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**Western Electricity Coordinating Council
Modeling and Validation Work Group**

**WECC PV Power Plant
Dynamic Modeling Guide**

**Prepared by
WECC Renewable Energy Modeling Task Force**

April 2014

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1 Introduction

Grid-connected photovoltaic (PV) systems cover a wide range of applications. Most PV systems are residential (up to several kW) and commercial scale (up to several MW) connected to distribution networks. However, many PV systems are large generation facilities (some exceeding 100 MW) and are connected to the transmission system. NERC Reliability Standards require that power flow and dynamics models be provided, in accordance with regional requirements and procedures. Under the existing WECC modeling guidelines¹ all PV power plants with aggregated capacity 20 MVA or larger must be modeled explicitly in power flow and dynamics. This means that these plants must not be load-netted or modeled as negative load. Manufacturer-specific dynamic models commonly provided for interconnection studies are not adequate for regional planning. For this application, WECC requires the use of approved models, that are public (non-proprietary), are available as standard-library models, and have been tested and validated in accordance to WECC guidelines. Approved models are listed in the WECC Approved Dynamic Model List.

This document is a guide for the application WECC PV power plant generic dynamic models recently been adopted by WECC. The user should always refer to module documentation maintained by the simulation software vendor. For additional technical details, the user can reference the WECC-approved model specifications². Subject to some limitations, and with proper selection of model structure and parameters, the models are suitable for representation of large-scale PV plants and distribution-connected PV aggregated to a transmission bus. Both PV system models require explicit representation of the generation in the power flow model. PV power plant modeling will continue to be an area of active research. Models will continue to evolve with changes in technology and interconnection requirements. Also, PV power plants model validation against reference data remains a challenge due to limited industry experience.

2 Background

Solar power plants are different than conventional power plants. The interface to the grid is an inverter (see Figure 1) connected to a PV array.

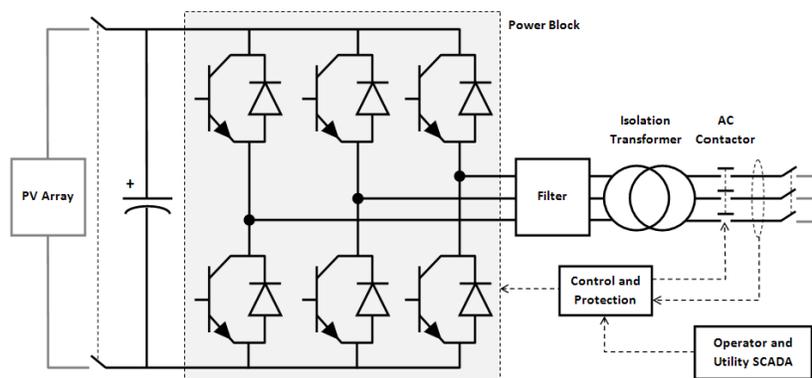


Figure 1 – A topology commonly found in utility-scale three-phase PV inverters.

¹ WECC Data Preparation Procedural Manual for Power Flow Base Cases and Dynamic Stability Data”, WECC System Review Work Group, Approved March 27, 2013.

² Model specifications are accessible from the WECC website in [this folder](#).

Inverters are characterized by low short circuit current contribution, lack of mechanical inertia, and high-bandwidth (fast) controls. A primary function of the inverter controls is to make the most efficient use of available energy being produced by the PV array, while ensuring that the magnitude of AC current does not exceed the rating of the inverter. PV plants do not have any inherent inertial or frequency response capabilities.

Figure 2 shows the topology of a large PV power plant. Large PV plants typically have several medium voltage radial feeders. The PV inverters are connected to the feeders via step-up transformers, with several inverters sharing one step-up transformer. Some plants designs include capacitors or other reactive support systems that work in conjunction with the inverters to meet reactive power capability and control requirements at the point of interconnection. A plant controller provides the power factor reference to the inverters³ and plant-level reactive power support equipment, if present. The plant controller processes measurements at the point of interconnection and commands issued from the fleet remote operations center or directly from the transmission system operator.

