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Reactive Power Interconnection Requirements for PV and Wind Plants – Recommendations to NERC

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Abstract

Voltage on the North American bulk system is normally regulated by synchronous generators, which typically are provided with voltage schedules by transmission system operators. In the past, variable generation plants were considered very small relative to conventional generating units, and were characteristically either induction generator (wind) or line-commutated inverters (photovoltaic) that have no inherent voltage regulation capability. However, the growing level of penetration of non-traditional renewable generation – especially wind and solar – has led to the need for renewable generation to contribute more significantly to power system voltage control and reactive power capacity. Modern wind-turbine generators, and increasingly PV inverters as well, have considerable dynamic reactive power capability, which can be further enhanced with other reactive support equipment at the plant level to meet interconnection requirements. This report contains a set of recommendations to the North-America Electricity Reliability Corporation (NERC) as part of Task 1-3 (interconnection requirements) of the Integration of Variable Generation Task Force (IVGTF) work plan. The report discusses reactive capability of different generator technologies, reviews existing reactive power standards, and provides specific recommendations to improve existing interconnection standards.

CONTENTS

FIGURES

ACRONYMS

AESO	Alberta Electric System Operator
AVR	automatic voltage regulator
CAISO	California Independent System Operator
ERCOT	Electric Reliability Council of Texas
FAC	Facility Connection Standards (NERC)
FERC	Federal Energy Regulatory Commission
HECO	Hawaiian Electric Company
kV	kilovolt
kVA	kilovolt-ampere
kW	kilowatt
LGIP	Large Generator Interconnection Procedures
MVA	mega volt-amperes
MVAr	megavolt ampere reactive
MW	megawatt
NERC	North American Electric Reliability Corporation
pf	power factor
POI	point of interconnection
PSS	power system stabilizer
pu	per unit
PV	photovoltaic
SAR	Standards Authorization Request
SGIP	Small Generator Interconnection Procedures
SPP	Southwest Power Pool, Incorporated
STATCOM	static compensator
SVC	static var compensator

1 INTRODUCTION

1.1 NERC's Mission

The North American Electric Reliability Corporation (NERC) is an international regulatory authority for reliability of the bulk power system in North America. NERC develops and enforces Reliability Standards; assesses adequacy annually via a 10-year forecast and winter and summer forecasts; monitors the bulk power system; and educates, trains, and certifies industry personnel. NERC is a self-regulatory organization, subject to oversight by the U.S. Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC assesses and reports on the reliability and adequacy of the North American bulk power system divided into eight regional areas as shown on the map below (see Figure 1). The users, owners, and operators of the bulk power system within these areas account for virtually all the electricity supplied in the United States, Canada, and a portion of Baja California Norte, México.

Note: *The highlighted area between SPP and SERC denotes overlapping regional area boundaries: For example, some load serving entities participate in one region and their associated transmission owner/operators in another.*

ERCOT Electric Reliability Council of Texas	**RFC** Reliability *First* Corporation
FRCC Florida Reliability Coordinating Council	**SERC** SERC Reliability Corporation
MRO Midwest Reliability Organization	**SPP** Southwest Power Pool, Incorporated
NPCC Northeast Power Coordinating Council, Inc.	**WECC** Western Electricity Coordinating Council

Figure 1. NERC regional entities.

1.2 Integration of Variable Generation Task Force

In 2009, NERC assigned the Integration of Variable Generation Task Force (IVGTF) the task of reviewing existing standards and providing recommendations to more adequately address variable generation, including wind and photovoltaic (PV) generators. IVGTF Task 1.3 addresses interconnection requirements such as active and reactive power capability, voltage and frequency tolerance, and fault current contribution. This report discusses reactive capability of different generator technologies, reviews existing reactive power standards, and provides specific recommendations to improve existing interconnection standards.

2 REACTIVE POWER CAPABILITY AND INTERCONNECTION REQUIREMENTS

2.1 Background

Voltage on the North American bulk system is normally regulated by generator operators, which typically are provided with voltage schedules by transmission system operators. In the past, variable generation plants were considered very small relative to conventional generating units, and were characteristically either induction generator (wind) or line-commutated inverters (PV) that have no inherent voltage regulation capability. Bulk system voltage regulation was provided almost exclusively by synchronous generators. However, the growing level of penetration of non-traditional renewable generation – especially wind and solar – has led to the need for renewable generation to contribute more significantly to power system voltage and reactive regulation. For the most part, new wind plants use doubly fed asynchronous generators or full-conversion machines with self-commutated electronic interfaces, which have considerable dynamic reactive and voltage regulation capability. If needed to meet interconnection requirements, the reactive power capability of solar and wind plants can be further enhanced by adding of a static var compensator (SVC), static compensators (STATCOMS), and other reactive support equipment at the plant level. It should be noted that converters need to be sized larger to provide reactive power capability at full output. Currently, inverter-based reactive capability is more costly compared to the same capability supplied by synchronous machines. Partly for this reason, FERC stipulated in Order 661-A (applicable to wind generators) that a site-specific study must be conducted by the transmission operator to justify the reactive capability requirement up to 0.95 lag to lead at the point of interconnection. For solar PV, it is expected that similar interconnection requirements for power factor range and low-voltage ride-through will be formulated in the near future. Inverters used for solar PV and wind plants can provide reactive capability at partial output, but any inverter-based reactive capability at full power implies that the converter need to be sized larger to handle full active and reactive current.

Nonetheless, variable generation resources such as wind and solar PV are often located in remote locations, with weak transmission connections. It is not uncommon for wind parks and solar PV sites to have short circuit ratios (i.e., ratios of three-phase short circuit mega volt-amperes (MVA) divided by nominal MVA rating of the plant) of 5 or less. Voltage support in systems like this is a vital ancillary service to prevent voltage instability and ensure good power transfer.

Voltage regulation in distribution systems is normally performed at the distribution substation level and distribution voltage regulation by distributed resources is not allowed by IEEE 1547. Normally, distributed resources operate with fixed power factor with respect to the local system.

2.1.1 Reactive Capability of Synchronous Generators

Customarily, when reactive capability of variable generation resources is specified for transmission interconnections, it is done at the point of interconnection (POI), which is the point at which power is delivered to the transmission system. This is often (but not always) at the high side of the main facility transformer. A typical requirement would be 0.95 lag to lead power factor[1] at the POI, meaning that the machine should be capable of injecting or absorbing the equivalent of approximately 1/3 of its active power rating (MW) as reactive power (MVAr). This lag to lead specification originated from FERC Order 2000 (Large Generator Interconnection Agreement) and was suggested by NERC as a representative synchronous generator capability. In reality, synchronous generators are almost always applied with power factor measured at the terminals, not at the POI. Conventional synchronous generator reactive power capability is typically described by a "D curve" that covers the range from zero to rated output. However, it should be noted that synchronous generators are limited by the minimum load capability of the generating plant. Some conventional generators are designed to operate as synchronous condensers, allowing them to provide reactive power at zero load, but they still cannot operate between zero and minimum load. The ability to provide reactive power at zero load must be designed into the plant and it is not possible with many larger plant designs. The significance of the discussion above is that the practical reactive power capability of a typical synchronous generator is more limited than the typical "D curve" shows (see Figure 2).

