Reactive Power-Voltage Control of Inverter Based Resources

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1 Introduction

There are two types of electric power. Active power is the power transmitted to loads and converted into useful forms of energy, such as mechanical, heat, or light. Reactive power does not perform useful work but is used to establish and maintain electromagnetic fields that are needed to generate, transmit, and convert electric power in an AC network.

Reliable operation of the bulk power system requires that frequency and voltage be controlled within defined limits through the balancing of active and reactive power supply and demand [1]. At every moment, the active and reactive power produced must equal customer demand plus losses. If active power demand exceeds production, frequency will decline until active power balance is restored. Similarly, a shortage of reactive power will cause voltage to decline until reactive power balance is restored.

Reactive power supply and voltage control is an ancillary service needed to maintain reliable operation of the bulk power system. Historically, this ancillary service was provided by conventional synchronous generators, and wind generators were exempt from reactive power requirements. Exempting wind generators was not likely to affect system reliability in 2005 when wind represented 0.4% of the total electricity (kWh) generated in the U.S. [2] and there were no solar PV installations larger than 20 MW. By 2016, wind and solar PV had grown to 6.8% of the total electricity generated [3] and continuing to exempt these non-synchronous generators could have caused reliability issues as penetration increased and synchronous generators were retired from operation. The Federal Energy Regulatory Commission (FERC) issued Order No. 827 in 2016, which applies comparable reactive power requirements to synchronous and non-synchronous generators.

Wind turbines, solar PV inverters, and battery energy storage inverters are asynchronously connected to the grid and either partially or completely interfaced through power electronics. For this reason, non-synchronous generators are also referred to as Inverter-Based Resources (IBRs).

This paper reviews reactive power requirements for non-synchronous generators, associated performance criteria, and modeling of reactive power-voltage controls for planning and operating studies. These concepts are illustrated using a typical wind power plant and a typical solar PV power plant.

2 Reactive Power Requirements

In 2003, FERC established standard procedures for large generator interconnections with an output rated over 20 MW. Order No. 2003 required that large generators provide reactive power in the range of 0.95 leading to 0.95 lagging at the point of interconnection [4]. The standard interconnection procedures were designed around the needs of large synchronous generators, and FERC recognized that different requirements might be needed for newer technologies, such as wind generators. FERC exempted wind plants from the Order No. 2003 reactive power requirement but left a placeholder in the standard Large Generator Interconnection Agreement for requirements of generators relying on newer technologies [5].

In 2005, FERC Order No. 661 established standard requirements for the interconnection of large wind plants. Most wind turbines manufactured at the time utilized conventional induction generators or variable rotor-resistance induction generators that could not control voltage and used power factor correction capacitors to maintain the power factor at the generator terminals. Recognizing that wind plants would have to install costly equipment to have reactive power capability, FERC preserved the exemption unless the transmission provider showed, through the System Impact Study, that reactive power capability was required to ensure safety or reliability [6]. This exemption applied only to large wind plants and did not apply to non-wind technologies. There were no solar PV plants subject to the standard procedures for large generator interconnections (rated output greater than 20 MW) prior to 2009.

FERC Order No. 827 was issued in 2016 and eliminated the exemption for wind plants from the requirement to provide reactive power. FERC eliminated the exemption in part because of improvements in technology and declining costs for new wind generators to provide reactive power.

Order No. 827 established four requirements for all newly interconnecting non-synchronous generators [7]:

1. **Power Factor Range.** The generating facility is required to provide dynamic reactive power within the power factor range of 0.95 leading to 0.95 lagging, unless the transmission provider has established a different power factor range that applies to all non-synchronous generators in the transmission provider’s control area on a comparable basis.
2. **Point of Measurement.** The reactive power requirement for non-synchronous generators is measured at the high side of the generator substation (i.e. the high side of the main facility transformer).
3. **Dynamic Reactive Power Capability.** Non-synchronous generators may meet the dynamic reactive power requirement by utilizing a combination of the inherent dynamic reactive power capability of the inverter, dynamic reactive power devices, and static reactive power devices to make up for losses.
4. **Real Power Output Level.** Generating facility is required to meet the reactive power requirements at all levels of real power output.

3 Static Versus Dynamic Reactive Power

Order No. 827 allows non-synchronous generators to meet the dynamic reactive power requirement by utilizing a combination of the inherent dynamic reactive power capability of the inverter, dynamic reactive power devices, and static reactive power devices to make up for losses.

The main difference between static and dynamic reactive resources is how quickly they respond to power system changes [8].

- **Static Reactive Resources**
  - Provide fixed reactive power output at nominal voltage and output varies according to the square of the system voltage
  - Switched on or off in discrete blocks based on system conditions
  - Mechanically switched so switching times are on the order of cycles
  - Examples include mechanically switched shunt capacitors and reactors
  - Use as a dynamic resource is limited because of switching times and because capacitors need to discharge for several minutes after switching off
- **Dynamic Reactive Resources**
  - Output is continuously adjusted to provide variable amounts of reactive power independent of system voltage.
  - Response time is milliseconds.
  - Examples include synchronous generators, synchronous condensers, static var compensators (SVCs) and static compensators (STATCOMs)

Static reactive resources are usually switched in response to slowly changing system conditions, such as daily load cycles or variable renewable energy; whereas, dynamic reactive resources are used to respond to rapidly changing conditions due to system disturbances.

4 Reactive Power and Voltage Control

Reactive power and voltage control at a wind or solar PV power plant is accomplished using the following controls.

- Plant-level voltage controller
- Inverter-level controls
- Plant-level capacitor and reactor banks (if present)
- OLTC (if present) or DETC on main power transformer

Figure 1 shows an equivalent power flow representation of a wind or solar PV power plant. This representation is used to model the plant for steady state power flow and positive sequence stability analyses when our focus is performance at the POI and not within the plant. This representation includes a single equivalent generator, equivalent GSU transformer, and equivalent collector system. The plant-level reactive compensation, main power transformer, and interconnection tie line are modeled explicitly.

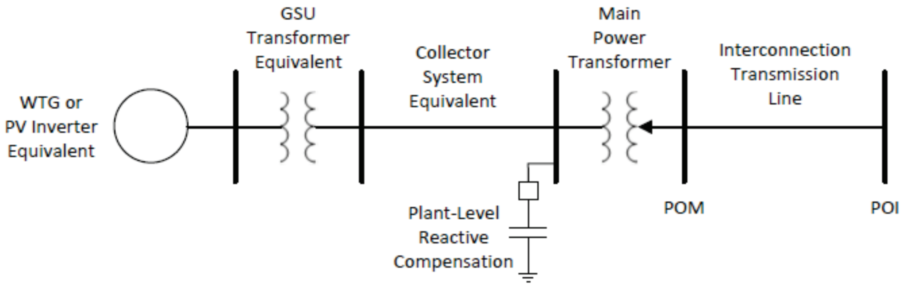

Figure 1. Wind or Solar PV Power Plant Model

NERC Reliability Standard VAR-002-4.1 requires that each generating facility operate in automatic voltage control mode and maintain the voltage schedule provided by the Transmission Operator. Voltage control at the POI or POM is one of the functions of the plant-level controller, which provides supervisory control over all inverters in the generating facility as shown in Figure 2. The plant-level controller distributes voltage or reactive power setpoints to each inverter based on the difference between the scheduled and measured voltage. Inverters inject reactive power in response to command from the plant controller. Individual inverters may also provide fast control of local voltage or reactive power, in which case the plant level controls and inverter controls should be coordinated.