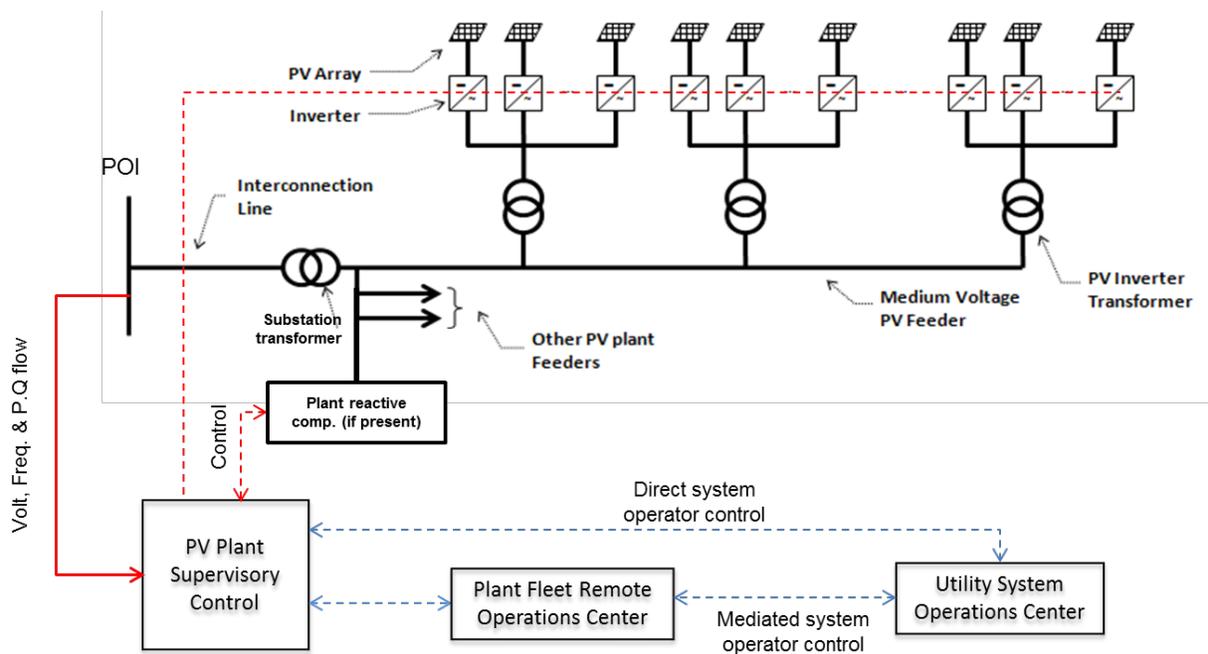


Figure 2 – Typical PV Power Plant Topology

Much of the existing PV generation in WECC consists of small PV systems deployed in customer premises, connected directly to distribution service voltage. These systems do not typically have a plant controller, and the inverter manages the grid interface. Some PV systems as large as 20 MW are connected directly to distribution substations using a dedicated medium voltage feeder.

³ Although not used commonly, the plant controller could also provide active power to the inverters to prevent the plant output from exceeding a certain limit.

PV plants are considered non-dispatchable because the energy source (solar irradiance) is variable. However, reactive power is dispatchable within the capability of the inverters and plant-level reactive compensation.

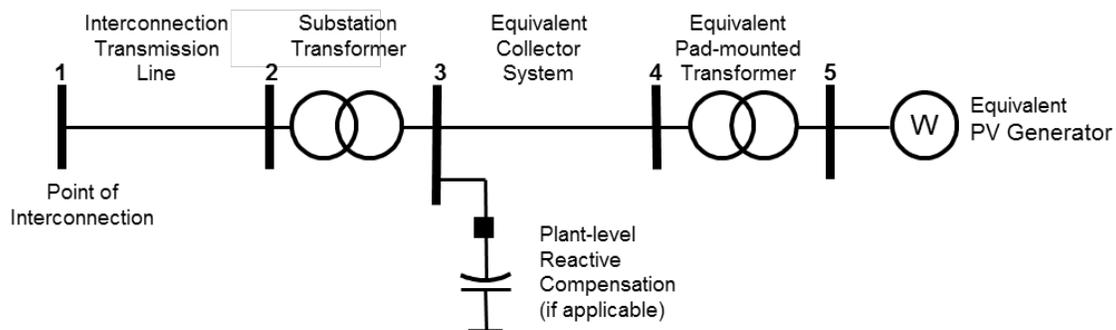
3 General Considerations for Dynamic Simulation of PV Plants

