Reactive Power Compensation for Wind Power Plants

IEEE PES Wind Plant Collector System Design Working Group

***Contributing Members*: E.H. Camm, M. R. Behnke, O. Bolado, M. Bollen, M. Bradt, C. Brooks, W. Dilling, M. Edds, W. J. Hejdak, D. Houseman, S. Klein, F. Li, J. Li, P. Maibach, T. Nicolai, J. Patiño, S. V. Pasupulati, N. Samaan, S. Saylors, T. Siebert, T. Smith, M. Starke, R. Walling**

Abstract—**This technical paper provides the basic guidelines for the application of reactive compensation systems to be used as part of a wind power plant. A brief history of wind plant reactive compensation system is discussed, then the fundamental needs of why reactive compensation is required. The paper will then provide some alternatives for reactive compensation, how to size the reactive compensation, and finally some of the principles on how different compensation devices work.**

Index Terms— **voltage ride-through, induction generator, reactive power, wind power generation**

I. Introduction

The application of wind plants has grown dramatically in the recent past. Historically wind power plants (WPPs) have been smaller in size (less megawatts) per plant. The amount of wind penetration was not an issue for almost all applications. With the continued growth/increase in the individual turbine size and the number of turbines connected to the grid at a single connection point, wind plants can easily be in the hundreds of megawatts. The traditional turbine was usually a simple induction generator with little capability for voltage ride through (VRT) or power factor (PF) control. During systems disturbances the plant would most likely trip off-line. In addition, the wind plant did not have to supply any ancillary services such as voltage control, variable power factor, dynamic system support, etc. In general, older wind plants did not require reactive compensation systems. The recent generation of turbines has far greater capability. Wind power plant centralized control systems can provide the ancillary services required by the interconnection agreements. In addition, more requirements are being applied to have the wind plants respond like traditional synchronous machine generation plants during fault conditions, and to have dynamic response and control capability. All of these factors require the wind plant to have a collector system design that can accommodate these conditions.

II. Reactive Power Compensation

The requirements and type of reactive power compensation in conjunction with the collector system are key to having a compliant wind plant system.

A. Requirements

There are multiple areas for consideration when deciding on the reactive power compensation system within the WPP collector design. Most WPPs have an interconnection agreement that may define the parameters of what is required. In the United States the Large Generator Interconnection Agreement (LGIA) for WPPs rated 20 MW or more defines the requirements associated with reactive power compensation. These requirements could refer to certain standards issued by FERC/NERC, local ISO requirements such as ERCOT and WECC, or local utility requirements. Some requirements could be the result of a system impact study that may have been performed. FERC Order 661-A [1] defines the minimum power factor and VRT requirements for the interconnection of WPPs to transmission providers under FERC jurisdiction. A wind power plant designer should be aware that a reactive power compensator alone may not ensure low voltage ride- through for the wind power plant. Rather, it is the interaction with the grid of the reactive power compensator with the particular wind turbine generators in the WPP as a system that influences compliance with these requirements.

Once the main requirements are known there is a secondary listing that may further define items such as the response time, voltage control requirements, power factor control requirements, constant susceptance requirements, low voltage ride-through, high voltage ride-through, post fault contingency requirements, and voltage recovery requirements as part of the wind power plant and reactive compensation system.

1) Power Factor Requirement

FERC Order 661-A requires WPP to operate at power factors from 0.95 leading through 0.95 lagging if the Transmission Provider's System Impact Study shows that such a requirement is necessary to insure operational security

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of the system. It is typically stated that the power factor (PF) compliance of the WPP must be met at the POI (Point of Interconnection). The WPP is allowed to meet power factor requirement through the capabilities of the WTG (Wind Turbine Generator), fixed and switched shunt capacitors/reactors or a combination of the two. The WPP is usually required to follow the voltage schedule (static voltage) imposed by the Transmission Provider which consequently determines the WPP operating PF required at any given time. It is recognized that the WPP may not be able to meet the power factor range requirement under all possible operating scenarios. For instance, when there is near zero power generation and only a couple of turbines may be online at low power levels, some transmission providers and grid codes allow a lower amount of power factor control [9].

2) Dynamic Voltage Support Requirements

FERC Order 661-A states that WPPs shall be able to provide sufficient dynamic voltage support (as opposed to static) in lieu of power system stabilizer and automatic voltage regulation of conventional generating units. Such requirements are imposed only if the Transmission Provider's System Impact Study concludes that the dynamic capability of the WPP is necessary for operational security of the system. Some ISOs/RTOs further define the response time for reactive support.

