hence, these models, particularly the generic models, are used for larger system modeling purposes.

Chapter 4: Coordination and Potential Solution Options

There are a number of potential solutions that can be considered and deployed to address weak grid conditions. Some of the solutions can mitigate the weak grid condition from occurring entirely. Others help support the integration of inverter-based resources under the weak grid conditions. In either case, the potential reliability risks described previously can be minimized. Similar to the weak grid issue, the solutions deployed are dependent on the system characteristics for each inverter-based resource interconnection, as well as the manufacturer capabilities of the inverter-based resource. Coordination and engagement with the manufacturer is critical to identify the best solution for each potential given weak grid issue.

Manufacturer Involvement

Manufacturers play an integral role in the design of WTG and plant performance and should be incorporated into any discussions around weak grid conditions. The most important aspect of identifying and mitigating issues with inverter-based resources in a weak grid is coordination and communication between the TP, GO, and equipment manufacturer. Increased coordination between these entities helps ensure any weak grid issues that may arise can be addressed and mitigated effectively. The following considerations are useful when interacting with manufacturers:

- **Short Circuit Thresholds:** The manufacturers should understand what a "weak grid" is for their equipment and controls, and should be able to clearly articulate this to the TP. TPs should request documentation and demonstration that the equipment to be installed on the system can meet the performance specifications under the expected low short circuit levels. The manufacturer may need additional information to understand how the SCR-based metric was used and applied. Detailed EMT simulations or comparable manufacturer information should be provided to the TP to clearly illustrate that the PV converter or WTG product has a stable performance in similar system strength conditions. This should include the ranges of system strength that the equipment can tolerate and operate as designed (e.g., ride-through). Prior to commercial operation and as part of the planning evaluation, TPs should have an understanding of the controls design, expected performance, and demonstrated results showing this performance. TPs should not simply ask for the 'acceptable' SCR level from manufacturers; rather, a bidirectional engineering conversation should address these considerations.

- **Control Design:** Operation of inverter-based resources in weak grid conditions can be an important consideration in the control design for manufacturers. In the design process, manufacturers evaluate the capability to comply with performance requirements with different system strengths for predefined product configurations. It should be noted that at the product design stage, the specific BPS topology and characteristics of all future inverter-based resource applications with this product are unknown. In this context, manufacturers can characterize applications with system strength levels that are well covered within the design processes. For example, strong and weak system strength may be well within the design verifications.

- **Additional Inverter-Based Resource Studies:** Manufacturers may also suggest low system strength levels where additional inverter-based resource application studies may be required to complement the product performance design verifications. For example, for very weak system strength, a manufacturer (or TP) may recommend to evaluate the performance in a detailed EMT study, particularly early in the interconnection process.

- **Performance Requirements:** There is no industry standard for what strong, weak, or very weak system strength means. This characterization is useful for comparison with the design criteria of the product under consideration. The different control technologies used in the industry can result in a wide range of capabilities related to weak grids. Early dialogue with the manufacturers related to the application characteristics will typically reduce potential weak grid issues.

It is recommended that planners, developers, and consultants characterize the system strength of an inverter-based resource application and discuss with the manufacturer potential performance concerns. The analysis and product configuration to mitigate issues integrating inverter-based resources into very weak grids requires understanding of the power electronic controls and capabilities, operational understanding of how the plant will perform, and understanding of the specific equipment used in each application.

Key Takeaway:
TPs, PCs, and GOs should coordinate with the manufacturer of the inverter-based resource to characterize the system strength, understand potential performance concerns, and develop necessary solutions. Manufacturers should ensure that their equipment will reliably operate during potential weak grid conditions. Further, the TP and PC should ensure sufficient justification from the manufacturer that any potential weak grid issues have been addressed prior to interconnection.

Potential Solution Options

Potential solution options to mitigate issues associated with weak grids include:

- **Synchronous condenser:** Synchronous condensers are often the primary solution for weak grid issues, primarily due to the multifaceted benefits from these resources. Some of the benefits include large capability to supply fault current (higher short circuit capacity), increased system inertia, voltage capability and improved voltage stability, and other power quality improvements. This solution is particularly useful in situations where synchronous resources are being retired (or being considered for retirement) since there are a number of options that can be explored. New synchronous condensers can be installed or the existing unit(s) may be able to be used as synchronous condensers.

- **Plant Control Changes:** In some cases, changes to the plant control system(s) may alleviate weak grid issues. Time constants and gains may be adjusted to reduce the risks of unstable response under weak grid conditions. Voltage control strategies such as reactive droop can be deployed to minimize inter-plant control interactions. These changes are system specific and should be determined in close coordination between the TP, GO, and manufacturer. The evaluation of these changes can be time consuming, and may not be a viable option in the timeframe needed for maintaining grid reliability (e.g., interconnection study process, necessary maintenance outages, etc.).

- **Converter Control Changes:** In some cases, changes to the power electronic controls in WTG or PV converters may alleviate weak grid issues. These changes can consist of modifications to control parameter values and/or modifications to the control structures. These modifications may require complex engineering efforts, but can avoid the need to add equipment to the project. Not always weak grid issues can be fully addressed with converter control changes. In some cases the required changes may be significant and impractical modifications to the selected products. Terminal voltage control or PLL enhancements are examples of potential control modifications in weak grid systems. These changes should be determined in close coordination between the TP, GO, and manufacturer.