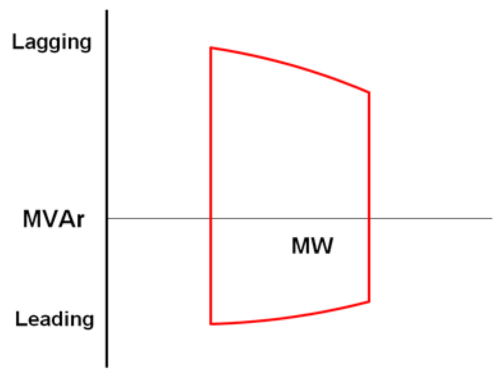

Figure 2. Example of reactive power capability of a synchronous generator considering plant minimum load.

Assuming negligible auxiliary load, the corresponding power factor at the transmission interface can be easily calculated given the generator power factor at the terminals and the reactance of the generator step-up transformer. Generally, a generator with a reactive capability of 0.9 lag, 0.983 lead (measured at the generator terminals) connected to the transmission system through a transformer with a leakage reactance of 14% on the generator MVA base can provide 0.95 lag to lead at the transmission interface if the transmission system is at nominal (i.e., 100%) voltage.

Typical specifications for synchronous generators require 0.90 lag (over-excited) and 0.95 lead (under-excited) at the machine terminals in order to allow voltage regulation at a transmission voltage range within 90% to 110% of nominal. Synchronous generators have maximum continuous voltages of 105%, and minimum continuous voltage of 95%. Depending on the system voltage and generator output level, these limits may come into play, in which case the reactive power capability would be reduced. For example, Figure 3 depicts the reactive power capability at the POI for a synchronous generator at rated power with a typical reactive capability

[1] In this document, a generator convention is used for power factor sign. Lagging power factor means that the generator is injecting reactive power to the grid. Leading power factor means that the generator is absorbing reactive power from the grid. In conventional generators, lagging and leading power factor are commonly referred to as over-excited and under-excited, respectively.

of 0.90 lag to 0.95 lead at the machine terminals, connected to the system by a 14% (on the generator MVA base) reactance step-up transformer. Note that over-excited power factor range at the POI is roughly 0.95 lag for system voltages at nominal or below, but drops off sharply at voltages above nominal. Similarly, under-excited power factor range at the POI is actually close to -0.9 lead (i.e., Q = 0.48 x P) for voltages above 100% of nominal, but the capability drops off for system voltages below nominal.

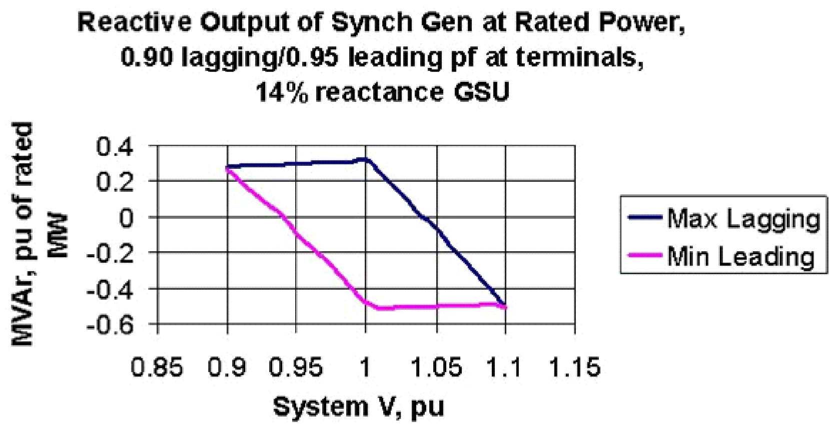

Figure 3. Influence of voltage on reactive power capability of a synchronous generator.

A specification of 0.95 lag to lead at full power is commonly stipulated for variable generation. However, terminal voltage limitations also affect reactive power capability of variable generators; therefore, to capture this effect, the reactive power versus voltage characteristic should be specified separately from the reactive range. For example, in addition to a 0.95 lag to lead reactive range requirement, the chart shown in Figure 4 could be used to specify the reactive power capability versus voltage characteristic.

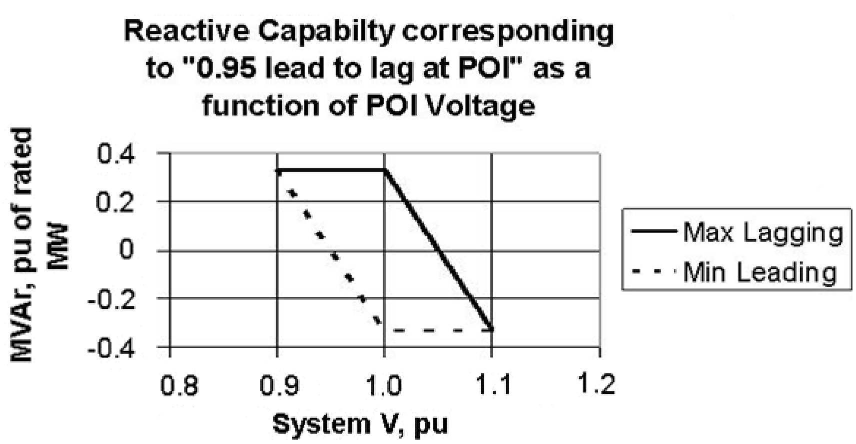

Figure 4. Illustration of reactive power requirements as a function of POI voltage.

2.1.2 Reactive Capability or Requirements for Wind and Solar PV Generators

PV generators and some types of wind generators use power converters. The reactive capability of converters differ from those of synchronous machines because they are normally not power-limited, as synchronous machines are, but limited by internal voltage, temperature, and current constraints. The sections below discuss reactive power capability of individual wind turbine generators and solar PV inverters.

Wind Generators

Wind generators with converter interface are often designed for operation from 90% to 110% of rated terminal voltage. Lagging power factor range may diminish as terminal voltage increases because of internal voltage constraints and may diminish as terminal voltage decreases because of converter current constraints. Leading capability normally increases with increasing terminal voltage. These characteristics also apply to PV inverters. Doubly fed and full-converter wind generators are often sold with a “triangular,” “rectangular,” or “D shape” reactive capability characteristic, shown in Figure 5. This represents the reactive power capability of individual wind generators or PV inverters. Reactive power capability at the plant level is discussed in Section 2.1.3.