3) Low Voltage Ride-Through Requirements

WPPs are required to demonstrate low voltage ride-through capability to interconnect to the transmission system. FERC Order 661-A states that the WPPs are required to remain in-service during three-phase faults with clearing time between 4 to 9 cycles. In other words, the WTGs should not trip for zero voltage at the high voltage side of the WPP substation transformer lasting up to 0.15 seconds. The WPP should also remain in-service during single-line-to-ground faults with delayed clearing, and subsequent post-fault voltage recovery to pre-fault voltage. The LVRT requirements do not apply for faults between the WTG terminals and the high voltage side of the WPP. The WPP may meet the LVRT requirements of this standard by the performance of the generators or by installing additional equipment or both

The LVRT requirements in the FERC order represents the minimum requirements. Some ISOs/RTOs have adopted these requirements, and others such as WECC have proposed additional requirements. The WECC has a proposal [2] that is currently out for comment and balloting which applies to all generating units, including WTGs. In this proposal, beside the previously mentioned LVRT requirements, the generator's protection system is required not to trip the generator for the low voltage deviations of 20% for 40 cycles (post-disturbance undervoltage) at the high voltage side of the WPP substation transformer. It is also required that the owner of the WPP have evidence that their protection systems for WTG do not trip the generator during three-phase faults with normal clearing (for a maximum of 9 cycles).

4) High Voltage Ride-Through Requirements

WPPs are subject to high voltages that can occur in the transmission system following fault clearance, loss of large loads, or other system transients. There is no HVRT requirement in FERC Order 661-A. Some ISO/RTOs, NERC, and Hydro Quebec are in the process of implementing or have implemented such requirements. In many European countries WPPs are required not to trip for a high voltage level up to 110% of the nominal voltage at the POI. WPPs are also required not to trip for higher voltage level if it lasts less than a pre-specified time period.

B. Wind Plant Details

With the requirements known the actual design and sizing of the reactive compensation can begin. The details of the wind plant will need to include the following items:

- Point of interconnection (POI).
- Minimum and maximum short-circuit levels with associated X/R ratios at the POI.
- Make, model, MW rating and number of wind turbine generators (WTGs).
- Control mode(s) at the POI; (i.e. voltage control, power factor control, constant susceptance control) along with the acceptable tolerances, dead bands, slopes, or other measures of dynamic response for these items.
- Location of turbines relative to the POI.
- WTG power factor capability, control modes available (i.e., power factor, voltage, or reactive power).
- WTG and wind power plant SCADA dynamic response times, WTG VRT capability.
- WTG step-up transformer details (MVA, percent impedance, X/R ratio, and available taps).
- Collector cable schedules, including cable types, sizes, and lengths.
- If applicable, details of collector substation transformer(s) (MVA, percent impedance, X/R ratio, and available taps)
- If applicable, transmission line data (R, L, C) and distance from the collector substation transformer to the POI.

C. Wind Plant Analysis

As mentioned previously, a system impact study may have been completed already to provide the requirements of the reactive power compensation system for the wind power plant. It will be necessary to perform more detailed studies to further define the actual components of the reactive power compensation system. Some of the standard studies that are done in conjunction with the reactive compensation system are steady-state load flow, dynamic (or voltage stability), and harmonic analyses.

The studies will incorporate the wind plant requirements and the actual details of the wind plant. The type of reactive compensation could be from any combination of the WTGs, mechanically-switched devices (i.e., shunt capacitor or reactor banks), STATCOMS, SVCs, etc. The actual devices chosen will have to comply with the requirements of the wind plant. Further items for consideration may include voltage limitations during switching of shunt capacitors, power quality requirements such as flicker during start up or cut-in, harmonics, etc.

Studies which involve the reactive power compensation system are discussed next. Other wind power plant studies are discussed in a companion Working Group paper.

1) Load Flow Studies

Load flow studies typically require a detailed model of the collector grid with the actual cables and routing taken into account. The POI should be clearly defined and in accordance with the interconnection requirements. This may be on the high side or low side of the main substation transformer, or even located miles away if an additional transmission line was added for the wind power plant.

Some wind power plants have on-load tap changers (OLTCs) on the main substation transformer. The turbine PF range capability shall be taken into account. Note some turbines have the ability to vary power factor while others maintain a constant power factor. The reactive compensation needs to be modeled also. The types of reactive compensation are discussed in section III.B.

