

Review of Existing Reactive Power Requirements for Variable Generation

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Abstract—In order to reliably operate the bulk electric grid generators are expected to meet certain reactive power requirements depending on the system they operate in. In the past reactive power requirements were tailored to the capabilities of synchronous generators. Variable generators such as wind and solar plants were in the past small enough relative to the entire system that they were not required to supply voltage support to the grid. As the penetration of renewable resources have grown beyond insignificance, it is now the trend that variable generators connected to transmission and sub-transmission grids should be required to provide reactive power support.

The goal of this paper is to educate the reader on the current state of reactive power requirements for variable generation. This paper discusses reactive power requirements from various regions across the world with a focus on those in North America.

Index Terms—Interconnection Requirements, reactive power, solar plant, variable generation, voltage regulation, wind plant.

I. INTRODUCTION

THIS paper discusses the key reactive power requirements applicable to variable generation in North America and internationally. There is a lot of debate today on how variable generation should contribute to the reliable operation of the electric grid. For the most part variable generation is treated more like a negative load, where the burden is on conventional generation (synchronous machines) to respond properly to changes in variable generation output, both in real and reactive power. As renewable energy technology has matured, through the use of power electronics these devices are now capable of providing reactive power support and voltage regulation. The industry is now facing the challenge of how to reconcile existing standards to take advantage of

renewable energy's capability to support the reliable operation of the bulk electric grid. The following sections discuss where the industry is at today with that effort in regards to reactive power support.

II. STANDARDS APPLICABLE TO NORTH AMERICA

The major governing bodies in North America are the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC). FERC is a United States agency responsible for regulating interstate commerce sales and wholesale electricity rates. NERC is a nonprofit corporation whose mission is to ensure that the bulk power system in North America is reliable. The following sections discuss the reactive power requirements of these governing bodies as well as some regional entities within North America.

A. FERC

FERC Order 661-A applies specifically to wind power plants with aggregated nameplate capacity greater than 20 MVA [1]. FERC Order 661-A places the burden on the transmission operator to demonstrate, through a system impact study, whether there is a need for a power factor requirement up to the 0.95 leading/lagging power factor range, and whether there is a need for dynamic reactive capability. Some transmission operators would prefer to interpret the ± 0.95 power factor and dynamic control capability criteria in FERC 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 FERC Order 661-A requiring that wind farms provide sufficient dynamic voltage support in lieu of power system stabilizer (PSS) and automatic voltage regulator (AVR). It should be noted that FERC Order 661-A does not apply to solar generation. However, some transmission service providers apply the same approach outlined in the FERC order to solar plants.

B. NERC

Applicability of NERC standards to generators is defined in NERC's Criteria Statement of Compliance Registry Criteria (Revision 5.0) [2]. Generators larger than 20 MVA, a plant/facility larger than 75 MVA in aggregate, and any

This work was supported in part by the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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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 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 [3]. The connection requirements must address reactive power capability and control requirements (R2.1.3 and R2.1.9). 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 [4] 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 [5].

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 [6],[7]. For example, the Idaho Power statement of compliance with NERC’s FAC-001 states in Section R2.1.9 that [8]:

“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) [9]. For generators smaller than 20 MW, section 1.8 of IPC’s Small Generator Interconnection Agreement (SGIA) describes the requirements [10].

In contrast, the PG&E Generation Interconnection Handbook states in Section G3.1.2.2 [11]:

“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 are reviewed below.

C. ERCOT

ERCOT Generator Interconnection or Change Request Procedures 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 [12]. The required power factor range is 0.95 lead/lag at maximum power output and must be supplied at the POI (transmission). At power output levels equal to or greater than 10% of rated output, 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. While ERCOT has explicit requirements for wind generators, work is in progress to develop requirements for solar generators that are anticipated to be similar.

D. California Independent System Operator

Solar generation LGIA’s in California have recently incorporated Interconnection Requirements similar to FERC Order 661-A. 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 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 under 20% of rated active power output. The CAISO proposal 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. The CAISO proposal also contained specific requirement for automatic voltage regulation and included definitions for voltage deadband and response time. FERC rejected the CAISO proposal for a baseline reactive power requirement and reaffirmed the approach taken in FERC Order 661-A that reactive power capability as well as volt/var control requirements should be justified through a specific interconnection study [13].

E. Hawaiian Electric Company

Due to the relatively small size of the Hawaiian Electric Company their standards for generation interconnections are more in line with those typically used at the distribution level similar to IEEE 1547 (see section G). Appendix I of HECO

Rule No. 14 discusses operating requirements for distributed generation and states that the generation facility shall not attempt to control or regulate the utility voltage and must remain within ± 0.85 pf [14].