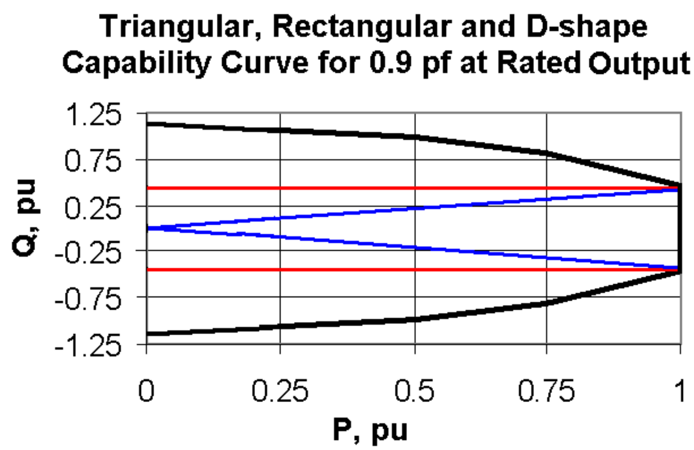

Figure 5. Various reactive power capability curves for wind generators at nominal voltage.

Machines with a rectangular or D-shaped reactive capability characteristic may be employed to provide voltage regulation service when they are not producing active power (e.g., a low-wind-speed condition for a wind resource or at night for a PV resource, or during curtailment) by operation in a STATCOM mode. However, this capability may not be available or may not be enabled by default. Unlike doubly fed or full-converter wind turbine generators, induction-based wind generators without converters are unable to control reactive power. Under steady-state conditions, they absorb reactive power just like any other induction machine. Typically, mechanically switched capacitors are applied at the wind generator terminals to correct the power factor to unity. Several capacitor stages are used to maintain power factor near unity over the range of output.

PV Inverters

PV inverters have a similar technological design to full-converter wind generators, and are increasingly being sold with similar reactive power capability. Historically, however, PV inverters have been designed for deployment in the distribution system, where applicable interconnection standards (IEEE 1547) do not currently allow for voltage regulation. Inverters for that application are designed to operate at unity power factor, and are sold with a kilowatt (kW) rating, as opposed to a kilovolt-ampere (kVA) rating. Like inverter-based wind generators, PV inverters are typically designed to operate within 90% to 110% of rated terminal voltage. Reactive power capability from the inverter, to the extent that is available, varies as a function of terminal voltage. Furthermore, DC input voltage could also affect reactive power capability where single-stage inverter designs are used. For example, a low maximum power point (MPP)[2] voltage could reduce the lagging reactive power capability. With the increased use of PV inverters on the transmission network, the industry is moving towards the ability to provide reactive power capability. Some PV inverters have the capability to absorb or inject reactive power, if needed, provided that current and terminal voltage ratings are not exceeded. Considering that inverter cost is related to current rating, provision of reactive power at "full output" means that the inverter needs to be larger for the same plant MW rating, which comes at a higher cost compared to existing industry practice. Figure 6 shows the reactive capability of an inverter based on current limits only. Based on historical industry practice, this inverter would be rated based on unity power factor operation (P1 in Figure 6). Inverters would be able to produce or absorb reactive power when it operates at a power levels lower than P1 (e.g., P2). However, in response to recent grid codes like the German BDEW, more PV inverter manufacturers have "de-rated" their inverters and now provide both a kW and KVA rating. In principle, inverters could also provide reactive power support at zero power, similar to a STATCOM. However, this functionality is not standard in the industry. PV inverters are typically disconnected from the grid at night, in which case the inverter-based reactive power capability is not available. This practice could, of course, be modified, if site conditions dictate the use of reactive capability during periods when generation is normally off-line.

[2] The DC power supplied to the inverter from a PV source is a non-linear function of voltage. The voltage level that corresponds to the maximum power point (MPP) varies with temperature, irradiance and other factors. PV inverters have a maximum power point tracking function which continuously adjusts the DC voltage of the PV array to operate the array at the MPP. In single-stage inverters, the dc voltage of the array is the same dc voltage applied to the inverter. In dual-stage inverters, a dc-to-dc boost stage allows the dc voltage applied to the inverter to be independent of the array dc voltage, and thus these inverters have reactive power capability that is independent of the array dc voltage.

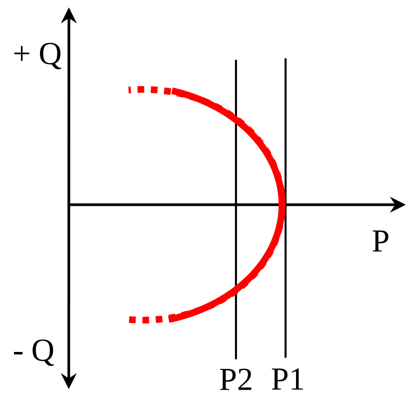

Figure 6. Reactive power capability of an inverter (red curve) based on current limit.

2.1.3 Reactive Capability of Variable Generation Plants

Reactive power requirements for interconnection are specified at the POI. This is an important consideration for wind and solar plants. First of all, it means that several technical options can be considered in the plant design to meet interconnection requirements. Technically, a plant with inverter-based wind or solar generators could rely on the inverters to provide part or all of the necessary reactive power range at the POI. It may be more economical to use external static and dynamic devices such as a STATCOM, an SVC, or mechanically switched capacitors (MSCs). The additional amount of reactive support required depends on the reactive capability of individual wind generators of PV inverters and how it is utilized. Sometimes, external dynamic reactive support is required to assist with voltage ride-through compliance.

During periods of low wind or solar resource, some generators in the plant may be disconnected from the grid. The DC voltage for solar PV inverters may limit the reactive power capability of the inverters. This should be taken into consideration when specifying reactive power capability for variable generation plants. Below a certain output level, it makes sense for the specification to show a reduced power factor range, or a permissive MVAr range. Figure 7 shows several possible reactive power capability specifications for variable generation, applicable at the POI.