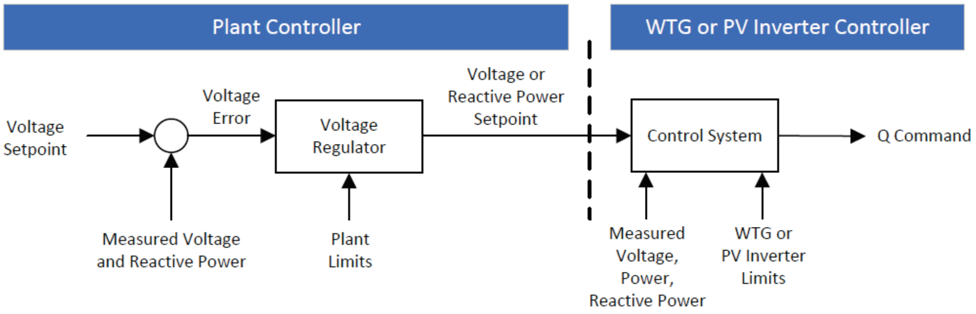

Figure 2. Plant Reactive Power and Voltage Control [9]

Wind or solar PV power plants may have plant-level capacitor banks to make up for reactive power losses within the plant. These capacitors are usually controlled with the objective of maintaining inverter dynamic reactive power capability and are switched based on reactive power flow. Capacitor banks are static resources and switched based on steady state reactive power requirements but not short duration events handled by the inverter reactive power capability.

The main power transformer will be equipped with an on-load tap changer (OLTC) or a de-energized tap changer (DETC) to adjust the transformer taps. The objective of the tap changer is to maintain the 34.5 kV collector system in a range to maximize the supply and absorption of reactive power by the inverters. This objective means that the collector system voltage should be kept near nominal. If the transformer is equipped with an OLTC, the controls are normally set to hold a voltage near nominal. If the transformer is equipped with a DETC, the tap is selected to maximize the supply and absorption of reactive power over the expected voltage range at the POM.

5 Performance Requirements

Wind turbines, solar PV inverters, and battery energy storage inverters are asynchronously connected to the grid and either partially or completely interfaced through power electronics. Unlike synchronous generators, the response of these non-synchronous generators is dominated by the controls programmed into the inverters and plant level controller instead of the physical design of the equipment.

IEEE has a working group that is drafting a standard (P2800) that will establish the recommended interconnection capability and performance criteria for inverter-based resources. This section of the paper highlights performance recommendations for reactive power-voltage control and reactive current-voltage control from the NERC Reliability Guideline: BPS-Connected Inverter-Based Resource Performance [10].

5.1 Order No. 827

The NERC Reliability Guideline recommends that Transmission Owners ensure that FERC Order No. 827 requirements are implemented correctly by the Generator Owner. Order No. 827 requires that generating facilities provide reactive power within the power factor range of 0.95 leading to 0.95 lagging at all levels of real power output.

Figure 3 shows the Order No. 827 requirement along with a typical generating facility capability curve at the POM. The critical points are usually with the generating facility operating at rated output and with the generating facility operating at low output near 0 MW. Many wind turbines and solar inverters cannot control voltage at zero active power output unless this option is purchased by the Generator Owner. This capability should always be confirmed, even if the reactive power capability provided by the manufacturer is D-shaped.

The plant shown in Figure 3 requires mechanically switched capacitors to satisfy Order No. 827 requirements when operating above 90% of rated output.

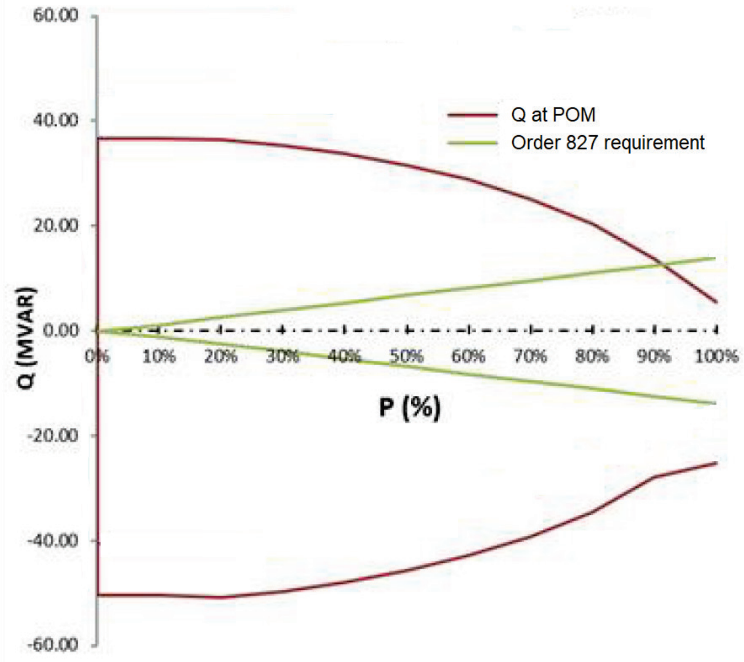

Figure 3: Plant Capability Curve, POI Voltage = 1.0 per unit [10]

Figure 3 assumes nominal voltage at the POI, and Order No. 827 does not specify a voltage range for the reactive power requirement. System voltage affects the reactive capability of the generator as well as the need for reactive power from the plant. To ensure proper implementation, the Transmission Owner should consider power factor requirements at different system voltages.

For instance, the Australian Energy Market Operator relaxes reactive power requirements for leading or lagging power factor depending on whether voltage is below or above 1.0 per unit as shown in Figure 4 [11]. When voltage is 1.0 per unit, the plant is required to provide reactive power within the power factor range of 0.95 leading to 0.95 lagging. Leading capability must be maintained when voltage is higher than nominal, and lagging capability must be maintained when voltage is lower than nominal.