- **Reduction in Plant Capacity or Power Output:** Short circuit ratio and potential negative impact of an inverter-based resource can have on the BPS can be improved by either reducing the plant capacity or limiting plant output. As the capacity or output reduces, the SCR will increase; similarly, any sensitivities to active or reactive power output will be reduced by the reduction in plant capacity or output. Other solution options may be more applicable in the planning stages; however, this may be the only viable short-term solution if weak grid conditions are encountered in real-time or near real-time. Restricting plant output under specific operating conditions may be used as a bridge strategy until a longer-term solution such as reinforcement or controls improvements can be implemented. In cases where the SCR is so low that the transfer of power is

unfeasible during a particular N-1 condition (i.e., SCR well below unity), inverter-based resource output may need to be reduced rapidly to avoid system instabilities. In such cases, the TP, GO, and manufacturer may need to agree on an operating plan that reduces the power output of the inverter-based resource under certain operating conditions where the critical contingency could result in weak grid issues or during all operating condition depending on the complexity of the situation and the ability of the operator to manage these conditions and ensures stability and BPS reliability.

- **Transmission Reinforcement:** Transmission system reinforcement (e.g., line reconductoring, new transmission circuits, new or larger transformers) can increase SCR at the point of connection of the inverter-based resource, particularly when coupled with system upgrades necessary to accommodate the capacity of the new generating resource in the weak system area. Series compensation can also mitigate some aspects of weak grid operation and can be an effective way of mitigating the need to build additional lines. Care should be taken in using series compensation for transmission of inverter-based resources, as it introduces the risk of sub-synchronous oscillation phenomena.

- **FACTS Devices:** FACTS devices such as SVCs and STATCOMs can help control BPS voltages by providing dynamic reactive support. This may help in controlling voltage fluctuations under weak grid conditions as well as help with transient ride-through capability. However, these devices have fast control loops that can interact with inverter-based resources on weak grids, are limited in their contribution to fault current (similar to an inverter-based resource) and do not provide any system inertia. Battery energy storage systems are becoming more common, and may be able to provide fast frequency response and mitigation for voltage control instabilities. However, care should be taken as these devices may also be subject to weak grid instabilities depending on their control philosophy.

Chapter 5: Conclusion

Most inverter-based resource control systems rely on the voltage magnitude and angle at their terminals to not be largely affected by its current injection for stable operation. System strength refers to the sensitivity of the terminal voltage of the inverter-based resource to variations of current injections. Weak grid conditions with a higher sensitivity are a key consideration when integrating inverter-based resources to the BPS.

Weak grids are typically system-specific and require system-specific studies and solutions. It is important for TPs to apply appropriate tools, techniques, and simulation approaches in weak grid systems and higher penetration of inverter-based resources. To identify these systems, a number of SCR-based metrics have been developed by the industry. The benefits and drawbacks of each method, as well as a high-level description of how to apply the method, are provided in this guideline. There is no specific short circuit threshold one can consider as a "weak grid", so understanding system short circuit levels, and engaging with the GO and manufacturer of the inverter-based equipment is key to reliably planning and operation under these weak grid conditions.

The most important aspect of identifying and mitigating issues related to integrating inverter-based resources into potentially weak grid conditions is coordination and communication between the TP, GO, and the equipment manufacturer. With increasing penetration of inverter-based resources, a number of issues may manifest and have been discussed in this guideline to raise industry awareness along with the means by which to study these issues. Controls instability, control interactions, small signal instability, and classical voltage stability issues are more prominent in weak grids. This guideline provides a description of each phenomenon, as well as some illustrative examples of weak grid issues that have been experienced by grid operators across North America. Simulation tools and their inherent limitations should be understood by the planners identifying potential weak grid conditions. Conventional positive sequence, phasor-based simulation tools may not be able to capture some of the weak grid issues described in this guideline. More advanced EMT modeling may be required in certain situations, and these models should be provided by the GO to the TP for any potential weak grid area of the system.

Solutions to weak grid issues are also system specific and will depend on the weak grid issue identified, the local grid characteristics, and plant control capabilities. Potential solution options are described briefly in this guideline to provide TPs with a suite of options to explore in more detail.

The changing resource mix and increasing penetration of inverter-based resources are driving parts of the BPS towards "weak grid" conditions. This guideline serves as a high-level overview of how to identify potential weak grid conditions, considerations TPs can make when studying these types of systems, and potential mitigation techniques to ensure a reliable BPS when interconnecting inverter-based resources to weak grids. The recommendations are based on industry experience during the interconnection planning process and experience operating inverter-based resources in weak grids.

Appendix A: Requirements for EMT Modeling

Specific modeling requirements for an EMT study depend on the type of study to be performed. An EMT study that may cover topics such as weak system interconnection, ride-through evaluation, voltage control and event response, control interactions with nearby devices, and islanding performance should require a model that has the characteristics[17] described in the following sections.