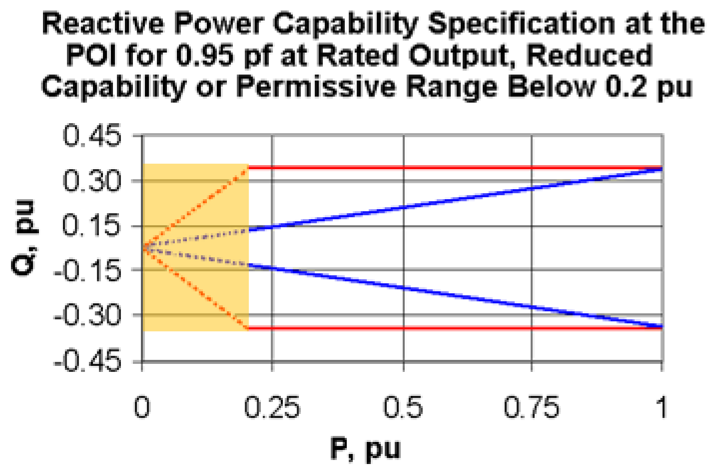

Figure 7. Example of reactive capability specification at the POI. At low output levels, as indicated by the shaded area, a permissive reactive range may be considered.

The interconnection requirements such as those shown in Figure 7 are often applied to transmission-connected wind power plants. In the case of PV, a requirement to maintain reactive power range at full output represents a change with respect to historical industry practice. This cost impact could be substantial if the PV plant relies on the PV inverters to provide a portion or all of the required plant-level reactive power capability. Figure 8 shows the reactive capability curve for a PV-plant-based unity power factor operation (red line), and how it compares with a "triangular" reactive power requirement (blue line) that is commonly specified for transmission interconnection. In this case the PV plant would not meet the requirement at full output without adding inverter capacity, de-rating the plant, or installing external reactive power support devices. In order to achieve a power factor range of 0.95 lag to lead at the POI at rated plant output using only the inverters, the total inverter rating would have to increase by as much as 10%, considering reactive losses. It should be noted that that both PV plants and inverter-based wind plants are technically capable of providing reactive capability at full output. The difference is that such a requirement is new to the solar industry compared to the wind industry.

The requirement implied by the blue curve in Figure 8 may not be needed for all transmission-connected PV plants. Considering that most PV plants are relatively small and the output is variable, operation along the red curve or at unity power factor may be just as beneficial to the system as operation along the blue curve. During periods where system conditions warrant, these plants could be instructed to reduce active power output such that a reactive power range can be maintained.

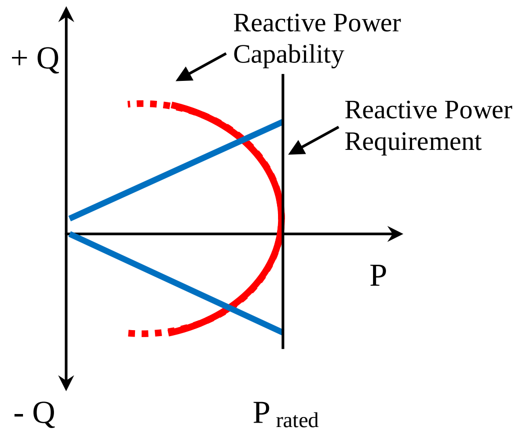

Figure 8. Reactive power capability of a PV plant compared to a typical triangular reactive power requirement.

In addition to the reactive capability versus output level discussed above, a complete specification should address the expected reactive capability during off-nominal voltage conditions, as illustrated in Figure 4.

2.1.4 Static Versus Dynamic Reactive Capability

The provision of dynamic reactive capability may have cost implications different than that of static reactive capability, and thus should be separately specified. Some grid codes specify both a dynamic range and a total range of reactive operation. For example, a grid code may specify a dynamic range of 0.95 lag to lead and a total range of 0.90 lag to 0.95 lead, indicating a need for smooth and rapid operation between 0.95 lag and 0.95 lead, but allowing for some time delay for lagging power factors below 0.95. Dynamic reactive capability from converters can be provided almost instantaneously in a manner similar to that of synchronous machines, responding almost instantly (i.e., within a cycle) to system voltage variations, to support the system during transient events, such as short circuits, switching surges, etc. Fixed capacitors or reactors can be used to shift the dynamic reactive capability toward the lagging or leading side, respectively, as needed. If there is inadequate dynamic reactive capability available from the variable generation resources, it may be necessary to supplement the variable generation resources with an SVC or STATCOM.

Non-dynamic reactive sources, such as supplemental mechanically switchable capacitors or reactors, can be installed to increase total (but not dynamic) reactive capability. Breaker times are in the range of cycles, not seconds. However, once disconnected, capacitors cannot be re-inserted without first being discharged (unless synchronous switching is used). Normally, discharge takes five minutes. Rapid discharge transformers can be applied to execute discharge in a few seconds. Good engineering practice requires that consideration be given to operation of switched reactive resources. For example, it is sometimes required that lagging reactive capability be placed in service as a function of variable generation output, irrespective of system voltage conditions. A transmission operator may require, for example, that capacitors be placed in service to compensate for transmission reactive losses whenever the output of a wind park exceeds 90% of rated capability. If the system voltage is high and the turbines are already operating at the leading power factor limit, placing capacitors in service may cause a high transient and steady-state overvoltage that can result in turbine tripping and other operational difficulties. It may be necessary to adjust transformer taps to bias turbine voltages in a safe direction if such operation is necessary.

2.1.5 Operational Considerations

Reactive capability on transmission systems is typically deployed in voltage regulation mode. The transmission system operator provides a voltage schedule and the generator (conventional or variable generation) is expected to adjust reactive output to keep the voltage close to the set point level. Normally this is done by regulating the resource's terminal voltage on the low side of the resource's main transformer. Another emerging practice is to adjust reactive output per a "reactive droop" characteristic, using the transmission voltage. Reactive droop in the range of 2% to 10% is typically employed. A typical droop of 4% simply means that the resource will adjust reactive output linearly with deviation from scheduled voltage so that full reactive capability is deployed when the measured voltage deviates from the scheduled voltage by more than 4%. A 1% deviation results in 25% of available reactive capability being deployed, etc. A voltage deviation less than the deadband limit would not require the resource to change reactive power output.

The specifications of the reactive droop requirement (e.g., the deadband of the droop response, together with the response time to voltage changes) may lead to requirements for dynamic reactive power support as well as potentially fast-acting plant controller behavior. Reactive droop capability is an emerging capability for solar PV plants, although there are no technical impediments to the implementation of such a control schemes. Individual wind generators and solar PV inverters typically follow a power factor, or reactive power, set point. The power factor set point can be adjusted by a plant-level volt/var regulator, thus allowing the generators to participate in voltage control. In some cases, the relatively slow communication interface (on the order of several seconds) of inverters limits the reactive power response time.