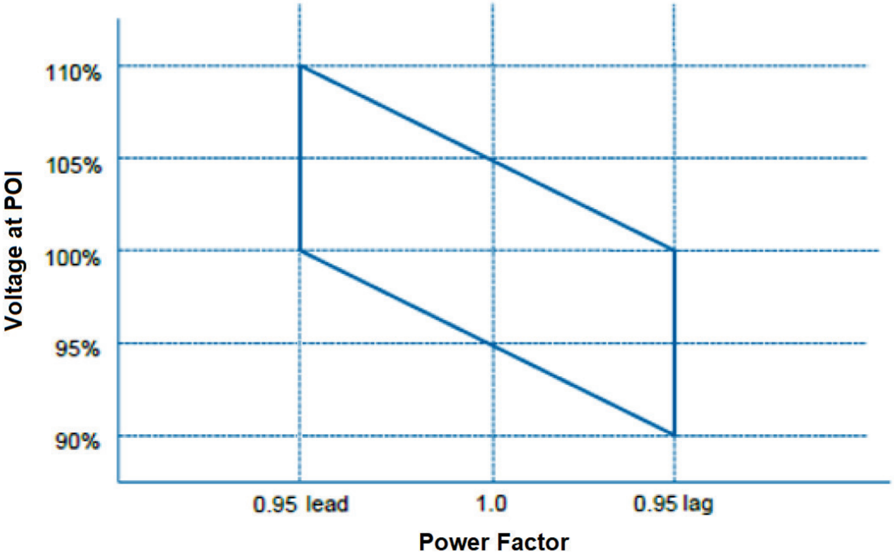

Figure 4. Example of Reactive Power Requirement as a Function of Voltage [11]

Examples of performance requirements where reactive power requirements are voltage dependent are listed below:

- Requirements with voltage-dependent limits
    - Australian Energy Market Operator [11]
    - Florida Power and Light [12]
    - National Energy Regulator of South Africa [13]
- Requirements with detailed calculation instructions
    - California ISO [14]
    - ISO New England [15]

5.2 Disturbance Performance Characteristics

The response to system disturbances is provided by the plant-level voltage controller and inverter-level controllers. NERC Reliability Standard VAR-002-4.1 requires that each generating facility operate in automatic voltage control mode, and NERC recommends that IBRs operate in closed-loop automatic voltage control to support voltage regulation and voltage stability [10]. To avoid voltage collapse, either the inverter-level controller or plant-level controller should provide a fast response.

For the typical reactive power and voltage control shown in Figure 2, the plant-level controller provides the primary response to small disturbances where voltage at the inverters remains within the continuous operating range, typically ±10% of nominal voltage. The inverter-level controllers provide the primary response to large disturbances that cause voltage to fall below the continuous operating range such that the inverters go into ride-through mode.

In order to support system voltage schedules, post-contingency voltage recovery, and voltage stability, the generating facility should meet or exceed the small disturbance performance characteristics in Table 1. The reactive power response to a change in POM voltage should occur without intentional delay; the 500 ms target given in Table 1 for reaction time is dependent in part on how often the plant-level controller updates inverter setpoints and any communication latencies. The NERC Reliability Guideline indicates that plants in high penetration areas of ERCOT are tuned with overall plant response times of less than 5 seconds [10].

Table 1. Small Disturbance Reactive Power-Voltage Performance [10]

Parameter	Description	Target
Reaction Time	Time between the step change in voltage and when the resource reactive power output begins responding to the change	< 500 ms
Rise Time	Time between a step change in control signal input (reference voltage or POM voltage) and when the reactive power output changes by 90 percent of its final value	< 1-30 sec
Overshoot	Percentage of rated reactive power output that the resource can exceed while reaching the settling band	< 5 %

The inverter-level controllers provide the primary response to large disturbances that cause voltage to fall below the continuous operating range such that the inverters go into ride-through mode. The inverters should meet or exceed the large disturbance performance characteristics in Table 2.

Table 2. Large Disturbance Reactive Current-Voltage Performance [10]

Parameter	Description	Target
Reaction Time	Time between the step change in voltage and when the resource reactive current output begins responding to the change	< 16 ms
Rise Time	Time between a step change in control signal input (reference voltage or POM voltage) and when the reactive current output changes by 90 percent of its final value	< 100 ms
Overshoot	Percentage of rated reactive power output that the resource can exceed while reaching the settling band	Determined by TP/PC

Some Transmission Planning entities have incorporated specific disturbance performance requirements for IBRs. Entergy has incorporated the NERC Performance Guidelines into facility interconnection requirements [16]. The Independent Electricity System Operator in the province of Ontario requires that a non-conventional generating facility demonstrate that both the speed and magnitude of reactive power response is comparable to an equivalent size synchronous machine [17].

6 Generic Models for Positive Sequence Stability Analysis

A good representation of the dynamic electrical performance of power plants is needed to perform accurate power system simulations for planning and operating studies. In the early 2000s, wind turbine manufacturers began providing Generator Owners with proprietary user-written models. Proprietary models present several challenges [18]:

- Models are considered proprietary by manufacturers and cannot be distributed.
- It is difficult to obtain model updates from manufacturers.
- Model may not be available in all commercial planning software platforms.

To address these challenges, the WECC Renewable Energy Modeling Task Force developed a suite of generic models for renewable energy plants that are available as standard library models in commercial planning software platforms. When using the WECC models, it is important to be aware of the model technical specifications [19]. It may be necessary to use manufacturer-specific models and/or EMT analysis for some studies where the system is weak.

- The models are intended to provide a representation of dynamic electrical performance at the point of interconnection with the electric system and not necessarily within the power plant.
- The models are intended for analyzing electrical phenomena in the frequency range of zero to 10 Hz.
- The models are applicable for systems with a short circuit ratio of 3 and higher at the point of interconnection.

The models are modular, and the modules used to represent a specific plant depend on the prime mover and other controls. Specific inverter and plant controller responses are represented using model parameters provided by the Generator Owner and manufacturers. The modules used to represent reactive power-voltage control are shown in Figure 5 and discussed in more detail in the following sections.

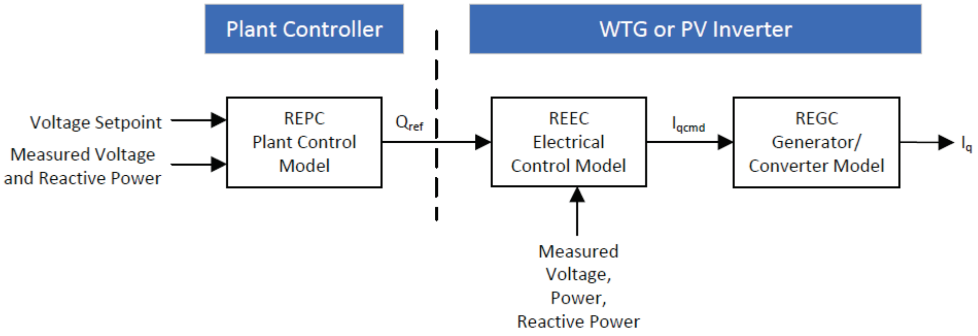

Figure 5. Generic Models for Plant Reactive Power and Voltage Control

6.1 Renewable Energy Generator/Converter Model

The Renewable Energy Generator/Converter (REGC) model represents the generator/converter interface with the grid. The model inputs are real (Ipcmd) and reactive (Iqcmd) current commands, and the outputs are real (Ip) and reactive (Iq) current injection into the network model. The model block diagram is shown in Figure 6.

The low voltage active current management is used to model the effect of terminal bus voltage variation on active power output. The high voltage reactive current management limits reactive current injection of the inverter.