Model Accuracy Features
For the model to be sufficiently accurate, it should:

- **Represent the full detailed inner control loops of the power electronics.** The model should not use the same approximations classically used in transient stability modeling, and should fully represent all fast inner controls as implemented in the actual equipment. It is possible to create models which embed the actual hardware code into an EMT model component, and this is the recommended type of model.[18] [19]

- **Represent all control features pertinent to the type of study being done.** This may include external voltage controllers, plant level controllers, customized PLLs, ride-through controllers, subsynchronous control interaction (SSCI) damping controllers, weak grid options, or other types of controls. Actual hardware code is recommended to be used for most control features. Operating modes that require system specific adjustment should be user accessible. In some cases, plant level voltage control should be represented along with adjustable droop characteristics. If the plant level controllers are very slow, these may be approximated using constant reactive power modes.

- **Represent all pertinent electrical and mechanical configurations.** This includes any filters and specialized transformers. There may be other mechanical features (e.g., gearboxes, pitch controllers, etc.) that should be modeled if they impact electrical performance.

- **Have all pertinent protection systems modeled in detail for both balanced and unbalanced fault conditions.** This typically[20] includes various over- and under-voltage protections (individual phase and RMS), frequency protections, DC bus voltage protections, and overcurrent protection. Actual hardware code is recommended to be used for these protection features.

Model Usability Features
In order to allow study engineers to perform system analysis using the model, the EMT model should:

- **Have control or hardware options which are pertinent to the study accessible to the user.** These may include adjustable protection thresholds or real power recovery ramp rates, for example. Diagnostic flags (flags to show control mode changes or protection activations) should also be accessible to aid in analysis.

- **Be capable of running at a minimum time step of 10 μs.** Most of the time, requiring a smaller time step (e.g., 10 μs) means that the control implementation has not used the interpolation features of the EMT simulation, or is using inappropriate interfacing between the model and the larger network. Lack of interpolation support

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[17] More specialized studies may require additional features.

[18] The model should be a full IGBT representation (preferred), or may use a voltage source interface that mimics IGBT switching (i.e., a firing pulse based model). A three-phase sinusoidal source representation is not acceptable. Code that is actually programmed into the actual controller of the inverter-based resource (e.g., C code) should be used in the model. Tools such as MATLAB can be used to generate the C code. Block diagram representations or other high-level code should not be used. The controller source code may be compiled into DLLs or binary if the source code is unavailable due to confidentiality restrictions.

[19] If the model is assembled using standard blocks available in the EMT simulation library, approximations are usually introduced and specific implementation details for important control blocks may be lost. In addition, there is a risk that errors will be introduced in the process of manually assembling the model. Note that for this type of manually assembled model, (i.e., not using "real code"), validation is recommended.

[20] There may be other types of protection that should be modeled based on the specific implementation.

introduces inaccuracies into the model at higher time steps. Models should be able to run at a small time step down to, at least, 10 μs.

- **Include documentation and a sample implementation test case.** Access to technical support engineers is desirable.

- **Be capable of initializing itself.** Model should initialize and ramp to full output without external input from simulation engineers.

- **Accept external reference values.** This includes real and reactive power reference values (for reactive power control modes), or voltage reference values (for voltage control modes).

Appendix B: Challenges with Weak Grid Issues

This section provides illustrative examples of challenges utilities have faced integrating inverter-based resources into weak grid conditions. These examples are intended to be useful references for future awareness and understanding of the various issues that may be faced moving forward.

High Penetration of Wind in West Texas

The Panhandle region of ERCOT in West Texas is remote from synchronous generators and load centers and is considered a weak grid with a large amount of wind generation. Several system characteristics and challenges that were detected and or studied in a weak grid include:

- In a highly compensated weak grid, static voltage collapse can occur within the normal operating voltage range (0.95 to 1.05 pu) masking voltage stability risks in real time operations. Static var compensators contribute to this effect and have limited effectiveness for further increasing transfer capability.

- A grid with low short circuit ratios and high voltage sensitivity of dV/dQ requires special coordination of various complex control systems. Typical voltage control settings can result in aggressive but un-coordinated voltage support strategies, causing un-damped oscillations potentially leading to overvoltage cascading or voltage collapse.

- Wind projects connected to the Panhandle region are effectively connected to a common POI such that each wind plant control may interact with other wind plants controls strategies.

ERCOT identified the need to maintain adequate system strength using WSCR in the Panhandle region to avoid potential control inability problems. The WSCR is a measure of system strength and therefore stability that accounts for the lack of conventional generation or significant load in the Panhandle region, the low fault current contribution of the region's wind units, and the mutual interactions between the power electronic converters through which these units are connected to the grid. To determine a proper threshold of WSCR, ERCOT conducted a detailed PSCAD EMT Program (EMTP) analysis and assessment of the ERCOT Panhandle region and confirmed that a WSCR of 1.5 is appropriate for the Panhandle region for the proposed network topology[21]. In addition, for Panhandle WSCR levels at 1.5 or higher, PSS/E dynamic models and PSCAD models performed adequately. As the WSCR drops below 1.5, the need for more detailed EMTP type models becomes more critical. System enhancements, including a newly added transmission circuit and two synchronous condensers, were verified to be adequate to improve the system strength and address weak grid issues.