Typically the power factor range is required at nominal voltage, but it may also be required if the POI voltage is varied (i.e. +/-5%) while maintaining required power factor range. The reactive compensation system usually is required to be operational between +/-10% voltage at the POI, but the available range may have a reduced range during this condition. The power factor requirement may also change as a function of the generation level [9]. The WPP does have auxiliary load that should be included in the analysis.

2) Dynamic Analysis

Dynamic analysis is performed to varying degrees between projects. This analysis may be provided by the transmission provider/ISO or by the WPP. If the interconnecting utility can supply the actual phasor (or rms) model with the base cases and contingencies this will yield the best results. Some utilities do not provide their system details, thus it may be required to build an equivalent utility system model (less preferred) from the known data. In addition to this model provided by the interconnecting utility or equivalent system, models of all other devices should be added as mentioned above for the load flow. The turbine dynamic model with actual settings is important. Refer to section IV on voltage ride-through for more detail.

Dynamic analysis has a base requirement per FERC Order 661-A. This requires zero voltage ride through for 3-phase faults on the high side of the main power transformer cleared in 4-9 cycles (depending on the fault clearing times of the circuit breakers involved and further definition provided by the local transmission provider) and single line-ground faults with delayed clearing. Typically single line-ground fault clearing times are provided by the transmission provider.

The studies may also include the response time of the complete system to meet the reactive power requirements. Some ISO's require that the WPP responds similarly to that of conventional synchronous generators and that power factor targets are met within a short duration (i.e. 1 second). This may be equivalent to traditional excitation systems on generators.

3) Harmonic and Flicker Analysis

Harmonic analysis will require the same inputs as used for the load flow studies with the addition of a few items. Any harmonics generation sources within the wind farm shall be included. This typically includes the WTGs and, if applicable, the reactive compensation devices. All types of turbines can create resonance conditions, due to passive elements in their design. In addition Type 3 and 4 [10] WTGs can create resonance due to their control design. The short-circuit level range at the POI with associated X/R ratios will also be needed. Care should be taken to insure frequency dependent elements are modeled correctly. It is also sometimes required to include any background/existing "ambient" harmonics and local reactive compensation devices. Typically the background harmonics are not known at the time of the studies, but may be required if analysis reveals resonance conditions at characteristic harmonic frequencies.

The harmonic analysis should cover all reasonable operating scenarios. Different combinations of generation output, components of the reactive compensation, short-circuit levels, etc will need to be modeled. Resonance conditions can occur due to substation switched capacitor banks and power factor correction capacitors (PFCCs) in WTGs. Detuning of the capacitor banks may be required in some cases, to ensure potential impacts do not negatively affect the collector system and equipment. It may not be possible to avoid all resonance conditions, but it should be avoided in the most common operating scenarios.

The harmonic generation level requirements may be defined in the generation interconnection details. In the United States IEEE Std. 519 [11] is commonly used as a guideline for these requirements.

Power quality of the WPP may be limited to the harmonic analysis, but may also include flicker calculations. The main concern for flicker is the voltage change that may occur when a SSD is switched or during WTG startup and cut-in. Large steps in voltage, 1% to 5% depending upon the turbine manufacturer, may have an adverse effect on the WTG, in particular the gear box. Other flicker concerns due to continuous or switching operations (such as startup and cut-in) are usually limited to small wind power plants connected to distribution systems that other customers may be directly connected to. To analyze this detail of flicker the turbine manufacturer needs to provide the associated flicker test data of their units.

III. Reactive Power Flow During Normal Operation

The reactive power flow from the grid to the wind plant at the POI is given, simplified, by the following expression:

$$Q_{poi} = Q_{gen} + 3I^2X - V^2\omega C - Q_{comp} \qquad (1)$$

where Q_{gen} is the leading (inductive) reactive power consumption of the turbines (which is negative when WTG is operating at a lagging (capacitive) power factor), X the equivalent series reactance of cables, lines and transformers, C the equivalent shunt reactance of (especially) cables, and Q_{comp} the reactive-power injected by any centralized reactive power compensation system. For simple induction generators the reactive power consumption depends on the loading and on the terminal voltage according to the following approximation:

$$Q_{gen} = \frac{V^2}{X_m} + 3I^2 X_l \quad (2)$$

Where X_m and X_l are the magnetizing and leakage reactance, respectively. For DFIG and full-power-converter machines the reactive power can be controlled on the terminals of the machine or at the grid side of the turbine transformer within the WTG capability.