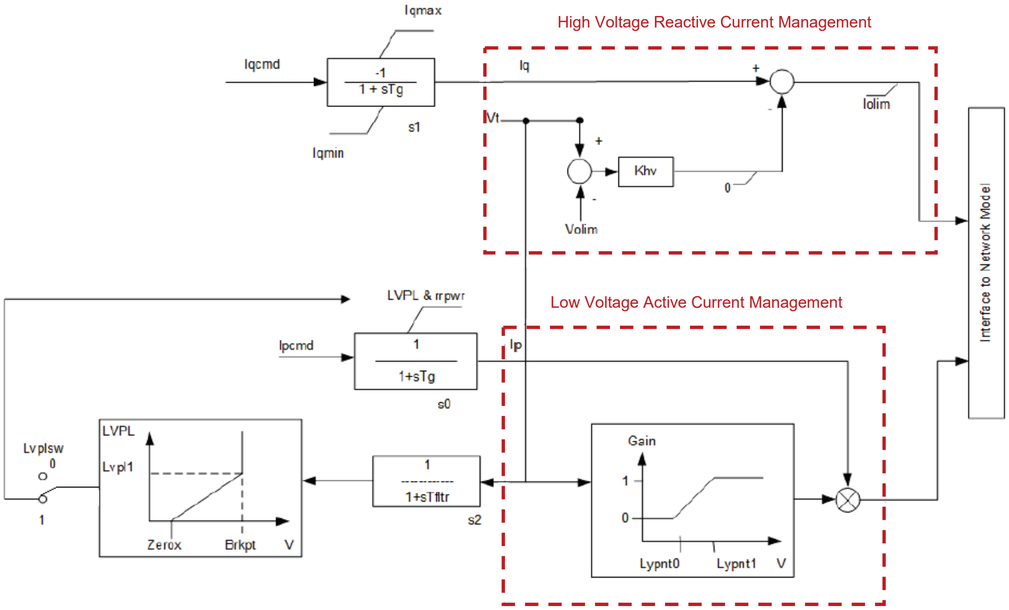

Figure 6: REGC Renewable Energy Generator/Converter Model [20]

6.2 Renewable Energy Electrical Control Model

The Renewable Energy Electrical Control (REEC) model represents the electrical control of the inverters and translates real and reactive power references into inverter current commands [21]. The references can be externally controlled using the REPC plant model. Depending on the mode of operation, the reactive power reference may correspond to either reactive power or voltage.

The four REEC models have slightly different structures in order to represent the controls associated with different prime movers:

- REEC_A, typically used for wind or solar PV
- REEC_B, use is no longer recommended by WECC
- REEC_C, typically used for energy storage
- REEC_D, typically used for solar PV

The REEC_A reactive power control structure is shown in Figure 7. The REEC model provides the ability to represent inverter-level voltage control and has several different operating modes that are selected using the flags PfFlag, VFlag and Qflag.

The upper path allows proportional control of local (terminal) voltage; in the REEC_A model, this path is only active when a voltage dip is detected. The middle path provides PI control of local voltage or coordinated local Q/V control. When Q/V control is used, the Q control generates a voltage reference that the V controller translates into a reactive current command. The lower path provides constant Q control.

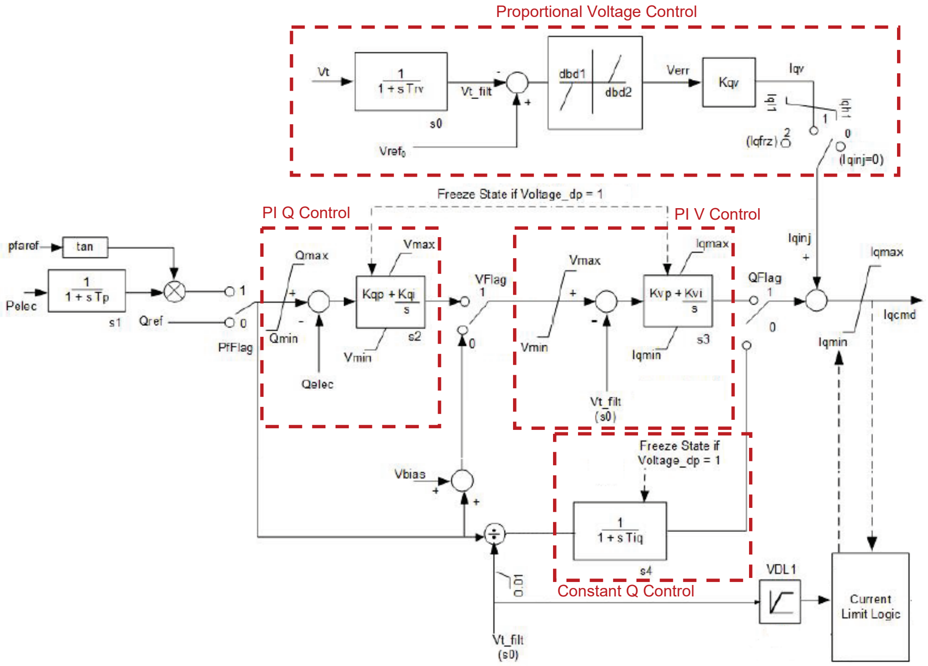

Figure 7: REEC_A Renewable Energy Generator/Converter Model Reactive Current Control (Active Current Control not Shown) [20]

6.3 Renewable Energy Plant Control Model

The Renewable Energy Plant Control (REPC) model represents the plant controller and generates real and reactive power references from plant-level inputs of regulated bus voltage, plant output, and system frequency. The reactive power control structure is shown in Figure 8, and can be used to provide plant-level voltage control or reactive power control.

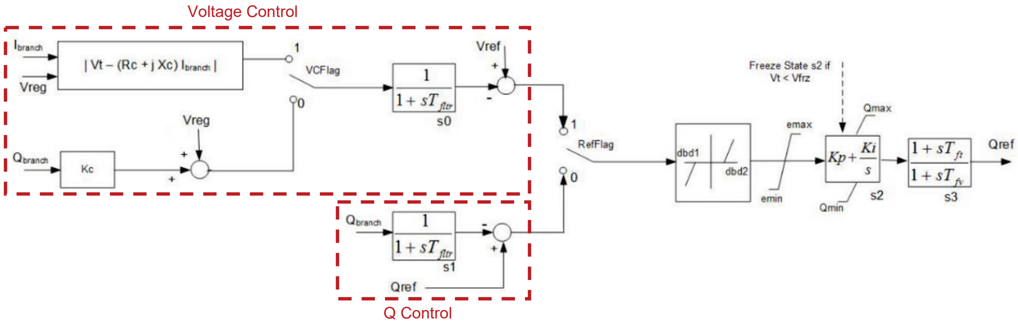

Figure 8: REPC Plant-Level Control Model Reactive Power Control (Active Power Control not Shown) [20]

In voltage control mode, VCFlag is used to select line drop compensation or reactive droop. Line drop compensation allows for regulation of voltage at a remote bus, such as the POI, by adding a voltage proportional to line current to the measured bus voltage. Reactive droop is used to avoid hunting when the point of regulation is on the high voltage system and there are plants or other voltage controlling equipment in close electrical proximity.

The droop is the voltage error that causes the reactive power output to go to the maximum (or minimum) value. Figure 9 shows a 3% reactive droop, which means that a 3% difference between the measured voltage and the reference voltage will result in a reactive power output equal to 33% of rated active power output (0.95 power factor). Reactive droop provides a reactive power setpoint based on the voltage error, which ensures coordinated control among resources in close electrical proximity.