3.1 Appropriate Models for Bulk System Simulations

The WECC generic models were designed for transmission planning studies that involve a complex network, and a large set of generators, loads and other dynamic components. The objective is to assess dynamic performance of the system, particularly recovery dynamics following grid-side disturbances such as transmission-level faults. In this context, WECC uses positive-sequence power flow and dynamic models that provide a good representation of recovery dynamics using integration time steps of one quarter cycle. This approach does not allow for detailed representation of very fast controls and response to imbalanced disturbances. It should be noted that generic dynamic models for inverter-based generator tend to produce a short-duration (a cycle or shorter) voltage spike at fault inception or clearing. These spikes should be ignored in most cases, as they do not represent the performance of actual hardware. They are simply a consequence of the model's limited bandwidth, integration time step, and the way current injection models interface with the network solution.

3.2 Power Flow Representation

The WECC generic dynamic models described in this guideline assume that the PV generators are represented explicitly in power flow, representing a single large plant or the aggregated output of multiple smaller plants connected to distribution systems. For bulk system studies, it is impractical and unnecessary to model the collector system network inside the plant to the level of detail shown in Figure 2. In accordance with the WECC PV Plant Power Flow Modeling Guide⁴, PV power plants must be represented by a simplified system consisting of one or more equivalent generators and unit transformers, equivalent collector system, substation transformer, and plant-level reactive support system, if present. For most PV plants, the single-generator equivalent model shown in Figure 3 is adequate for bulk-level power flow and dynamic simulations. The WECC PV Plant Power Flow Modeling Guide also describes a methodology to derive the parameters for the single-machine representation, including a way to derive the collector system equivalent from design data.



⁴ WECC Guide for Representation of Photovoltaic Systems in Large-Scale Load Flow Simulations, WECC Renewable Energy Modeling Task Force, Approved January 2011.

Figure 3 – Single-Generator Equivalent Power Flow Representation for a PV Power Plant

Similarly, it is impractical to represent the large number of PV systems connected to distribution systems. When it is necessary to study the effects of distributed PV generation in a given area, the aggregated PV generation could be represented at a suitable transmission node by an equivalent generator, preferably behind an equivalent station transformer and equivalent medium voltage feeder. The dynamic models suggested for distributed PV plants are simpler than the dynamic models used for PV power plants.

3.3 Implications of Collector System Equivalent

It is important that the equivalent impedance of the collector system be represented in dynamic simulations. Since PV systems typically extend over a large geographical area, the electrical impedance between the terminals of each PV system and the point of interconnection could be significantly different, leading to a diverse dynamic response. It is not possible to capture this level of detail with a single-machine equivalent. The same argument applies to situations where multiple distributed PV systems are aggregated into an equivalent generator. Therefore, it should be understood that the modeling approach provides an indication of the average response of the inverters, as opposed to the response of any particular inverter in the plant.

3.4 Active and Reactive Power Control

Average irradiance over a large PV plant can change appreciably during the span of a typical dynamic simulation (up to 30 seconds). By default, the WECC generic models assume a fixed reference generator output in the solved power flow case. Presently, there is no provision for incorporating simulation of irradiance variability in large-scale system studies. The generic models do allow for the specification of active power control, including ramp rate limits, frequency response and active/reactive power priority during voltage dips. Reactive power capability and response characteristics are an important consideration in system studies. A variety of reactive power control modes can be implemented in a PV power plant. Very large PV systems typically control voltage at the point of interconnection. Smaller plants are typically operated in power factor control mode. During a dynamic event, the reactive power response is the combined contribution of fast inverter response (in cycles) and slower supervisory control (in seconds) via the plant controller.