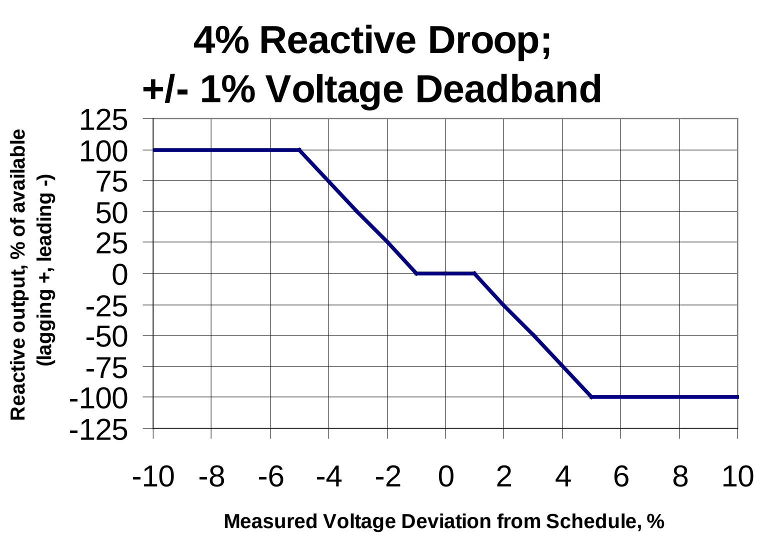

Figure 9. Example of reactive droop control with deadband.

Reactive droops of less than 2% for voltage regulation on the transmission system are essentially “bang-bang” voltage controls that may introduce oscillations, cause excessively rapid voltage fluctuations, and deplete reactive reserves for contingencies. They may be necessary in some weak systems, but they should generally be avoided, if possible. For large plants connected to the transmission system, reactive power control (fixed Q) and power factor control (fixed ratio of Q to P) is not generally used because they can result in inappropriate response to system voltage fluctuations and they generally detract from local system voltage stability. However, it should be noted that reactive control or power factor control are reasonable options when connected to a very stiff bus relative to the plant size. This is an important consideration in anticipation of smaller plants needing to be addressed in NERC standards. Moreover, reactive power control or power factor control are appropriate for distribution-connected generators.[3]

2.2 Review of Existing Reactive Power Standards

The following sections discuss the key reactive power requirements applicable in North America and Internationally. Appendix A contains a table summarizing several existing relevant standards regarding reactive support.

2.2.1 Standards Applicable in North America

a. FERC

FERC Order 661-A applies specifically to wind farms with aggregated nameplate capacity greater than 20 MVA. Wind generation plants are generally required by transmission operators to provide a 0.95 lag to lead power factor range at the point of interconnection, and voltage regulation functionality. Order 661A places the burden on the transmission operator to establish the need for a power factor requirement up to the 0.95 lag to lead power factor range, and the need for dynamic reactive capability. Some transmission operators would prefer to interpret Order 661-A as a baseline requirement based on a system-level need, and not on a case-by-case basis. There is still a great deal of uncertainty regarding this issue for all types of variable generation. Furthermore, there are different interpretations and a lack of clarity regarding the amount of dynamic versus static reactive power that is required, with Order 661-A requiring that wind farms provide sufficient dynamic voltage support in lieu of power system stabilizer (PSS) and automatic voltage regulator (AVR). FERC’s interconnection requirements currently do not contain language that applies to solar generation. However, generation interconnection procedures in California were recently revised to incorporate provisions similar to FERC Order 661A, but applicable to all asynchronous generators—see discussion in Section D below.

b. NERC

Applicability of NERC standards to generators is defined in NERC’s *Criteria Statement of Compliance Registry Criteria (Revision 5.0).* Generators larger than 20 MVA, a plant/facility larger than 75 MVA in aggregate, any generator that is a blackstart unit is subject to NERC standards. Regional standards and other requirements supplement the NERC standards. An important consideration is that NERC standards, unlike some regional grid codes, strive to be

[3] Most PV systems are distribution connected, or are small relative to the transmission system stiffness.

technology neutral. A good example of this philosophy is the PRC-024 standard on voltage and frequency tolerance, which is currently being drafted.

NERC FAC-001 directs the transmission owner to define and publish connection requirements for facilities, including generators. The connection requirements must address reactive power capability and control requirements (R2.1.3 and R2.1.9). As stated in the previous section, the manner in which reactive power capability may be used affects interconnection requirements. In that regard, NERC VAR standards address operating requirements with respect to reactive power control, although the language used is more pertinent to synchronous generation and could be modified to better address variable generation. VAR-001 R3 states that "The Transmission Operator shall specify criteria that exempt generators from compliance with the requirements defined in Requirement 4, and Requirement 6.1." VAR-001 R4 and R6.1 refer to requirements to operate in automatic voltage control or reactive power control. VAR-002 indicates that generators with automatic voltage regulators must operate in voltage control mode unless directed otherwise by the transmission operator.

Interconnection standards issued by transmission operators pursuant to FAC-001 are not uniform. Some transmission operators address the reactive power requirements explicitly, and some just refer back to the FERC pro-forma LGIA/SGIA. For example, the Idaho Power statement of compliance with NERC's FAC-001 states in Section R2.1.9 that "IPC's voltage, reactive power, and power factor control requirements for generators are described in its generator interconnection agreements. The requirements for generators larger than 20 MW are listed in section 9.6 of IPC's Standard Large Generator Interconnection Agreement (LGIA). For generators smaller than 20 MW, section 1.8 of IPC's Small Generator Interconnection Agreement (SGIA) describes the requirements." In contrast, the PG&E Generation Interconnection Handbook states in Section G3.1.2.2 that *"Wind generating facilities must provide unity power factor at the point of interconnection (POI), unless PG&E studies specify a range. PG&E may further require the provision of reactive support equivalent to that provided by operating a synchronous generator anywhere within the range from 95 percent leading power factor (absorbing Vars) to 90 percent lagging power factor (producing Vars) within an operating range of ±5 percent of rated generator terminal voltage and full load. (This is typical, if the induction project is greater than 1,000 kW.)"* Further, in G3.1.3, the PG&E document states that *"Inverter-based generating facilities need to provide reactive power (Vars) to control voltage. It shall be measured at the facility side (generally the low voltage side) of the step-up transformer that connects to PG&E. The facility reactive capability shall be at least capable of providing 43 percent of facility Watt rating into the system and capable of accepting 31 percent of facility Watt rating from the system."* Other standards related to reactive power capability are reviewed below.

c. ERCOT

ERCOT Generator Interconnection or Change Request Procedures[4] apply to single units larger than 20 MVA or multiple units (such as wind and solar generators) with aggregated capacity of 20 MVA connected to the transmission system. The required power factor range is 0.95 lag to lead at maximum power output and must be supplied at the POI (transmission). At partial

4 http://www.ercot.com/gridinfo/generation/ERCOTGenIntChngRequestProcedure09122007.doc.