For interconnections at the transmission level HECO is currently 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. Alberta Electric System Operator

The Alberta Electric System Operator (AESO) specifies reactive power requirements for wind generators, as shown in Figure 1 [15]. The basic requirement is that sustained reactive power capability shall meet or exceed $+0.9$ (producing) to -0.95 (absorbing) power factor based on the aggregated plant MW level. A portion of the reactive capability, $+0.95$ producing to -0.985 must be dynamic. Short-term reactive power capability that can be sustained for 1 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 $\pm 0.5\%$ 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 1) and voltage regulation is assessed at the low-voltage side of the transmission step-up transformer(s), and at rated collector system voltage.

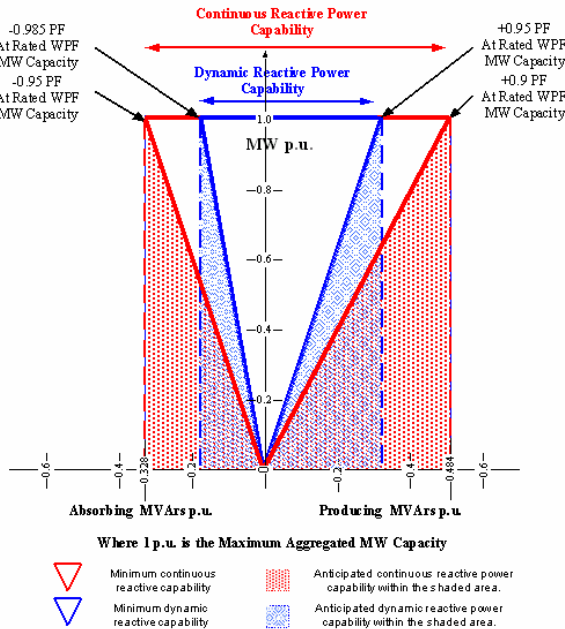


Fig. 1. Reactive power capability requirement for AESO.

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 lead/lag or higher [16]; 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 or reactive power control, required by NERC for transmission connected generation, is not permitted under IEEE 1547.

III. 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 2 and Figure 3) [17]. 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.

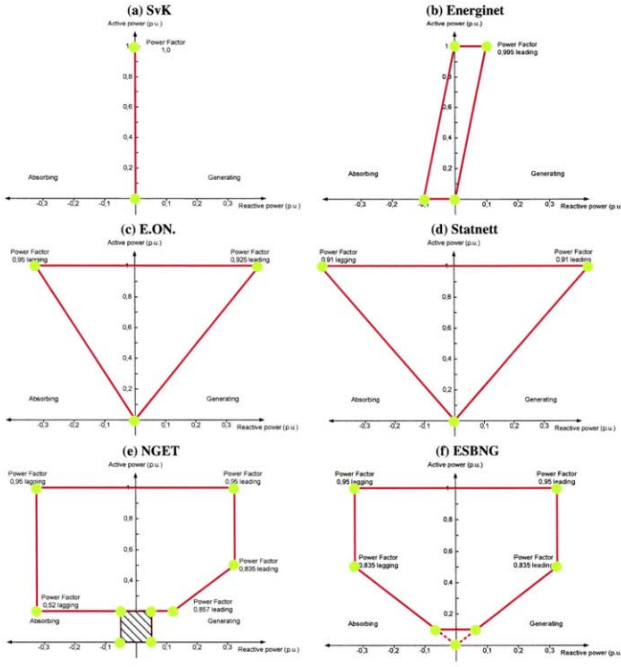


Fig. 2. Sample Reactive capability PQ charts from different transmission operators in Europe.

Most grid codes in Europe recognize that reactive power capability depends on voltage conditions, and contain specifications to that effect. This requirement is typically specified in terms of a reactive power versus voltage chart. Figure 3 shows an example of reactive power versus terminal voltage level.

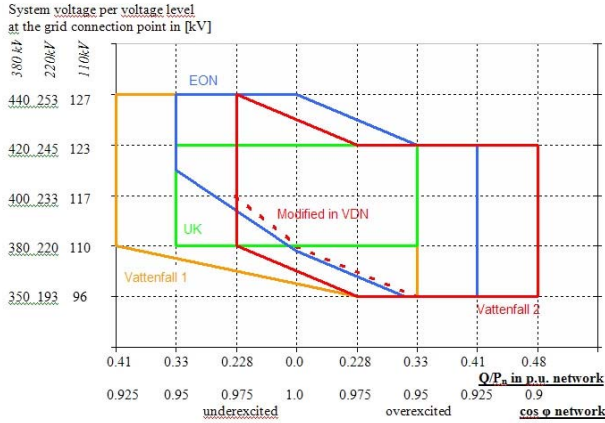


Fig. 3. Examples of Q versus V charts in Europe.