3.5 Fault Ride-Through and Representation of Protection Limits

An important part of a dynamic performance evaluation is whether the PV system will trip off line for a given voltage or frequency disturbance. The equivalent representation and simplified dynamic models described here are not recommended for evaluation of fault ride-through. Whether or not an inverter will ride through a voltage disturbance depends on the type of fault and the magnitude of the remaining voltage at the inverter terminals. The control actions that affect the behavior of the inverter during the span of a short fault are generally not modeled in detail in the generic dynamic models. This limitation is acceptable because system studies focus on the characteristics of the dynamic recovery, rather than on system conditions during the fault. Considering that terminal voltage can vary significantly across the plant, a single machine representation has obvious limitations with respect to assessment of voltage ride through.

3.6 Model parameters

As with any other equipment, appropriate parameters must be selected to represent the dynamic behavior of the corresponding PV plant. Default parameters provided are intended only for model testing, and do not represent any particular project. Consistent with established WECC practice, input from the plant operator and equipment manufacturer is required to correctly parameterize the model⁵. This is also true for the power flow representation.

4 WECC Generic Models

This section contains a general description of the WECC generic models based on REMTF technical specifications approved by WECC. The models are available as standard-library models in commercial simulation platforms used in WECC. The purpose of this document is to help model users understand the limitations of the models, the model structure, user-selectable options, requirements for scaling the plant size, and representation of protection settings.

4.1 Technical Specifications for the WECC Generic Models

The WECC generic models for PV plants are based on the following technical specifications:

- The models shall be non-proprietary and accessible to transmission planners and grid operators without the need for non-disclosure agreements.
- The models shall provide a reasonably good representation of dynamic electrical performance of solar photovoltaic power plants at the point of interconnection with the bulk electric system, and not necessarily within the PV power plant collector system.
- The models shall be suitable for studying system response to electrical disturbances, not solar irradiance transients (i.e., available solar power is assumed constant through the duration of the simulation). Electrical disturbances of interest are primarily balanced transmission grid faults (external to the solar PV power plant), typically 3 - 9 cycles in duration, and other major disturbances such as loss of generation or large blocks of load.
- Plant owners, inverter manufacturers and model users (with guidance from the integrators and manufacturers) shall be able to represent differences among specific inverter and/or plant controller responses by selecting appropriate model parameters and feature flags.
- Simulations performed using these models typically cover a 20-30 second time frame, with integration time steps in the range of 1 to 10 milliseconds.
- The models shall be valid for analyzing electrical phenomena in the frequency range of zero to approximately 10 Hz.
- The models shall incorporate protection functions that trip the associated generation represented by the model, or shall include the means for external modules to be connected to the model to accomplish such generator tripping.
- The models shall be initialized from a solved power flow case with minimal user intervention required in the initialization process.
- Power level of interest is primarily 100% of plant nominal rating. However, performance shall be valid, within a reasonable tolerance, for the variables of interest (current, active power, reactive power and power factor) within a range of 25% to 100% of rated power.

⁵ Periodic model validation is also required. This topic is addressed in a separate WECC guideline.

- The models shall perform accurately for systems with a short circuit ratio of 3 and higher at the point of interconnection. However, it should be noted that these generic models are NOT intended for studying parts of the system that are subject to very low short-circuit levels. In such cases, detailed vendor specific models may be needed.
- External reactive compensation and control equipment (i.e., external to the PV inverters) shall be modeled separately using existing WECC-approved models.

WECC approved the use of two generic dynamic models for PV plants: (a) a model consisting of plant controller, electrical controls and grid interface modules, intended for large-scale PV plants, and (b) a simplified model intended for distribution-connected, aggregated PV plants.

4.2 WECC Generic Model for Large-scale PV Plants

4.2.1 Model Structure

Dynamic representation of large-scale PV plants requires the use of three new renewable energy (RE) modules listed below and shown in Figure 4. These modules, in addition to others, are also used to represent wind and PV power plants. It is required that the PV plant be modeled in power flow, preferably using the single-generator equivalent system discussed in Figure 3.