power, reactive capability must be up to the MVAr range at rated power, or at least the required range at rated power scaled by the ratio of active power to rated power. The reactive range must be met at the voltage profile established by ERCOT. All generators are required to follow a voltage schedule, within the reactive capability of the generator, and operate in voltage regulation mode unless otherwise directed by ERCOT at power output levels equal to or greater than 10% of rated output.

d. California Independent System Operator

The California Independent System Operator (CAISO) recently proposed more detailed power factor requirements that apply to all forms of "asynchronous generation" (including wind and solar). The proposed requirement was a 0.95 lag to lead power factor baseline requirement at the POI. A parallelogram similar to the one in Figure 3 was used to specify reactive power capability versus voltage. The proposed standard also would have allowed a permissive reactive range when the generating facility output is below 20% of rated active power output. It also stated that the reactive power must be met at full real power output, and clarified that the reactive power capabilities could be met with external static or dynamic reactive power support equipment. Specific requirement for automatic voltage regulation included definitions for voltage deadband and response time. FERC rejected the CAISO proposal on the grounds that baseline reactive power requirements should be justified by a specific interconnection study.

e. HECO

The Hawaiian Electric Company (HECO) currently is determining the power factor requirements through the interconnection agreement and Power Purchase Agreement process, including for sites below 20 MW. The requirements are similar to that proposed by other bodies, with indications that a VAR requirement (that corresponds to 0.95 power factor at rated power) would be satisfactory in place of a power factor requirement.

f. AESO

The Alberta Electric System Operator (AESO) specifies reactive power requirements for wind generators, as shown in Figure 10. The basic requirement is that sustained reactive power capability shall meet or exceed 0.9 lag to 0.95 lead power factor based on the aggregated plant MW level. A portion of the reactive capability, 0.95 lag to 0.985 lead must be dynamic. Short-term reactive power capability that can be sustained for one second or longer counts toward the required dynamic reactive power capability. Subject to review and approval of the AESO, several wind plants connected to a common transmission substation may consider aggregating voltage regulation and reactive power from a single source to meet the overall reactive power requirement. The intent of voltage regulation requirements is to achieve reasonable response to disturbances as well as a steady-state regulation of +/- 0.5% of the controlled voltage. The standard identifies a minimum requirement for dynamic reactive power and permits some controlled reactive devices such as capacitor banks to satisfy total reactive power requirements. The reactive power performance (as shown in Figure 10) and voltage regulation is assessed at the low-voltage side of the transmission step-up transformer(s), and at rated collector system voltage.

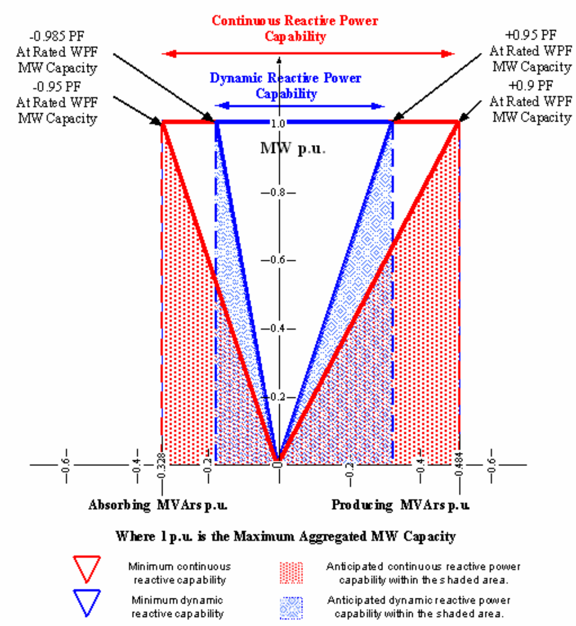

Figure 10. Reactive power capability requirement for AESO.

g. Reactive Power Requirements Applicable to Distribution Interconnection System

In North America, distribution interconnections generally conform to IEEE 1547 standards, as codified in FERC's Standard Generator Procedures (SGIP) and state-level interconnection processes. With respect to reactive power, IEEE 1547.1 states that output power factor must be 0.85 lag to lead or higher; however, distribution-connected PV and wind systems are typically designed to operate at unity or leading power factor under power factor control and can provide little or no reactive capability at full output. Operating in voltage control, often required for transmission connected generation, is not permitted under IEEE 1547.

2.2.2 International Standards

There are several good examples of interconnection standards that apply to interconnection of variable generation in Europe and elsewhere. Some examples are provided below.

a. Wind Generation "Grid Codes" in Europe

In Europe, interconnection standards for wind generation, known as "grid codes," are relatively mature compared to standards in North America. Standards vary across transmission operator jurisdictions, and there are efforts underway to harmonize the format of the standards. Power factor design requirements are expressed as a Q versus P capability curve. Some examples are provided below (Figure 11). These charts specify reactive power requirements across the full operating range of active power, not only at full output. As a point of reference, power factor design requirements at full output vary between unity and 0.9 under/over excited at the point of connection. Most codes recognize that reactive power capability depends on voltage conditions, and contain specifications to that effect.