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 [18]. The power factor design criterion is ± 0.95 at full output, which requires inverters to be oversized or de-rated. This standard also requires dynamic reactive power support during voltage excursions.

C. Australia

Australia's National Electricity Market has two sets of requirements, an "Automatic Standard" and a "Minimum Access Standard." If the generating plant does not meet the Automatic Standard, it must meet at least the Minimum Access Standard and then can work with the relevant local utility to establish a "Negotiated Access Standard." This approach allows for flexibility on both the utility and developer side. The Automatic Standard is a Reactive Power requirement rather than a power factor requirement, with the Negotiated Standard performed on an individual project basis. Some technical details are provided regarding Automatic Voltage Regulation.

IV. APPENDIX - SUMMARY OF EXISTING REACTIVE POWER REQUIREMENTS

TABLE I
SUMMARY OF FERC ORDER 661-A REACTIVE POWER REQUIREMENTS

FERC Order 661-A - Appendix G	
Technology Addressed	Wind Plants
Power Factor Requirements	± 0.95 leading/lagging at Point of Interconnection (POI), burden of proof required from Transmission Provider
Voltage Range	Not Specified
Equipment Specified (Static/Dynamic)	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
Control Modes	Not Addressed

TABLE II
SUMMARY OF NERC FAC-001 REACTIVE POWER REQUIREMENTS

	NERC FAC-001
Technology Addressed	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).
Power Factor Requirements	Directs 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.
Voltage Range	Not Specified

Equipment Specified (Static/Dynamic)	Not Addressed
Control Modes	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.

TABLE III
SUMMARY OF ERCOT REACTIVE POWER REQUIREMENTS

ERCOT	
Technology Addressed	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.
Power Factor Requirements	The required power factor range is 0.95 lead/lag 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.
Voltage Range	The reactive range must be met at the voltage profile established by ERCOT.
Equipment Specified (Static/Dynamic)	
Control Modes	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.

TABLE IV
SUMMARY OF CAISO REACTIVE POWER REQUIREMENTS

CAISO (Proposed; rejected by FERC)	
Technology Addressed	All Variable Energy Generation
Power Factor Requirements	±0.95 leading/lagging (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.
Voltage Range	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.

Equipment Specified (Static/Dynamic)	By means of inverters, switched or fixed capacitors, static devices (STATCOM) or a combination of these sources.
Control Modes	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.

TABLE V
SUMMARY OF HECO REACTIVE POWER REQUIREMENTS

HECO (PPA Example)	
Technology Addressed	Under negotiation
Power Factor Requirements	Minimum 0.95 leading, 0.95 lagging within the limits of the reactive power range at full apparent power.
Voltage Range	Specified at Nominal Voltage
Equipment Specified (Static/Dynamic)	
Control Modes	Reactive response speed (site-specific)

TABLE VI
SUMMARY OF AUSTRALIAN NEM REACTIVE POWER REQUIREMENTS

Australian NEM Minimum Connection Standards	
Technology Addressed	>30 MW, All technologies?
Power Factor Requirements (Minimum)	None
Power Factor Requirements (Automatic)	See VAR Requirement
Voltage Range	Not Specified
Equipment Specified (Static/Dynamic)	Regulates V, pf, or Q. Settling times of < 7.5 s for 5% change in voltage set point where this would not cause any limiting device to operate.
Equipment Specified (Static/Dynamic) (Minimum)	No capability to supply or absorb reactive power at the connection point (POI).

Equipment Specified (Static/Dynamic) (Automatic)	Capable of supplying and absorbing continuously at its POI equal to product of rated active power and 0.395, at any level of active power output and any voltage at the POI (within network limits) without a contingency event.
Control Modes (Minimum)	Regulates V, pf, or Q. Settling times of < 7.5 s for 5% change in voltage set point where this would not cause any limiting device to operate.
Control Modes (Automatic)	within 0.5% of setpoint, continuously controllable from 0.95 to 1.05 per unit of POI voltage without reliance on tap changing transformer. Settling times for P, Q, V of < 5 s for 5% change in voltage set point. Reactive power rise time < 2 s.

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VI. BIOGRAPHIES

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