- REGC_A module, used to represent the Generator/Converter (inverter) interface with the grid. It processes the real and reactive current command and outputs of real and reactive current injection into the grid model.
- REEC_B module, used to represent the Electrical Controls of the inverters. It acts on the active and reactive power reference from the REPC_A module, with feedback of terminal voltage and generator power output, and provides real and reactive current commands to the REGC_A module.
- REPC_A module, used to represent the Plant Controller. It processes voltage and reactive power output to emulate volt/var control at the plant level. It also processes frequency and active power output to emulate active power control. This module provides active reactive power command to the REEC_B module.

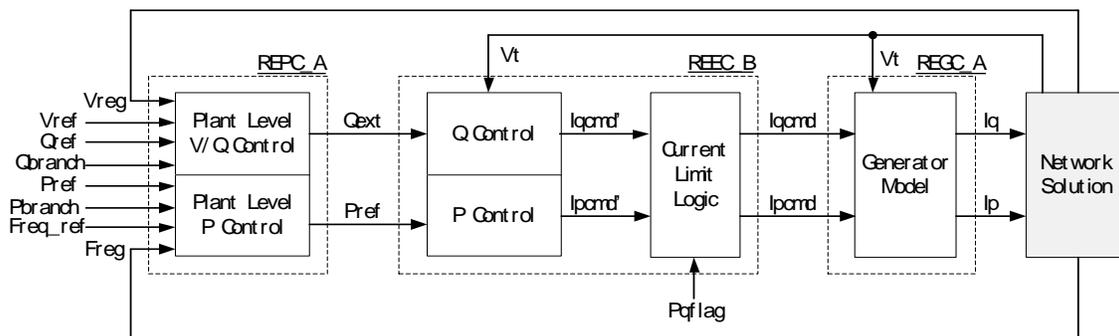


Figure 4 – Block Diagram Showing Different Modules of the WECC Generic Models

These modules do not include inverter or plant protection. However, existing generator protection models can be used to represent time-delayed voltage and frequency protection settings. Table 1 shows the list of PV power plant simulation modules implemented in two simulation platforms commonly used in WECC. As indicated, the plant controller and protection

modules are optional. Although the internal implementation may differ across simulation platforms, the modules have the same functionality and parameter sets.

Table 1 – REMTF models for PV power plants implemented in the PSLF™, PSS®E, and PowerWorld platforms

Module	PSLF™ modules	PSS®E modules	PowerWorld
Grid interface	regc_a	REGCAU1	regc_a
Electrical controls	reec_b	REECBU1	reec_b
Plant controller (optional)	repc_a	REPCAU1	repc_a
Voltage/frequency protection (optional)	lhvrt / lhfrt	VRGTPA / FRQTPA	lhvrt / lhfrt

Strictly speaking, only the REGC_A module is required to run a simulation; however, the rest of the modules are needed to enable control functionality. The appendix contains a detailed description of the large-scale PV plant dynamic modules. Default parameters are provided; however, these are intended for model testing only. They do not represent the performance of any particular plant or equipment. Consultation with the inverter manufacturer and the plant operator is required to properly select appropriate model parameters.

4.2.2 Model call

The model call varies according to the software platform. Users must follow the instructions provided with the model documentation. The model calls shown below for the various software platforms refer to the simple test system shown in Figure 5. This example is for a PV plant with total inverter capacity of 110 MVA and 100 MW, which would correspond to PV inverters sized for 0.95 leading or lagging power factor at rated power and rated voltage. In this particular hypothetical example, the equivalent generator is controlling voltage at bus 5.