It should be noted that WSCR is currently used to monitor the Panhandle region susceptibility to weak-grid problems and will require further analysis to evaluate applicability of such WSCR metrics in other regions. With the continued growth of renewable generation in the ERCOT system, periodic PSCAD studies should be considered to validate PSS/E studies and further develop WSCR planning metrics and practices.

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[21] Panhandle System Strength Assessment PSCAD Study.
Available:http://www.ercot.com/content/news/presentations/2016/Panhandle%20System%20Strength%20Study%20Feb%2023%202016%20(Public).pdf.

Synchronous Condenser and Wind Farm Interactions

The following example discusses the application of a synchronous condenser at a wind power plant. In the first steps of the interconnection study for the proposed wind facility, it was identified that the generator was interconnecting to a point on the system with low SCR through a long radial transmission line. In this case, the SCR was calculated using the standard SCR calculation methodology described earlier in this document. Because of the low SCR, EMT analysis was conducted for the project and confirmed that the project did not have stable response for certain credible contingencies. This unstable behavior was not observed using the positive sequence stability model. As a result of the unstable EMT performance, a synchronous condenser was proposed and sized to provide stable behavior for the conditions tested. As well as providing stable transient performance, the synchronous condenser can be used to help meet the interconnecting power factor and voltage control requirements for the facility. Figure B.1 shows a simplified one line diagram of the installation.
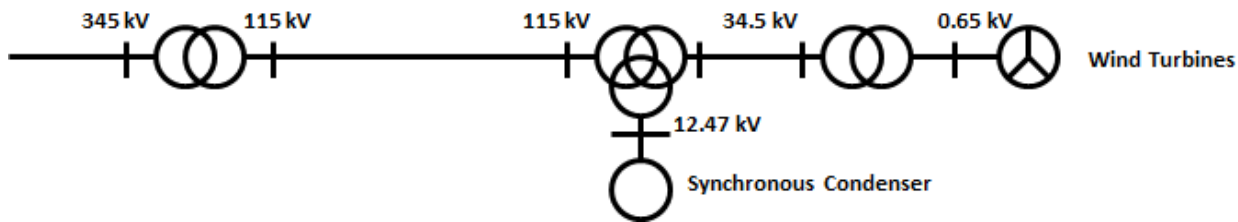
Figure B.1: Simplified One-Line Diagram of Wind Generating Facility with a Synchronous Condenser

Later, operations engineering studies identified further concerns. Stability analysis demonstrated that when the synchronous condenser was on-line, the limiting system condition was steady state post-contingency voltages. When the synchronous condenser was off-line, the limiting condition was actuation of the wind farm's low voltage ride through protection, which would cycle in and out actuation. Tripping the plant would cause local voltage to rise enough to allow reconnection of the plant, which in turn caused actuation of the low voltage ride through protection. The resulting voltage variation and transients were unacceptable, as was the loss of the plant for the limiting transmission contingency.

There are some limitations that need to be considered with this type of installation:

- The synchronous condenser should be sized for a reasonable range of system conditions, considering facility outages or maintenance; however, it is not practicable to cover all possible operating conditions.

- Since the project response is unstable without the synchronous condenser, the output of the generating facility may have to be limited when the synchronous condenser is out of service. This presents additional complications to the calculations of operating limits.

- The protection for the synchronous condenser will be challenging to coordinate, especially for contingencies that island the facility from the system.

- Determining the actual lagging operating limits of the synchronous condenser is key, and behavior of the condenser when that lagging limit is reached can be critical for local system performance.