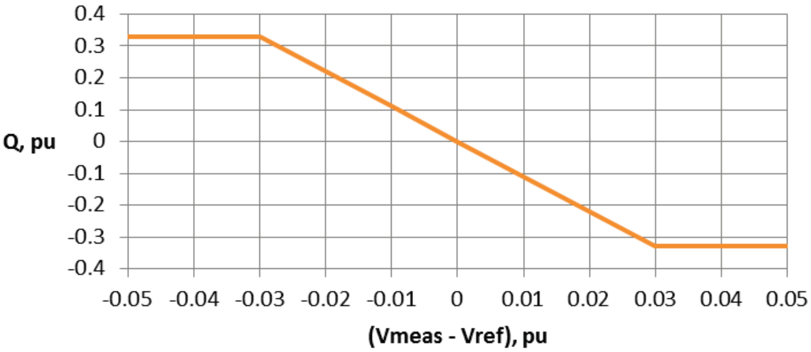

Figure 9: 3% Reactive Droop, Qmax = 33% of Prated [22]

6.4 Reactive Power-Voltage Control Options

NERC Reliability Standard VAR-002-4.1 requires that each generating facility operate in automatic voltage control mode, and IBRs control voltage with plant-level controls, inverter-level controls, or both. The flags in the REEC and REPC models can be used to simulate various combinations of plant-level and inverter-level controls. Table 3 shows a list of common control options, and the models and flags involved [19].

Table 3. Reactive Power-Voltage Control Options

Functionality	Required Models	PfFlag	VFlag	QFlag	RefFlag
Constant local power factor control	REEC	1	N/A	0	N/A
Local V control	REEC	0	0	1	N/A
Plant-level V control	REEC + REPC	0	N/A	0	1
Plant-level V control & local V control	REEC + REPC	0	0	1	1
Plant-level V control & local coordinated Q/V control	REEC + REPC	0	1	1	1
Plant-level PF control & local coordinated Q/V control	REEC + PLNTB	0	1	1	2

7 Wind Power Plant Example

Figure 10 shows an equivalent power flow representation of a 100 MW wind power plant comprising forty 2.5 MW wind turbines. The high side of the generator substation is connected to the POI by a short 161 kV transmission line, and the plant is set to regulate voltage at the high side of the generator substation to 1.02 per unit.

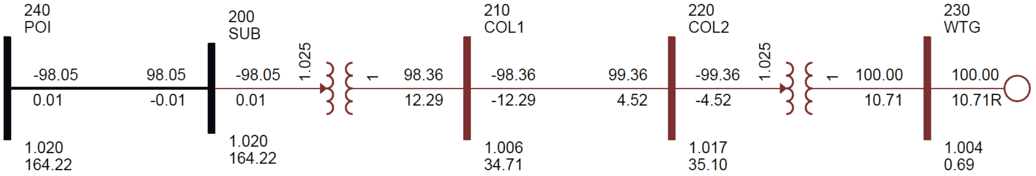

Figure 10: 100 MW Wind Power Plant

In the following sections, the wind power plant model is used to illustrate the following concepts.

- Local V Control
- Local Coordinated Q/V Control
- Plant-Level V Control & Local Coordinated Q/V Control
- Plant-Level V Control with Reactive Droop & Local Coordinated Q/V Control
- Small Disturbance Reactive Power-Voltage Performance
- Large Disturbance Reactive Current-Voltage Performance

7.1 Local V Control

In the first simulation, the wind plant is set to provide local voltage control at the equivalent turbine without plant-level control. This is done with the REPC model off and the REEC model flags set as shown for “Local V Control” in in Table 3.

Figure 11 shows the result of switching a 21 MVAr reactor at the POM at a simulation time of 1.0 second. When the terminal voltage falls in response to switching the reactor, the wind turbine quickly increases reactive power output to restore terminal voltage to the pre-switching level.

Initial and final values are shown in Table 4. In order to restore terminal voltage to the pre-switching level, the output of the equivalent turbine increases from 10 MVAr at the start of the simulation to 22 MVAr at the end of the simulation. The plant controller was turned off for this simulation so voltage at the POM is not regulated; POM voltage is 1.02 per unit at the start and 0.997 per unit at the end.

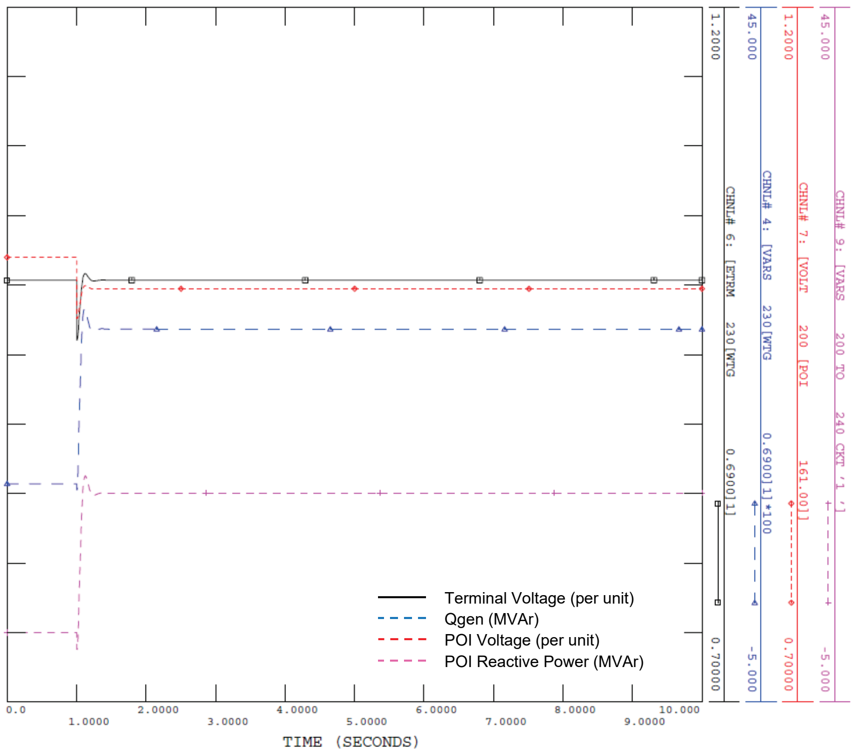

Figure 11: Local V Control

Table 4. Wind Farm Simulation Results

	Terminal Voltage (per unit)	POM Voltage (per unit)	Turbine Output (MVAr)	POM Output (MVAr)
Initial value	1.004	1.02	10.7	0
Local V control	1.004	0.997	21.8	10
Local coordinated Q/V control	0.956	0.972	10.7	-2.9
Plant-level V control & local coordinated Q/V control	1.046	1.02	32.7	21.8
Plant-level V control with droop & local coordinated Q/V control	1.027	1.01	27.8	16.5

7.2 Local Coordinated Q/V Control

The simulation is repeated with the wind plant providing coordinated Q/V control at the equivalent turbine. This is done with the REPC model off and the REEC model flags shown for “Local Coordinated Q/V Control” in Table 3.