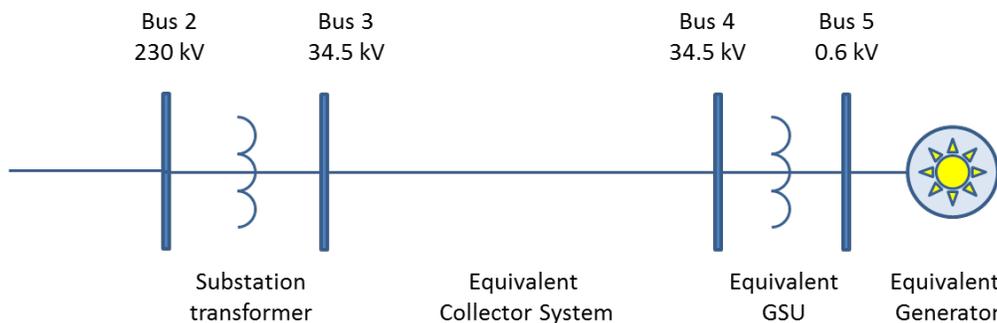


Figure 5 – Test system for large-scale PV plant model

GE PSLF™

```
regc_a 5 "Test" 0.6 "1" " : #9 mvab=111. "lvplsw" 1. "rrpwr" 10.0 "brkpt" 0.9 "zerox"
0.4 "lvpl1" 1.22 "vtmax" 1.2 "lvpnt1" 0.8 "lvpnt0" 0.4 "qmin" -1.3 "accel" 0.7 "tg"
0.02 "tfltr" 0.02 "iqrmax" 999. "iqrmin" -999. "xe" 0.
```

```
reec_b 5 "Test" 0.6 "1" " : #9 "mvab" 0. "vdip" -99. "vup" 99. "trv" 0.2 "dbd1" -0.5
"dbd2" 0.5 "kqv" 0. "iqh1" 1.5 "iq11" -1.5 "vref0" 0. "tp" 0.5 "qmax" 0.4 "qmin" -0.4
"vmax" 1.1 "vmin" 0.9 "kqp" 0.0 "kqi" 0.1 "kvp" 0.1 "kvi" 100. "tiq" 0.2 "dpmax" 999.
"dpmin" -999. "pmax" 1. "pmin" 0. "imax" 1.3 "tpord" 0.4 "pfflag" 0. "vflag" 1.
"qflag" 1. "pqflag" 0.
```

```

regc_a 5 "Test" 0.6 "1 " : #9 "mvab" 0. "tfltr" 0.2 "kp" 18. "ki" 5. "tft" 0. "tfv"
0.15 "refflg" 1. "vfrz" -1. "rc" 0. "xc" 0. "kc" 0. "vcmpflg" 1. "emax" 999. "emin" -
999. "dbd" 0. "qmax" 0.44 "qmin" -0.44 "kpg" 0.1 "kig" 0.5 "tp" 0.25 "fdbd1" 0.
"fdbd2" 0. "femax" 999. "femin" -999. "pmax" 999. "pmin" -999. "tlag" 0.1 "ddn" 20.
"dup" 0.0 "frqflg" 0.

```

PowerWorld Simulator

```

regc_a 5 "Test" 0.6 "1 " : #1 mva=111. "lvplsw" 1. "rrpwr" 10. "brkpt" 0.9 "zerox" 0.4
"lvpl1" 1.22 "vtmax" 1.2 "lvpnt1" 0.8 "lvpnt0" 0.4 "qlim" -1.3 "accel" 0.7 "tg" 0.02
"tfltr" 0.02 "iqrmax" 999. "iqrmin" -999. "xe" 0.

```

```

reec_b 5 "Test" 0.6 "1 " : #1 "mvab" 0. "vdip" -99. "vup" 99.0 "trv" 0.2 "dbd1" -0.5
"dbd2" 0.5 "kqv" 0. "iqh1" 1.5 "iql1" -1.5 "vref0" 0. "iqfrz" 0.15 "thld" 0. "thld2"
0. "tp" 0.5 "qmax" 0.4 "qmin" -0.4 "vmax" 1.1 "vmin" 0.9 "kqp" 0. "kqi" 0.1 "kvp" 0.1
"kvi" 100. "vref1" 0. "tiq" 0.2 "dpmax" 999. "dpmin" -999. "pmax" 1. "pmin" 0. "imax"
1.3 "tpord" 0.4 "pfflag" 0. "vflag" 1. "qflag" 1. "pflag" 0. "pqflag" 0.