Weak Grid Voltage Stability Issues Interconnecting on Weak Circuits

BPA encountered classical voltage instability conditions caused by a high penetration of WPPs connected near the midpoint of a long (nearly 200 miles) 230 kV transmission line. This relatively weak part of the network experienced high dV/dP and dV/dQ sensitivities. Figure B.2 shows a wind power hub with a Type 2 plant and Type 3 plant operating in power factor mode in late 2010. Illustrated differently, Figure B.3 shows a wind ramp at this location in December 2011, expressed as a classical PV plot. The wind plant and local network experienced a voltage collapse following the wind ramp.
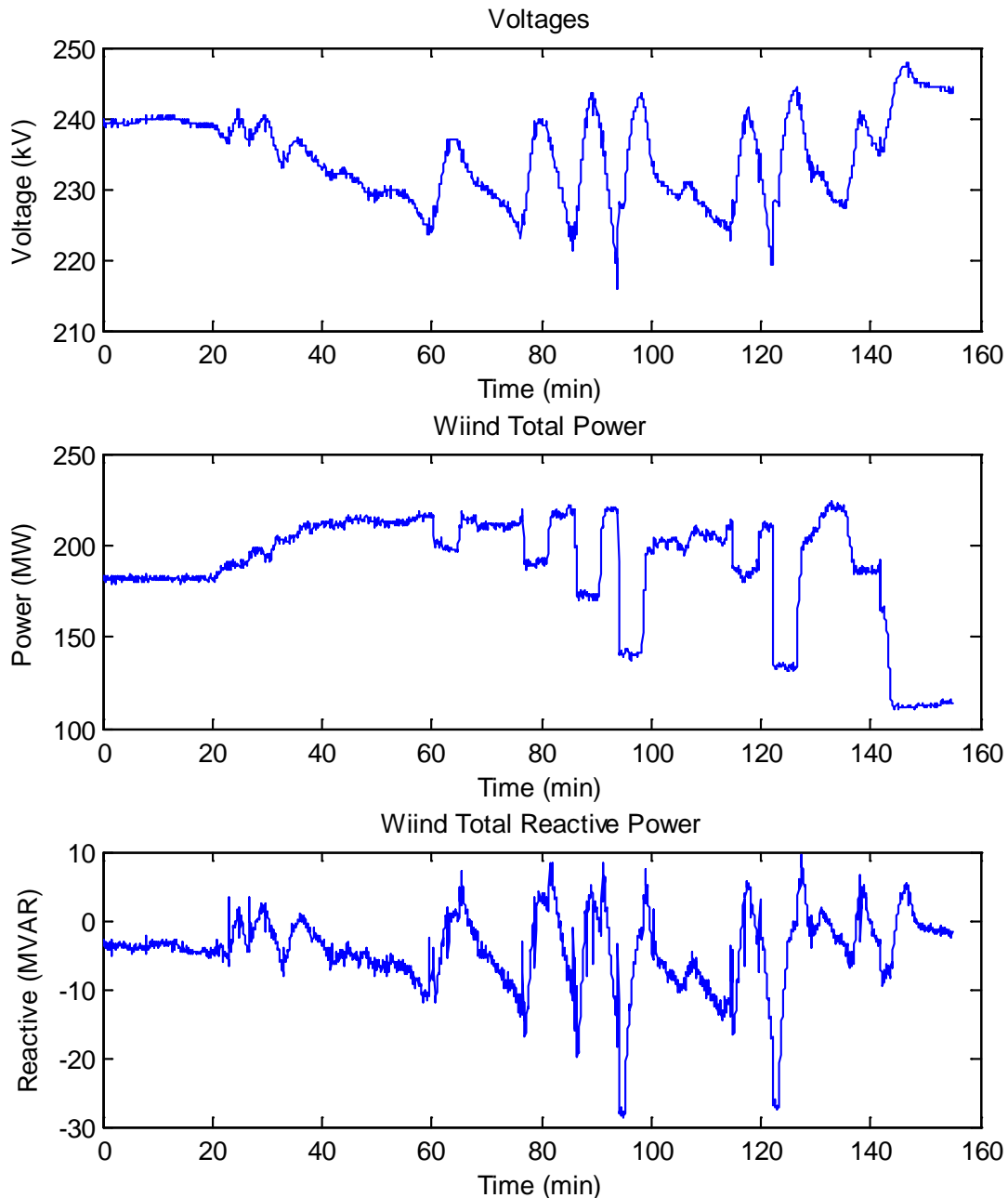
Figure B.2: Voltage Fluctuation Issues for a WPP Connected to a Weak Grid Area [Source: BPA]
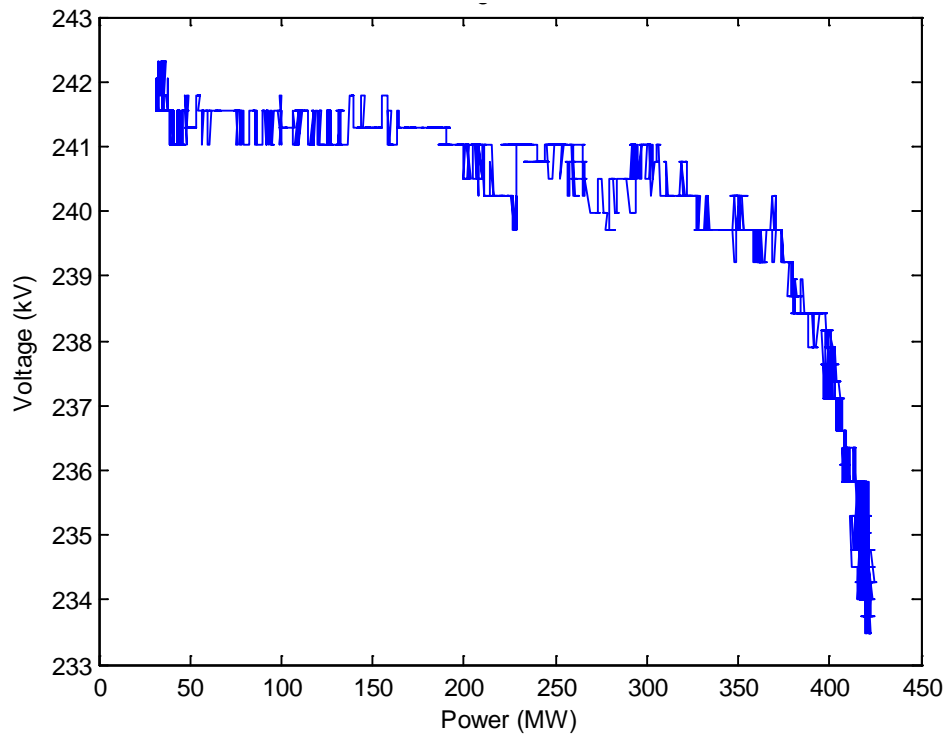
**Figure B.3: Classical Voltage Instability (PV Curve) for a Wind Ramp Event
[Source: BPA]**