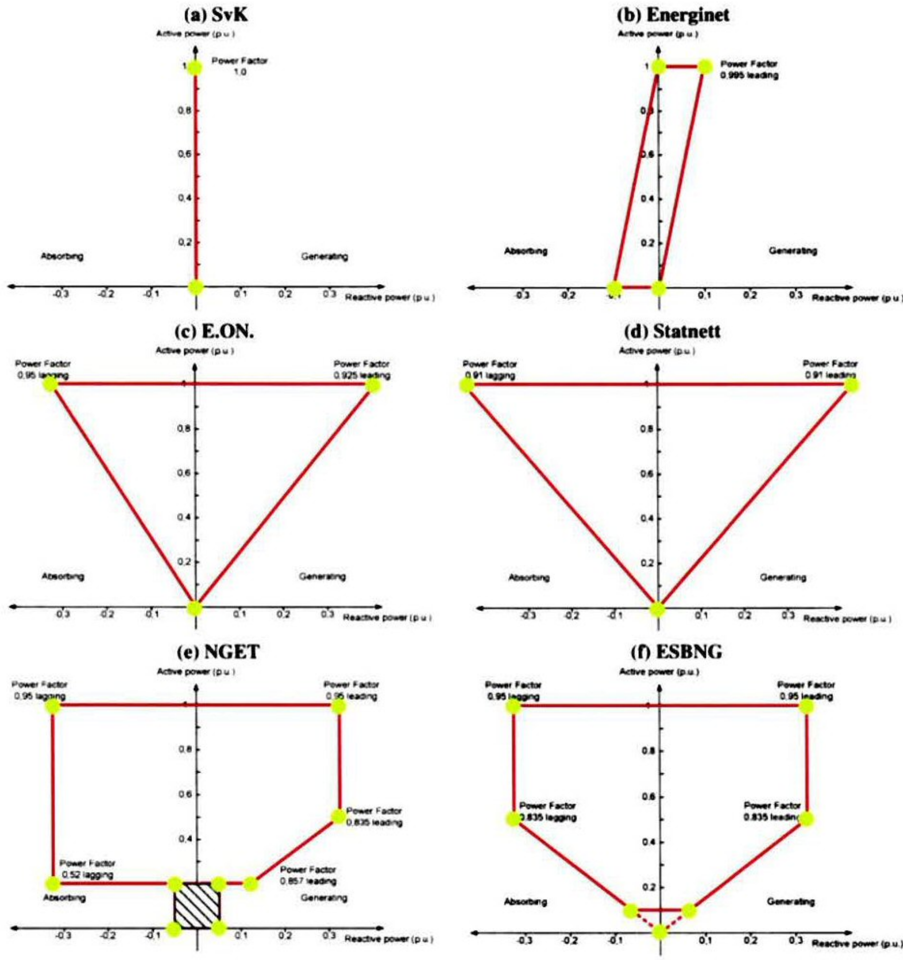

Figure 11. Sample reactive capability PQ charts from different transmission operators in Europe.

Some grid codes specify the portion of the capability curve that must be dynamic, similar to the AESO standard (Alberta). Some grid codes discuss how this reactive capability may be utilized in operations (voltage/droop control, power factor control, and reactive power control), and the expected response time for each. Some grid codes also discuss the control strategy required during fault conditions, which could play a role in the system design and equipment selection.

b. Medium Voltage Standards in Germany

Interconnection requirements for solar PV systems installed at medium voltage (10 kV to 100 kV) were recently put into effect in Germany. The power factor design criterion is 0.95 lag to lead at full output, which requires inverters to be oversized or de-rated. This standard also requires dynamic reactive power support during voltage excursions.

3 RECOMMENDATIONS FOR MODIFICATION OF EXISTING NERC STANDARDS

3.1 General Considerations for Standards Development and Reconciliation

NERC should consider revisions to Facility Connection (FAC) and VAR standards to ensure that reactive power requirements for all generators are addressed in a technically clear and technology-neutral manner. As with all new or changing requirements, appropriate consideration should be given to the applicability to existing generators. Suggested updates are as follows:

- Consider adding a clarification to FAC-001 expanding R.2.1.3 or as an appendix, stating that interconnection standards for reactive power must cover specifications for minimum static and dynamic reactive power requirements at full power and at partial power, and how terminal voltage should affect the power factor or reactive range requirement (see Section 2.1 for technical guidelines).

- Consider modifying VAR-001 to include the term "plant-level volt/var controller" (in addition to "AVR"), which is more appropriate for variable generation. Specific recommended changes are underlined below:

  "VAR-001 R4. Each Transmission Operator shall specify a voltage or Reactive Power schedule at the interconnection between the generator facility and the Transmission Owner's facilities to be maintained by each generator. The Transmission Operator shall provide the voltage or Reactive Power schedule to the associated Generator Operator and direct the Generator Operator to comply with the schedule in automatic voltage control mode (AVR or plant-level volt/var regulator in service and controlling voltage)."

A large amount of variable generation, including most of the solar PV deployment, will be relatively small plants with capacity below the threshold specified in the existing NERC Registry Criteria, and connected at voltages below 100 kV. This includes residential and commercial systems, as well as larger plants connected to the distribution or sub-transmission system. To the extent that these systems, in aggregate, can affect the reliability of the bulk grid, the FAC and VAR standards should be extended or revised to accommodate them. A prospective NERC standard addressing reactive requirements for smaller plants should recognize that distribution-connected variable generation plants have traditionally been operated in power factor control mode.

For the most part, existing NERC and FERC interconnection standards were developed with a class of equipment in mind (synchronous generators), and do not fully define performance requirements for reactive power support. This has resulted in unclear, inconsistent, and sometimes inappropriate interconnection reactive power requirements for generators, especially variable generation. Specific recommendations are as follows:

- NERC should promote greater uniformity and clarity of reactive power requirements contained in connection standards that transmission operators have issued pursuant to FAC-001. NERC, FERC, and other applicable regional standards should be reconciled.

- NERC should consider initiating a Standards Authorization Request (SAR) to establish minimum reactive power capability standards for interconnection of all generators, and provide clear definitions of acceptable control performance (see Section 2.1 for technical guidelines).

3.2 Technical Guidelines for Specification of Reactive Power Requirements

Variable generation technologies are technically capable of providing steady-state and dynamic reactive power support to the grid. Based on a review of best practices and operating experience, we offer the following technical guidelines for specification of reactive power capability and control requirements for interconnection of generating plants to the transmission system:

- **Applicability:** Generator interconnection requirements for reactive power should be clearly established for all generator technologies. NERC adheres to the notion of technology neutrality when it comes to reliability standards; however, certain unique characteristics of variable generation may justify different applicability criteria or appropriate variances. Technology differences were considered in nearly all international interconnection standards for wind generation. A key consideration is whether reactive power capability should be a baseline requirement for all variable generation plants, or if it should evaluated on a case-by-case basis. The later approach was adopted in FERC's Order 661A. A thorough analysis to establish the need for reactive power support necessitates the establishment and application of clear and consistent criteria for reactive planning that takes into account system needs such as steady-state voltage regulation, voltage stability, and local line compensation requirements under normal and contingency conditions. Without consistent application of a set of planning criteria, establishing the "need" for reactive power can become a complicated process considering that multiple transmission expansion plans and generator interconnection requests may be under evaluation. Application of a baseline requirement for reactive power to all generators would address this concern to a large extent. However, in some situations, additional reactive power from variable generation plants may not contribute appreciably to system reliability. NERC should consider giving transmission planners some discretion to establish variance based on the characteristics of their transmission system.

- **Specification of Reactive Range:** The reactive range requirement should be defined over the full output range, and it should be applicable at the point of connection. A Q versus P chart should be used for clarity. A baseline capability of 0.95 lag to lead at full output and nominal voltage should be considered. This design criterion is consistent with several grid codes and is becoming common industry practice. Unlike most conventional generators, variable generation plants routinely operate at low output levels, where it is difficult and unnecessary to operate within a power factor envelope. All or a portion of the generators in a wind or solar plant may be disconnected during periods of low wind or solar resource, which means that reactive power capability may be considerably reduced. For these reasons, it makes technical sense to allow variable generation to operate within a permissive reactive power range (as opposed to a power factor envelope) when the active power level is below a reasonable threshold such as 20% of plant rating.