```

```

regc_a 5 "Test" 0.6 "1 " : #1 "mvab" 0. "tfltr" 0.2 "kp" 18. "ki" 5. "tft" 0. "tfv"
0.15 "refflg" 1. "vfrz" -1. "rc" 0. "xc" 0. "kc" 0. "vcmpflg" 1. "emax" 999. "emin" -
999. "dbd" 0. "qmax" 0.44 "qmin" -0.44 "kpg" 0.1 "kig" 0.5 "tp" 0.25 "fdbd1" 0.
"fdbd2" 0. "femax" 999. "femin" -999. "pmax" 999. "pmin" -999. "tlag" 0.1 "ddn" 20.
"dup" 0. "frqflg" 0.

```

Siemens PTI PSS®E

```

5 'USRMDL' 1 'REGCAU1' 101 1 1 14 3 4 1 0.20000E-01 10.000 0.90000 0.50000
1.2200 1.2000 0.80000 0.40000 -1.3000 0.20000E-01 0.70000 9999.0 -9999.0
1.0000 /

```

```

5 'USRMDL' 1 'REECBU1' 102 0 5 25 6 4 0 0 1 1 0 -99.000 99.000 0.0000
-0.50000E-01 0.50000E-01 0.0000 1.0500 -1.0500 0.0000 0.50000E-01 0.43600
-0.43600 1.1000 0.90000 0.0000 0.10000 0.0000 40.000 0.20000E-01 99.000
-99.000 1.0000 0.0000 1.8200 0.20000E-01 /

```

```

5 'USRMDL' 1 'REPCAU1' 107 0 7 27 7 9 2 0 0 '0 ' 1 1 0 0.20000E-01
18.000 5.0000 0.0000 0.75000E-01 0.0000 0.0000 0.0000 0.20000E-01 0.10000
-0.10000 0.0000 0.0000 0.43600 -0.43600 0.10000 0.50000E-01 0.25000 0.0000
0.0000 999.00 -999.00 999.00 -999.00 0.10000 20.000 0.0000 /

```

The parameters shown are intended for model testing only, and do not represent the performance of any particular PV plant or equipment.

4.2.3 Scaling for the PV plant size and reactive capability

Model parameters are expressed in per unit of the generator MVA base (*mvab* parameter in the *regc_a* module in the example above). The specification of MVA base is implementation-dependent. For example, in the PSLF™ implementation, if the MVA base for those modules is zero, the MVA base entered for the REGC_A module applies to the electrical controls (REEC_B) and plant controller (REPC_A). A different MVA base can be specified for those modules, if desired.

To scale the dynamic model to the size of the plant, the generator MVA base parameter must be adjusted. The reactive range can be adjusted with the *qmin* and *qmax* parameters in the REEC_B module. Normally, the MVA base and reactive limits are the same as those used in power flow, taking into consideration that the capability is being specified for the equivalent generator, not the point of connection.

4.2.4 Volt/Var controls options

The plant-level control module allows for the following reactive power control modes:

- Closed loop voltage regulation (V control) at a user-designated bus with optional line drop compensation, droop response and dead band.
- Closed loop reactive power regulation (Q control) on a user-designated branch, with optional dead band.

Different function calls are required to specify the regulated bus or branch. In the electrical control module, additional reactive control options are available:

- Constant power factor (PF), based on the generator PF in the solved power flow case
- Constant reactive power, based either on the equivalent generator reactive power in the solved power flow case or from the plant controller
- Defined reactive power injection during a user-defined voltage-dip event

Various combinations of plant-level and inverter-level reactive control are possible by setting the appropriate parameters and switches. Table 5 shows a list of control options, and the models and switches that would be involved. The entry "N/A" indicates that the state of the switch does not affect the indicated control mode.

Table 2 – Reactive Power Control Options for large-scale PV plant generic model

Functionality	Models Needed	PfFlag	Vflag	Qflag	RefFlag
Constant local PF control	REEC_B	1	N/A	0	N/A
Constant local Q control	REEC_B	0	N/A	0	N/A
Local (gen terminals) V control	REEC_B	0	0	1	N/A
Local coordinated V/Q control	REEC_B	0	1	1	N/A
Plant level Q control	REEC_B, REPC_A	0	N/A	0	0
Plant level V control	REEC_B, REPC_A	0	N/A	0	1
Plant level Q control + local coordinated V/Q control	REEC_B, REPC_A	0	1	1	0
Plant level V control + local coordinated V/Q control	REEC_B, REPC_A	0	1	1	1

4.2.5 Active power control options

The plant controller allows a user to specify the active power control options listed below. Table 4 shows the active power control modes as well as the models and parameters involved.