To monitor plant performance in the future, BPA used V-Q plots to monitor the WPP modes of operation. Figure B.4 shows two examples of a plant's operation along with the required dynamic voltage control on a reactive droop characteristic. The left figure shows the plant operating in voltage control mode with a fairly aggressive (i.e., low) droop characteristic where small changes in voltage result in large changes in reactive power output. In response to this, the plant operator switched to power factor mode without notifying the TOP. The right figure shows the power factor mode of operation, where reactive power output is held near 0 regardless of system voltage (no dynamic voltage support).

To mitigate the conditions shown in Figure B.5 where one WPP at the wind hub is supplying reactive power and the other is consuming reactive power, BPA coordinated with the WPPs to ensure correct voltage control (and reactive power) mode of operation and also devised a wind hub voltage control scheme. The goal of the scheme was to automatically control two 230 kV capacitors to aid operators in managing voltage in this area, maximize dynamic reactive reserves, and maintain acceptable pre- and post-contingency voltage levels.

Figures B.4 and B.5 demonstrate that planned operation of a WPP can be very different from actual operation; therefore, monitoring a power plant's performance after energization is key.
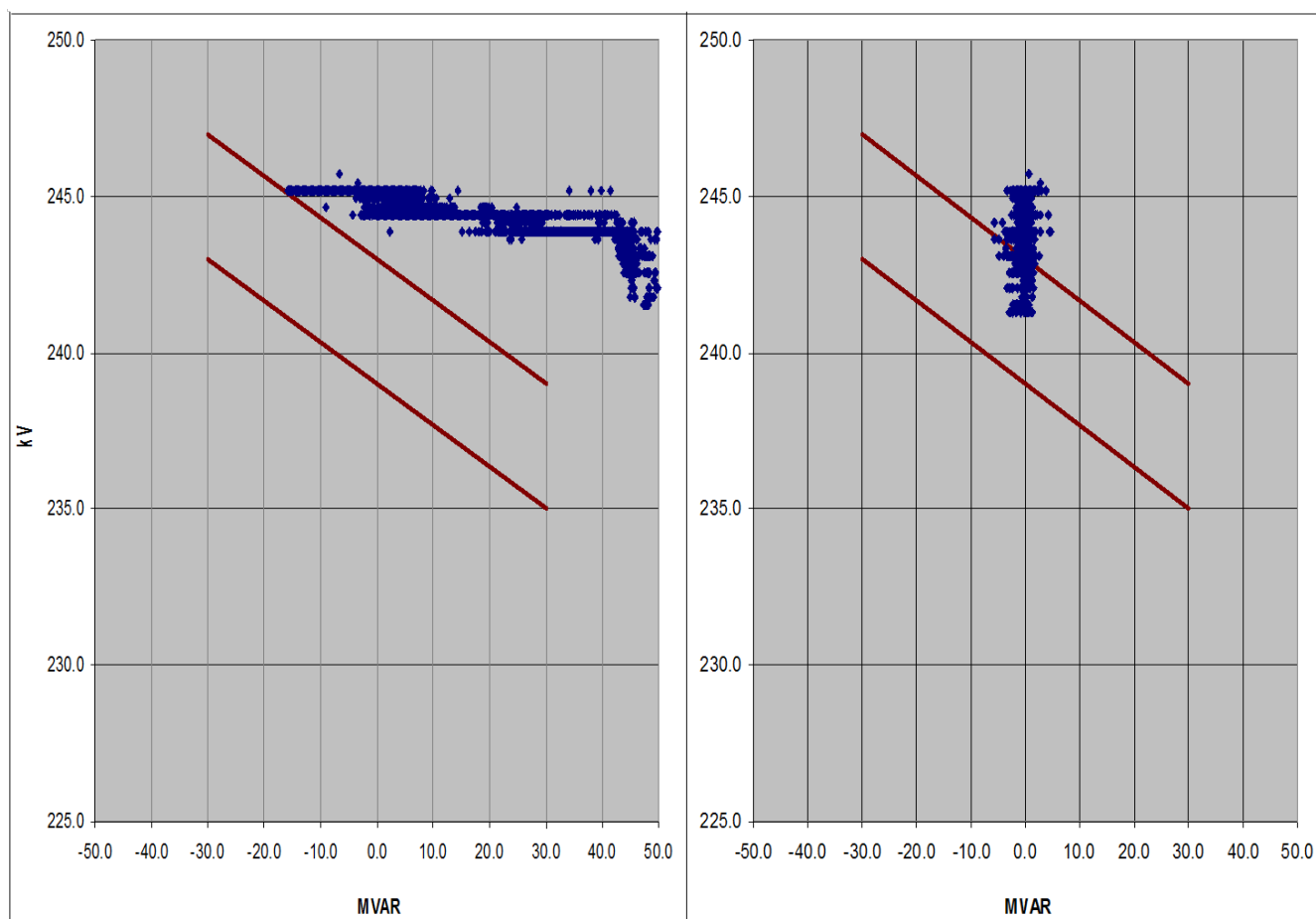
Figure B.4: WPP Volt/Var Droop: Desired vs. Actual Operation Examples [Source: BPA]
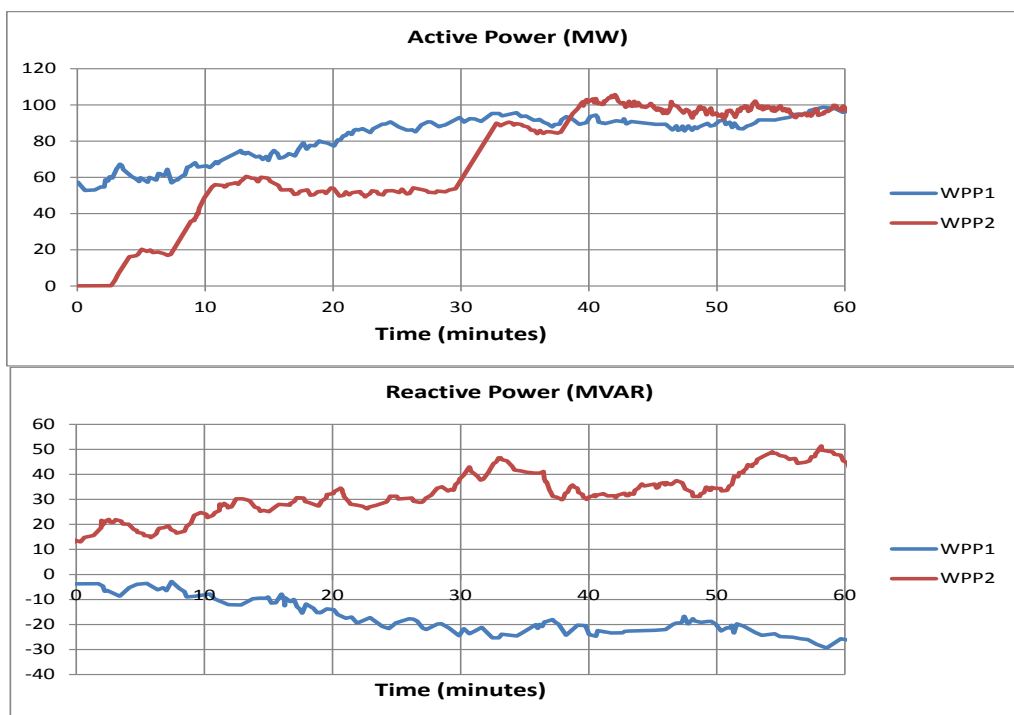