- **Impact of System Voltage on Reactive Power Capability:** It should be recognized that system voltage level affects a generating plant's ability to deliver reactive power to the grid and the power system's requirement for reactive support. A Q versus V chart could be used to describe the relationship between system voltage and reactive power. A reduced requirement to inject vars into the power system when the POI voltage is significantly above nominal and a reduced requirement to absorb vars when the POI voltage is significantly below nominal should be considered.

- **Specification of Dynamic Reactive Capability:** The standard should clearly define what is meant by "Dynamic" Reactive Capability. The standard could specify the portion of the reactive power capability that is expected to be dynamic. For example, the baseline requirement could be that at least 50% of the reactive power range be dynamic. This design criterion is consistent with several grid codes. Alternatively, the definition of control performance (e.g., time response) can be used to specify the desired behavior.

- **Definition of Control Performance:** Expected volt/var control performance should be specified, including minimum control response time for voltage control, power factor control, and reactive power control. For example, a reasonable minimum response time constant for voltage, power factor, or reactive power control may be 10 seconds or comparable to a synchronous generator under similar grid conditions. Consistent with existing VAR-002, voltage control should be expected for transmission-connected plants; however, as discussed in Section 2.1, power factor control is a technically reasonable alternative for plants that are relatively small. An interim period for the application of precisely defined control capabilities should be considered.

- **Effect of Generator Synchronization on System Voltage:** Synchronization of generators to the grid should not cause excessive dynamic or steady-state voltage change at the point of connection. A 2% limit may be considered as a baseline.

- **Special Considerations:** NERC should investigate whether transmission operators can, under some conditions, allow variable generating plants to operate normally or temporarily at an active power level where dynamic reactive capability is limited or zero. If needed for reliability and upon command from the system operator, these plants could temporarily reduce active power output to maintain a reactive range. Such an approach could make sense depending on the size of the plant (more appropriate for smaller plants) and the location on the system. The possibility of operating in this manner could be considered as part of the interconnection study.

- **Technical Alternatives for Meeting Reactive Power Capability:** The reactive power requirements should be applicable at the point of interconnection. Technical options to meet the interconnection requirements should not be restricted. For example, reactive power support at the point of interconnection need not be provided by inverters themselves; they could be provided by other plant-level reactive support equipment.

- **Commissioning Tests:** Commissioning tests, which are part of the interconnection process, often include a test to demonstrate plant compliance with reactive power capability requirements. Commissioning tests often include verification of reactive power capability at rated power as a condition to allow operation at that level of output. An alternative approach should be used for variable generation plants, considering that the output cannot be controlled. For example, PV plants may be designed such that maximum output is reached only during certain months of the year, and it may not be possible to conduct a commissioning test at rated power output for several months.

4 FURTHER READING

The following resources may be useful to obtain further information on the topic of this report.

- NERC Reliability Standards, http://www.nerc.com/page.php?cid=2|20.
- T. Degner, et al., "Utility-Scale PV systems: Grid Connection Requirements, Test procedures and European harmonization," http://derlab.eu/media/pdf/press/PVI4-08_3.pdf.
- A. Ellis, "Interconnection Standards for PV Systems," *UWIG Fall Meeting*, Cedar Rapids, IA, 2009, www.uwig.org/pvwork/4-Ellis-InterconnectionStandards.pdf.
- FERC Large Generator Interconnection Agreement, http://www.ferc.gov/industries/electric/indus-act/gi/stnd-gen/2003-C-LGIA.doc.
- FERC Large Generator Interconnection procedures, http://www.ferc.gov/industries/electric/indus-act/gi/wind/appendix-G-lgia.doc.
- European Wind Energy Association, "Generic Grid Code Format for Wind Power Plants," November 2009, http://www.ewea.org/fileadmin/ewea_documents/documents/publications/091127_GGCF_Final_Draft.pdf.

APPENDIX A: Summary of Existing Reactive Power Standards

Standard	Technology Addressed	Power Factor Requirements	Voltage Range	Equipment Specified (Static/Dynamic)	Control Modes
FERC 661A - Appendix G	Wind Plants	0.95 lag to lead at point of interconnection (POI), burden of proof required from Transmission Provider	Not Specified?	By means of power electronics within the limitations due to voltage level and real power output or fixed and switched capacitors as agreed by the transmission provider	Not Addressed
NERC FAC-001	Generators larger than 20 MVA, plant/facility larger than 75 MVA in aggregate, any generator that is a blackstart unit, and any generator connected to the bulk transmission system (typically 100 kV and above).	Directs the transmission owner to define and publish connection requirements. The connection requirements must address reactive power capability and control requirements. Interconnection standards issued by transmission operators pursuant to FAC-001 are not uniform.	Not Specified?	Not Addressed	VAR-001 R4 and R6.1 refer to requirements to operate in automatic voltage control or reactive power control. VAR-002 indicates that generators with automatic voltage regulators must operate in voltage control mode unless directed otherwise by the transmission operator.
ERCOT	Single units larger than 20 MVA or multiple units (such as wind and solar generators) with aggregated capacity of 20 MVA connected to the transmission system.	The required power factor range is 0.95 lag to lead at maximum power output and must be supplied at the POI (transmission). At partial power, reactive capability must be up to the MVAr range at rated power, or at least the required range at rated power scaled by the ratio of active power to rated power.	The reactive range must be met at the voltage profile established by ERCOT.		All generators are required to follow a voltage schedule, within the reactive capability of the generator, and operate in voltage regulation mode unless otherwise directed by ERCOT at real power output levels of 10% and higher.

Standard	Technology Addressed	Power Factor Requirements	Voltage Range	Equipment Specified (Static/Dynamic)	Control Modes
CAISO (Proposed)	All Variable Energy Generation	0.95 lag to lead (consuming/producing) at POI when variable generation resources (VER) is exporting >20% of maximum rated power to the POI. Maximum VAR is a function of real power delivered (triangle VAR support above 20% rated capacity). Example, a VER is exporting 10 MW to the POI, the VER should be capable of injecting or absorbing up to 3.3 MVAr at the POI.	Ability to provide the full range of reactive power support at voltages between 0.95 and 1.05 pu was initially proposed but is under review.	By means of inverters, switched or fixed capacitors, static devices (STATCOM) or a combination of these sources.	Voltage control mode is default with ability to operate in power factor control mode. Per Western Electricity Coordinating Council requirements. Regulate voltage at POI under steady state and disturbance conditions, per the voltage schedule by use of Automatic Voltage Control System (AVCS). All reactive power devices must be controlled by AVCS. No mention of dynamic voltage support or time response. Within the limits of the rating of the equipment.
HECO (PPA Example)	Under negotiation	Minimum 0.95 lag to lead within the limits of the reactive power range at full apparent power.	Specified at Nominal Voltage		Reactive response speed (site-specific).

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