Figure 12 shows the result of switching a 21 MVAr reactor at the POM. When the terminal voltage falls in response to switching the reactor, the local V control quickly increases wind turbine reactive power output to restore terminal voltage, and then local Q control slowly reduces the turbine reactive power output back to the pre-switching level.

Initial and final values are shown in Table 4. Voltage at the POM is 1.02 per unit at the start of the simulation and 0.972 after switching the reactor and resetting the turbine reactive power output using local coordinated Q/V control. The POM voltage can be regulated by adding plant-level control.

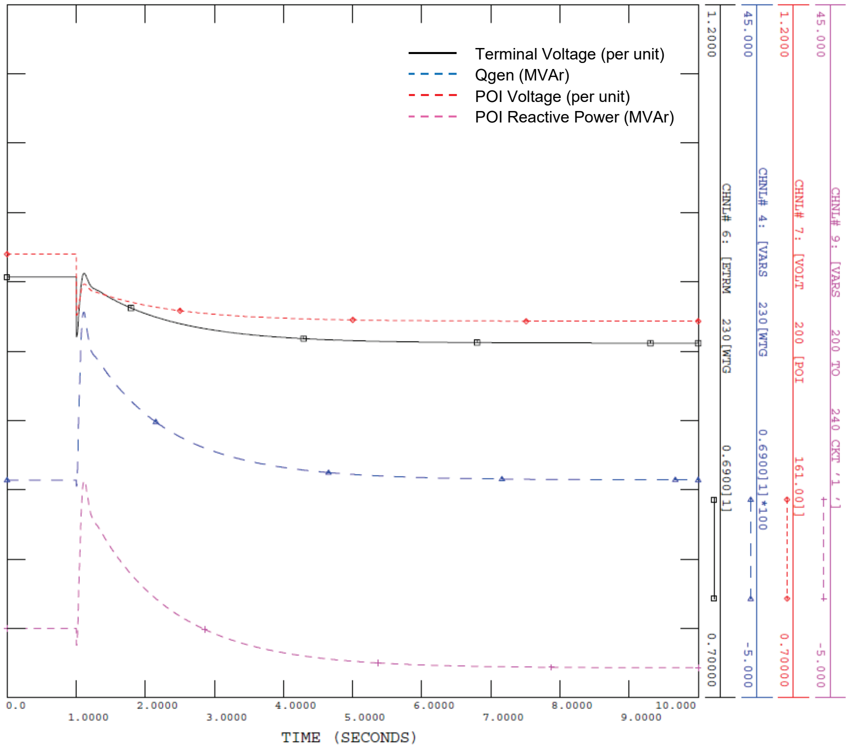

Figure 12: Local Coordinated Q/V control

7.3 Plant-Level V Control & Local Coordinated Q/V Control

Plant-level voltage control is added using the REPC model without reactive droop. The REEC electrical controller is modeled with local coordinated Q/V control.

Figure 13 shows the result of switching a 21 MVAr reactor at the POM. When the terminal voltage falls in response to switching the reactor, local V control quickly increases wind turbine reactive power output to restore terminal voltage, and then local Q control starts to reduce the turbine reactive power output back to the pre-switching level. At a simulation time around 2 seconds, the turbine starts to increase reactive power output as a result of the plant controller changing the REEC reactive power reference in order to restore the voltage at the POM.

Initial and final values are shown in Table 4. Voltage at the POM is 1.02 per unit at the start of the simulation and 1.02 after switching the reactor.

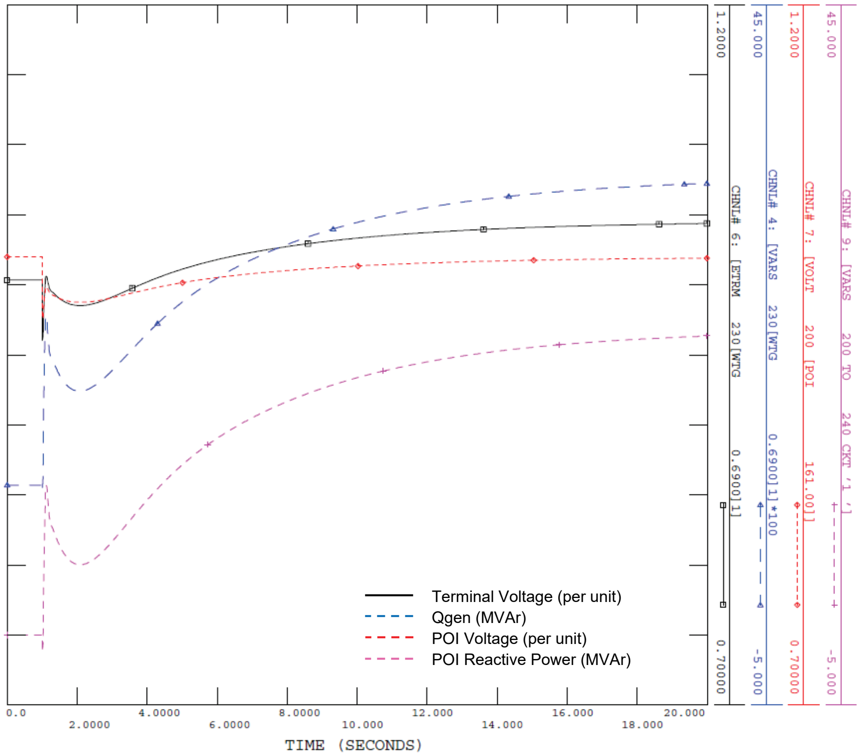

**Figure 13: Plant-Level V Control
& Local Coordinated Q/V Control**

7.4 Plant-Level V Control with Reactive Droop & Local Coordinated Q/V Control

As discussed in Section 6.3, reactive droop is used to avoid hunting when the point of voltage regulation is on the high voltage system. The droop is the voltage error that causes the reactive power output to go to the maximum (or minimum) value.

Droop is modeled using the parameter K_C in Figure 8. From Figure 8,

$$V_{ref} = V_{reg} + K_C \times Q$$

where V_{reg} is voltage at the POM and Q is reactive power flow at the POM. If the reactive droop is set to 2% on a 0.95 power factor base, the reactive output will be 0.33xrated power at a voltage error of 2%. K_C needs to be specified on the aggregate MVA rating of the turbines, which is 1.11 times rated power in this example. From the equation above,

$$K_C = \frac{V_{ref} - V_{reg}}{Q} = \frac{0.02}{0.33 \times \frac{100}{111}} = 0.0673\ per\ unit$$

Figure 14 shows the result of switching a 21 MVAr reactor at the POM. The final voltage error at the POM is 0.01 per unit and the corresponding reactive power flow is 16.5 MVAr, which is consistent with the 2% droop setting.

$$Q = \frac{V_{ref} - V_{reg}}{K_C} = \frac{0.01}{0.0673} = 0.149\ per\ unit \times 111\ MVA = 16.5\ MVAr$$