**Figure B.5: Poorly Coordinated Volt/Var Control during Wind Ramp [Source: BPA]**

Transformer Energization in Weak Grids

Energizing a transformer can cause it to draw significant initial inrush currents that are unbalanced in nature and that decay over time to much smaller steady state magnetizing currents. The main factors affecting the inrush current magnitude and duration include transformer design, initial conditions, and network factors. These inrush currents that can take several seconds to decay are supplied by the system, and flow through the network impedance which results in system voltage drop. In energizing transformers from weak grids, there is increased likelihood of resultant system voltage drops exceeding allowable limits or even the withstand level of any voltage-sensitive industrial loads or other inverter-based resources in the vicinity.

Power quality monitoring systems have captured significant voltage drops associated with energization of the transformers of several solar facilities (see Figure B.6 for illustration of typical interconnection) that have connected to the BPS. Figure B.7 shows the rapid voltage changes on the three phases measured at a 12 kV bus in response to energization of a solar facility connected to a nearby weak 46 kV bus. It can be seen that inrush caused 12 kV bus voltage to drop from pre-energization value of 1.02 pu to 0.87 pu for the worst phase and the recovery to pre-energization voltage took around five seconds. It may be noted that the voltage at the 46 kV bus dropped to an even lower value of 0.85 pu. Such rapid voltage changes easily exceed the typical limit of 5% (for up to four instances per day, IEEE 1453.1) at a PCC of a fluctuating facility connected to BPS.
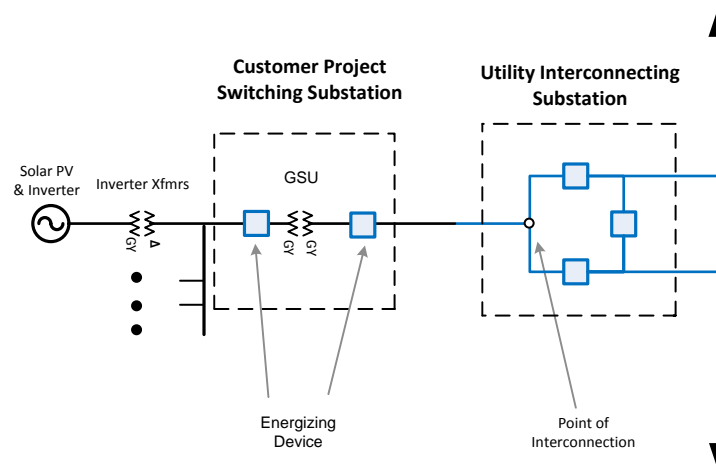
Figure B.6: Illustration of Typical Solar Facility Interconnection to Utility System [Source: Southern Company]
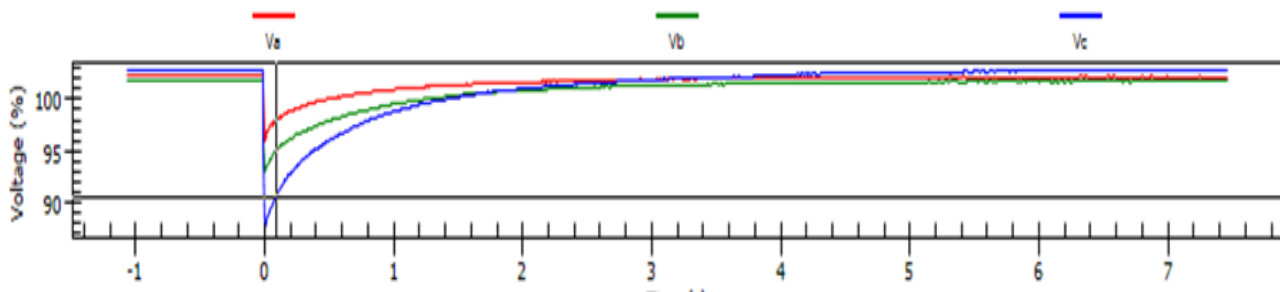
Figure B.7: Example Rapid Voltage Change due to GSU Energization at a Solar Facility [Source: Southern Company]

Solutions being investigated to address these issues include:

- **Pre-insertion Switching:** This solution involves use of a switching device that is equipped with a pre-insertion resistor. It is a very effective solution to mitigate the transient magnetizing currents and resultant system voltage drops. It may be noted that a comprehensive EMT study is recommended for each location where this is to be applied, to arrive at an optimal value for the pre-insertion resistor and insertion time.

- **Point-on-Wave (POW) Control Switching:** This solution involves using segregated pole breakers with special purpose point-on-wave control. It is another effective strategy but more complicated to implement in practice.

- **Moving interconnection:** In some cases, it may be possible to move the point of interconnection to a higher voltage level where the SCR is expected to be higher, resulting in smaller rapid voltage changes on the BPS.

- **Energizing Solar Facility Transformers in Stages:** Energizing the GSU along with all the inverter transformers yields the worst case scenario. Therefore, energizing the GSU first followed by various inverter transformers in stages may help minimize the rapid voltage changes caused by energization.

Appendix C: References

[1]   WG B4.62, "Connection of Wind Farms to Weak AC Networks," Cigré Technical Brochure 671, December 2016.

[2]   WG C4.601, "Modelling and dynamic behavior of wind generation as it relates to power system control and dynamic performance," Cigré Technical Brochure 328, August 2007.

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[6]   WECC MVWG, "WECC Second Generation Wind Turbine Models," Western Electricity Coordinating Council, Salt Lake City, UT, January 2014. [Online]. Available:https://www.wecc.biz/Reliability/WECC%20Second%20Generation%20Wind%20Turbine%20Models%20012314.pdf.

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[9]   Y. Zhang, S. H. F. Huang, J. Schmall, J. Conto, J. Billo and E. Rehman, "Evaluating system strength for large-scale wind plant integration," 2014 IEEE PES General Meeting, National Harbor, MD, 2014, pp. 1-5.

Appendix D: List Of Acronyms

Acronym	Term
AC	Alternating Current
BPS	Bulk Power System
BES	Bulk Electric System
CSCR	Composite Short Circuit Ratio
DC	Direct Current
EHV	Extra High Voltage
EMT	Electromagnetic Transient
ERO	Electric Reliability Organization
FACTS	Flexible AC Transmission System
FERC	Federal Energy Regulatory Commission
GO	Generator Owner
GOP	Generator Operator
HVDC	High Voltage Direct Current
IF	Injection Factor
LCC	Line Commutated Converter
NERC	North American Electric Reliability Corporation
PC	Planning Coordinator
PLL	Phase Locked Loop
POI	Point of Interconnection
POW	Point-on-Wave
SCMVA	Short Circuit MVA
SCR	Short Circuit Ratio
SCRIF	Short Circuit Ratio with Injection Factors
SSCI	Subsynchronous Control Interaction
STATCOM	Static Compensator
SVC	Static Var Compensator
TO	Transmission Owner
TOP	Transmission Operator
TP	Transmission Planner
VER	Variable Energy Resource
WPP	Wind Power Plant
WSCR	Weighted Short Circuit Ratio
WTG	Wind Turbine Generator

Table D.1: List of Acronyms

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Name	Entity
Sebastian Achilles	General Electric
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Shih-Min Hsu	Southern Company
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Al McBride	ISO New England
Mohamed Osman	North American Electric Reliability Corporation
Ryan Quint	North American Electric Reliability Corporation