Without any reactive power compensation, the reactive-power exchange consists of a term proportional to the square of the voltage and a term proportional to the square of the current. As the voltage variations are much less than the current variations, it is the latter term that requires the main compensation.

A. *Example*

The generation and consumption range of reactive power for 200 MW WPP is summarized in Table I. The WPP consists of 100 2-MW Type 3 WTG with PF capabilities from 0.98 leading to 0.98 lagging. A total of 72 MVAR (6 steps, 12 MVAR each) of reactive power compensation is installed on the substation MV bus. The reactive power generated by the cables is given for rated voltage. The variations in collector cable reactive-power generation are small during normal operation. The reactive power consumed by the series reactance of the cables and transformers is given for rated current. The reactive-power consumption varies with the square of the current. It is this variation that requires compensation to meet the requirements at the POI.

TABLE I
REACTIVE POWER FLOWS FOR A CERTAIN OPERATING SCENARIO IN A 200 MW WPP

Elements of WPP	Reactive power generated at rated voltage	Reactive power consumed at rated current
Substation transformer (235 MVA, 345/34.5 kV)	------	38 Mvar
Substation based reactive compensation	0 to 72 Mvar	------
Collector 38 kV cables/OH lines	11 Mvar	7 Mvar
WTG Transformers	------	23 Mvar
WTGs (Type 3, PF range from 0.98 leading to 0.98 lagging)	0 to 40 Mvar	0 to 40 Mvar
Total	11 to 123 Mvar	68 to 108 Mvar

B. *Types of Reactive Power Compensation*

The following is a listing of the main types of reactive power compensation equipment and some general principles of operation.

1) *Mechanically-Switched Shunt Capacitors*

Capacitors banks typically consist of a grouping of individual capacitor units. The bank is then either considered fixed or it can be switched using appropriately rated devices. These banks can either be “metal enclosed” or “open rack” design. It is important that special attention be paid to the switches. They should be rated for capacitor switching [4]. It is only possible to control slow variations in reactive power. The capacitive VAr output is a function of the voltage such that the VArs decrease with the square of the voltage (i.e. 90% voltage will provide 81% VAr capability) Using a number of capacitor banks of different size, the reactive power exchange can be kept within a range. Capacitor banks typically require a 5 minute discharge time before they can be re-energized, but there are also designs that allow for shorter durations on a limited basis.

2) *Mechanically-Switched Shunt and Regulated Reactors*

Reactors are typically mechanically switched devices. Again, it is only possible to control slow variations in reactive power. The inductive VAr output is a function of the voltage such that the VArs decrease with the square of the voltage (i.e. 90% voltage will provide 81% VAr capability).

Regulated shunt reactors are shunt reactors equipped with a tap-changer as used for voltage control with a transformer. Using such a ”regulated shunt-reactor”, a more smooth control of reactive power can be achieved [6]. A study presented in [5] shows the feasibility of this tool for reactive power control with large wind power plants.

3) *Static Var Compensator*

An SVC is typically a fixed shunt capacitance in parallel with reactance that is controlled using thyristors. This type of controller is made using static components. When the thyristors are used in the control process, then the controller is considered dynamic. These allow for a control of reactive power at time scales down to the order of a 100 milliseconds. Additional filters must be used to avoid harmonics which are created when the current wave shape distorts from the thyristor switching. Further details on SVC can be found in IEEE Std.1031.

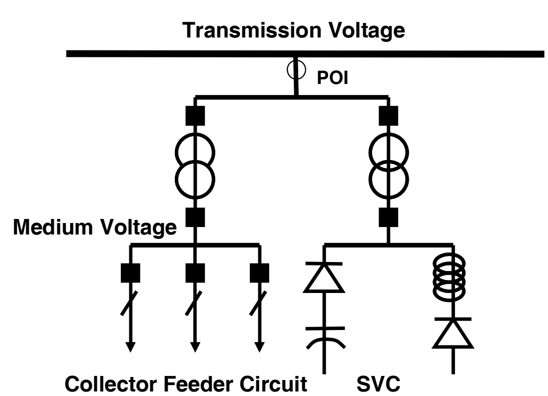

Figure 1. Typical configuration of SVC for WPPs.