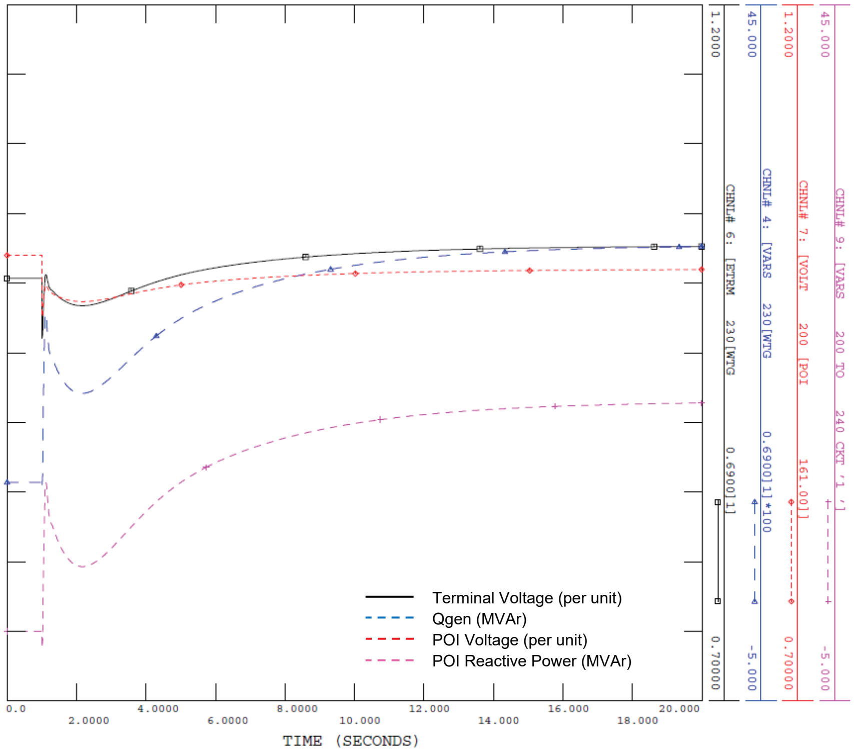

Figure 14: Plant-Level V Control with Reactive Droop & Local Coordinated Q/V Control

7.5 Small Disturbance Reactive Power-Voltage Performance

As discussed in Section 5.2, the plant-level controller provides the primary response to small disturbances where voltage at the inverters remains within the continuous operating range. Small disturbance performance can be evaluated using techniques similar to those used for MOD-026-1. Performance of the wind plant model was checked by applying a 2% step to the plant reference voltage. The plant was modeled with plant-level V control with reactive droop and inverter-level coordinated Q/V control as described in Section 7.4.

Plant reactive power response to the 2% step is shown in Figure 15 and summarized in Table 5. Performance exceeds the targets from the NERC Inverter Based Resource Performance Guideline.

Table 5. Small Disturbance Reactive Power-Voltage Performance

	Target	Simulated
Reaction Time	< 500 ms	25 ms
Rise Time	< 1-30 sec	6.5 sec
Overshoot	< 5 %	0%

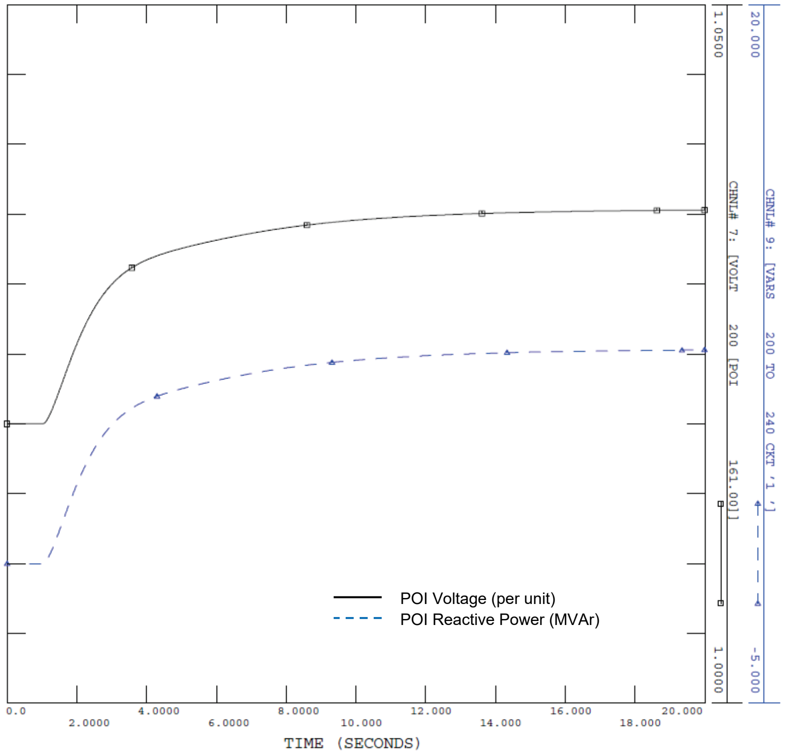

Figure 15: Small Disturbance Reactive Power-Voltage Performance

7.6 Large Disturbance Reactive Current-Voltage Performance

The inverter-level controllers provide the primary response to large disturbances that cause voltage to fall below the continuous operating range such that the inverters go into ride-through mode. Performance of the wind plant model was checked by applying a permanent fault at the POI sufficient to drive voltage at the terminals of the equivalent wind turbine to 0.70 per unit.

Plant reactive current response is shown in Figure 16 and summarized in Table 6. Performance exceeds the targets from the NERC Inverter Based Resource Performance Guideline.

Table 6. Large Disturbance Reactive Current-Voltage Performance

	Target	Simulated
Reaction Time	< 16 ms	16 ms
Rise Time	< 100 ms	42 ms

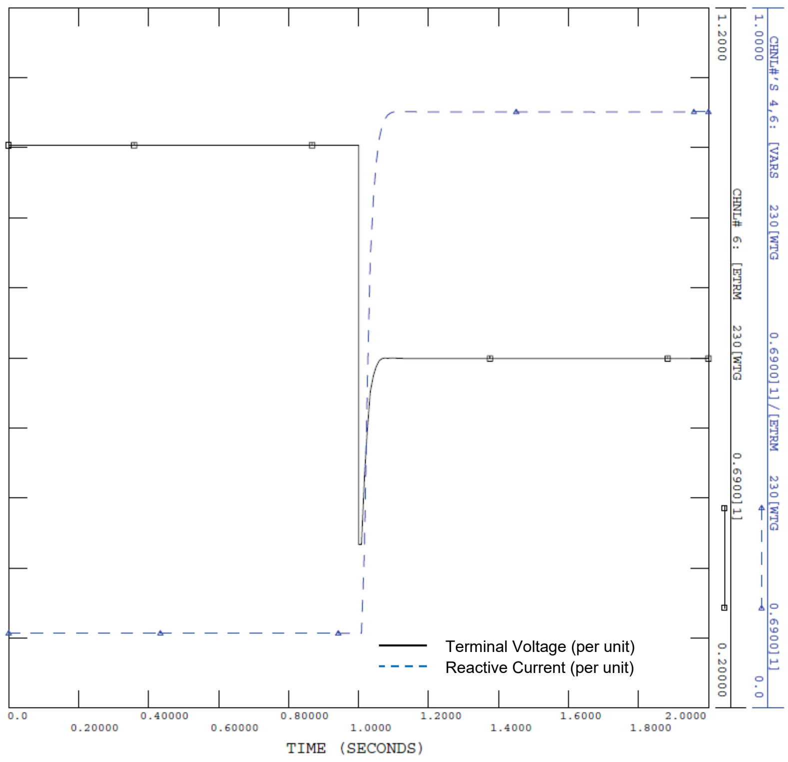

Figure 16: Large Disturbance Reactive Current-Voltage Performance

8 Solar PV Power Plant Example

This example uses a 100 MW solar PV power plant that has an equivalent power flow representation similar to the wind power plant shown in Figure 10. The plant has plant-level V control with reactive droop and inverter-level coordinated Q/V control as described in Section 7.4.