4) Static Synchronous Compensator

A STATCOM is a voltage-source converter. It does not use thyristors for switching, but instead uses IGBT (Insulated-Gate Bipolar Transistor) or IGCT (Integrated Gate Commutated Thyristor) switching devices to either source or sink reactive power to the electric network. Some STATCOM units may have short-time overload capabilities for 2 to 4 seconds. The VAr output is a linear function of the voltage, VArs decrease linearly with the voltage (i.e. 90% voltage will provide 90% VAr capability) since they are constant current controllers.

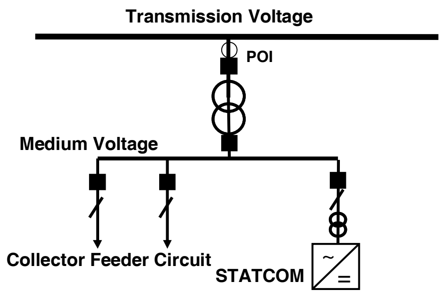

Figure 2. Typical configuration of STATCOM for WPPs.

5) WTGs

WTGs can provide or consume reactive power, depending on the type. Simple induction generators typically employ PFCCs to correct the power factor at the terminals of the machine to unity of near unity. DFIG and full converter-based WTGs can operate dynamically over a defined power factor range (e.g. 0.95 inductive to 0.95 capacitive). A specific turbine may have different steady state vs. dynamic capability. Refer to a companion WG paper for more details on WTG reactive power capabilities.

C. Choice of reactive power compensation

The reactive power compensation for a wind plant typically consists of a combination of different technologies. Assume that the reactive power required to be generated by the wind power plant, is between inductive 50 Mvar to capacitive 100 Mvar. Some of the possible solutions could be:

- ✓ Qty 2 – 25 Mvar switched shunt reactors and Qty 4-25 Mvar switched shunt capacitors. This solution will not be able to hit a specific power factor or voltage target under all conditions.
- ✓ Qty 4 – 12.5 Mvar switched shunt reactors and Qty 8-12.5 Mvar switched shunt capacitors. This solution will be able to hit more specific power factor or voltage targets, but still not all under all conditions.
- ✓ Qty 1 – 25 Mvar switched shunt reactor, Qty 1- 25 Mvar regulated reactor and Qty 4 – 25 Mvar switched shunt capacitors. This solution should be able to come close to a specific power factor or voltage target under all conditions.
- ✓ Qty 2 – 25 Mvar switched shunt capacitors and +/-50 MVAR from WTG's, assuming WTG's have the capability. This solution should be able to hit a specific power factor or voltage target under all conditions.
- ✓ Qty 1 – -50 to +100 Mvar SVC. This solution will be able to hit a specific power factor or voltage target under all conditions.
- ✓ Qty 1 – -50 to +100 Mvar STATCOM. This solution will be able to hit a specific power factor or voltage target under all conditions.

The choice of reactive power compensation system is an economic decision considering initial investment and life-cycle cost, where the requirements set by the network operator act as an important boundary condition.

IV. Voltage Ride-Through

Transmission system operators often put strict requirements on the voltage ride-through of wind power plants. The details of the requirements differ between network operators and this paper does not aim at covering all possible requirements. There are however some common elements in most of the requirements on voltage ride-through.

- A worst-case voltage dip is defined for which the wind power plant should remain connected to the grid. In many cases a fault at the POI is assumed with a given duration. After the fault a slow voltage recovery is assumed.
- The wind power plant production should recover to its pre-fault value within a certain time after fault clearing.
- Some network operators also put requirements on active and/or reactive power flows during the fault.

Not all network operators have such requirements in place, but it is to be expected that with the growing penetration of wind power, soon all transmission network operators will enforce rather strict requirements on voltage ride-through.

A. Design requirements

Different solutions for voltage ride-through have been developed and are under development by different wind turbine manufacturers. Voltage ride-through may be obtained by making the turbine immune against the worst-case voltage dips or in combination with certain measures in the collection grid. It is possible that the WTG does have VRT capability and still fails to comply with the interconnect VRT requirements.

In this section we will discuss some of the aspects of voltage-ride-through, without being able to go into details. The requirements on voltage-ride-through also have their consequences on the protection and coordination of the WTGs.

1) During-fault behavior

A fault at the POI will put severe restrictions on the amount of active power that can be produced by the turbines. Consider a simple model with one aggregated turbine connected to the POI through an impedance $Z = R + jX$. For a three-phase fault at the POI, the active and reactive power flows from the turbines towards the grid are:

$$P = \frac{V^2}{Z^2} R \qquad (3)$$

$$Q = \frac{V^2}{Z^2} X \qquad (4)$$

where V is the terminal voltage of the turbines. Note that the power flowing into the grid is zero since the voltage at the POI is zero. This may result in the turbines accelerating and in power electronic converters either tripping or reaching their current limit. It is important to ensure that no dangerous overspeed is reached and that the converters remain connected or are reconnected quickly once the voltage has recovered

2) *Post-fault recovery*

The behavior after the fault depends strongly on the type of machine. With type 1 and 2 WTG's, sufficient reactive power should be available to bring the machines back to their nominal speed. A design rule, for industrial systems with large amounts of induction machines, is that the grid should be able to supply six times the rated power of the machines as reactive power, without the voltage at the machine terminals dropping below 0.7 pu. Additional sources of reactive power may be needed for this in wind power plants due to the large distances between the individual turbines. Sometimes a collector based solution (not within the turbine) is used.

An additional problem with DFIG machines is that the controller should be able to detect the transition from fault to post-fault. The response is dependent on the pre-fault operating state of the WTG (e.g., supersynchronous vs. subsynchronous speed), the nature of the fault (balanced or unbalanced), and the specific measures taken by the WTG manufacturer to limit the converter DC link voltage during these events. If the WTG does not crowbar during VRT it typically can supply reactive power during this time, if it does crowbar it will consume reactive power similar to a Type 1 WTG. The voltage at the turbine terminals needs to have recovered sufficiently for the DFIG controller to be able to switch back to normal operation. This may require some central source of reactive power as well. The details of this depend on the design of the turbine and its controller.

The recovery of turbines with a full power converter is easier as they do not require any reactive power. Once the voltage at the POI recovers, the voltage at the terminals of the converters recovers and their controllers can switch back to normal operation.

B. *Example*

Wind plants have a certain voltage ride-through capability even without additional measures. This depends among others on the voltage-sag immunity of the turbines. As mentioned before, for induction generators the source impedance at the generator terminals is an important factor as well. The voltage-ride-through of such a wind power plant is shown in Fig. 3 for two values of the short-circuit ratio (SCR) [7]. The requirements set by the network operator are typically more stringent than this so that additional measures are needed.

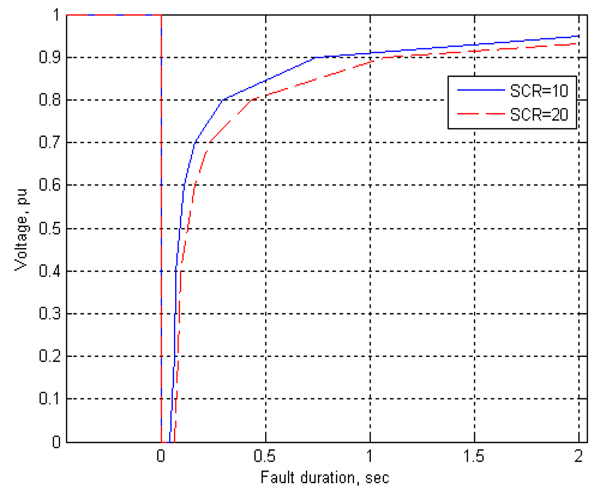

Fig. 3. Voltage ride-through of a wind power plant with induction machines without any additional ride-through measures as a function of the short circuit ratio.

C. *Simulations*

Once a preliminary design for the wind plant has been chosen, a dynamic simulation of the complete wind plant is needed to verify if it fulfills the requirements on voltage ride-through. Such a simulation should contain a detailed model of the turbines, including their control system, and of the complete collection grid. Any control equipment (like SVC or switched capacitor banks) present in the collection grid should also be included in the model.

It is strongly recommended to use a time-domain model (also known as "electromagnetic transient model") instead of just a phasor model (also known as "rms model").

To fulfill the voltage ride-through requirements it is also needed to obtain information from the turbine manufacturer about the behavior of the turbines during low voltage situations. In many cases it will be needed to obtain black-box models of the turbines and their control system.

Various studies have shown that aggregated or simplified models may not give accurate results of the voltage ride through. Such models may still be used to illustrate the impact of different parameters and to study different improvement methods. However to illustrate the fault-ride-through of a real wind power plant against a real grid, a complete and detailed model is needed.

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