8.1 Small Disturbance Reactive Power-Voltage Performance

Small disturbance performance of the solar plant model was checked by applying a 2% step to the plant reference voltage. Plant reactive power response is shown in Figure 17 and summarized in Table 7. Plant reactive power performance does not meet the targets from the NERC Inverter Based Resource Performance Guideline. This issue should be resolved with the project developer before performing any studies.

Table 7. Small Disturbance Reactive Power-Voltage Performance

	Target	Simulated
Reaction Time	< 500 ms	16 ms
Rise Time	< 1-30 sec	29.6 sec
Overshoot	< 5 %	22%

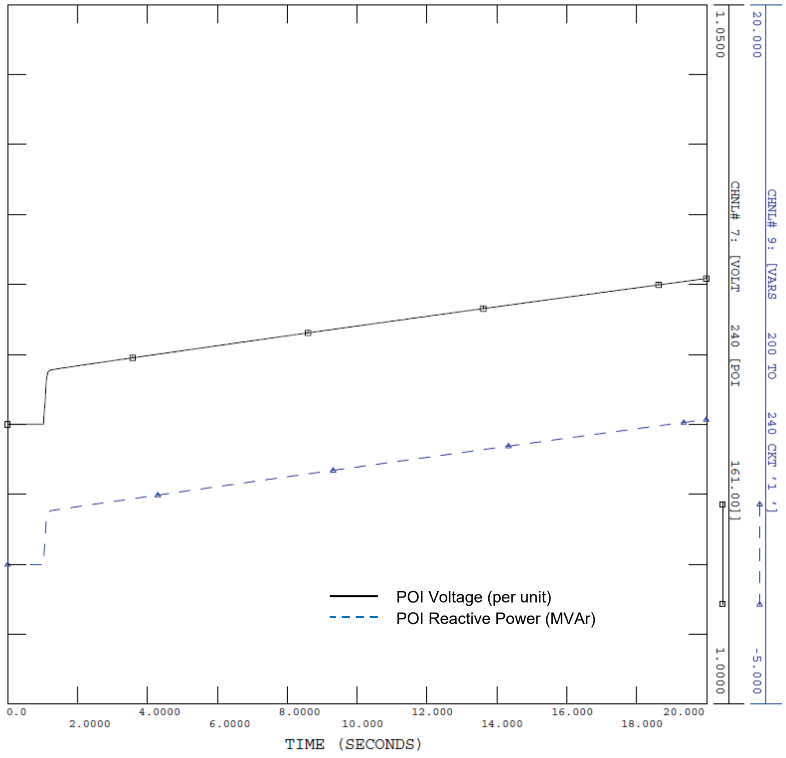

Figure 17: Small Disturbance Reactive Power-Voltage Performance

8.2 Large Disturbance Reactive Current-Voltage Performance

Large disturbance performance of the solar plant model was checked by applying a permanent fault at the POI sufficient to drive voltage at the terminals of the equivalent solar inverter to 0.50 per unit. Plant reactive current response is shown in Figure 18 and summarized in Table 8. Performance exceeds the targets from the NERC Inverter Based Resource Performance Guideline.

Table 8. Large Disturbance Reactive Current-Voltage Performance

	Target	Simulated
Reaction Time	< 16 ms	16 ms
Rise Time	< 100 ms	33 ms

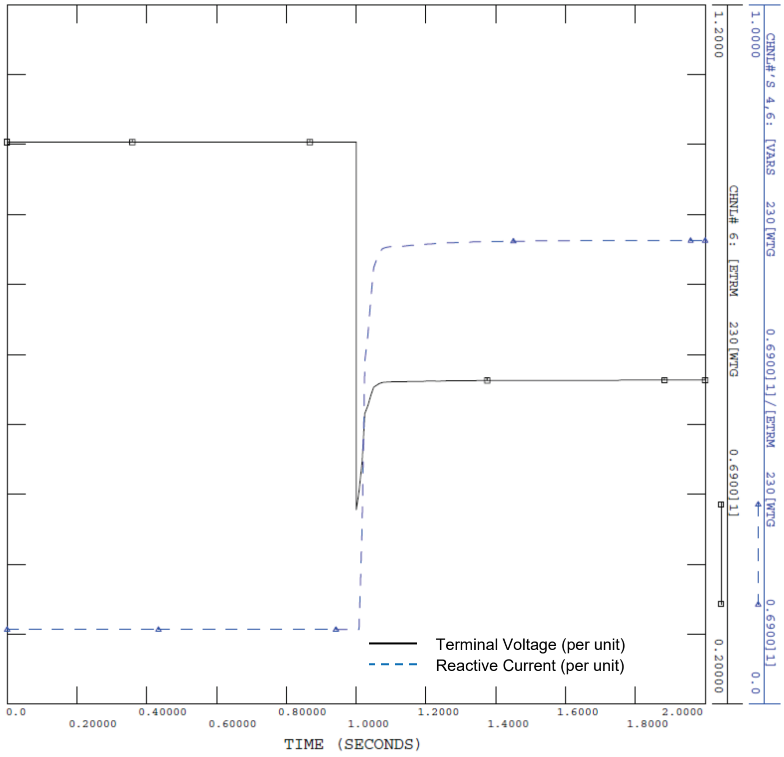

Figure 18: Large Disturbance Reactive Current-Voltage Performance

9 Conclusions

As the penetration of renewable energy resources continues to grow, these resources are being required to provide some of the ancillary services historically provided by conventional synchronous generators. FERC issued Order No. 827 in 2016, which applies comparable reactive power requirements to synchronous generators and to non-synchronous generators, such as wind and solar PV.

This paper reviewed Order No. 827 reactive power requirements and associated performance requirements being used by Transmission Planners and Planning Coordinators.

A good representation of the dynamic electrical performance of power plants is needed to perform accurate power system simulations for planning and operating studies. The WECC Renewable Energy Modeling Task Force has developed a suite of generic models for renewable energy plants, and this paper looked at the models used to represent reactive power-voltage control and how those models can be configured to represent different plant-level and inverter-level controls.

When developing regional transmission system models, the Eastern Interconnection Reliability Assessment Group (ERAG) has a dynamics initialization and checking procedure that includes validating exciter model response [23]. The NERC Performance Guidelines discussed in this paper provide small disturbance and large disturbance performance characteristics for non-synchronous generators that can be referenced by the Transmission Planner to determine whether or not model performance is acceptable before starting a system impact study or other planning or operating study.

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