- Constant active power, based on the generator output in the solved power flow case
- Governor droop response with different characteristics for over and under frequency conditions, based on frequency deviation at a user-designated bus.

Table 3 – Active Power Control Options

Functionality	Models Needed	Freq_flag	Ddn	Dup
No governor response	REGC_A, REEC_B	0	N/A	N/A
Governor response with down regulation, only	REGC_A, REEC_B, REPC_A	1	> 0	0
Governor response with up and down regulation	REGC_A, REEC_B, REPC_A	1	> 0	> 0

In situations where current limit of the equivalent inverter is reached, the user can specify whether active or reactive power takes precedence, by setting the *Pqflag* parameter in the REEC_B module.

4.2.6 Representation of Voltage and Frequency Protection

Frequency and voltage tolerance is required for transmission-connected PV plants. Because they are simplified, the WECC generic models may not be suitable to fully assess compliance with voltage and frequency ride-through requirement. The same limitation applies to other positive-sequence models. Voltage ride-through is engineered as part of the plant design, and requires far more sophisticated modeling detail than is possible to capture in a positive-sequence simulation environment. It is recommended that a standardized (existing) protection model with voltage and frequency thresholds and time delays can be used to indicate the minimum disturbance tolerance requirement that applies to the plant.

4.2.7 Sample simulation results

Figure 6 shows the results of a PV plant response to a 3-cycle fault bus 2, using the hypothetical test system and model parameters shown in Section 4.2.2. Transformer and equivalent generator parameters are as follows:

- GSU: $R = 0.0$ pu, $X = 0.05$ pu on 100 MVA base
- Station transformer: $R = 0.0$ pu, $X = 0.1$ pu on 100 MVA base
- Equivalent collector system: $R = 0.015$ pu, $X = 0.025$ pu, $B = 0.01$ pu on 100 MVA and 34.5 kV base

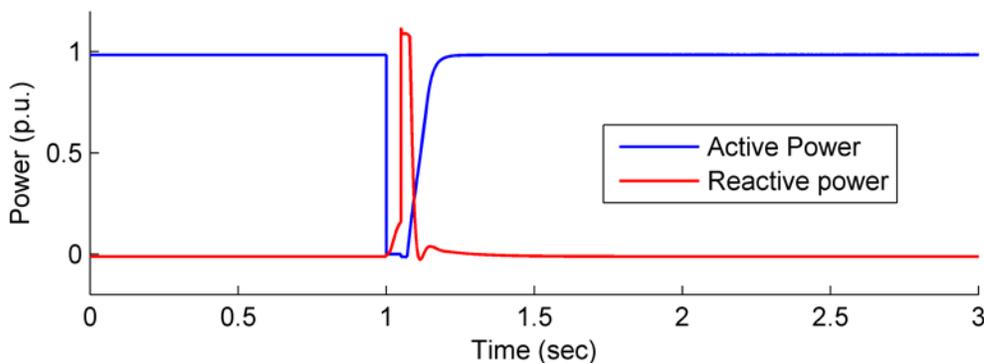


Figure 6 – Dynamic response of the sample PV plant from Section 4.2.2 to a 3-cycle bolted fault at Bus 2 (P and Q measured at Bus 2).

4.3 WECC Generic Model for Distributed and Small PV Plants

4.3.1 Model Structure

The generic model PVD1 shown in Figure 7 is recommended to represent distribution-connected small PV plants or multiple PV plants aggregated at a high voltage bus that is represented in power flow. The PVD1 model is much simpler than the modules discussed in Section 4.2, and

provides a basic set of control options. It requires that the PV generator be explicitly represented in power flow, preferably behind an equivalent transformer and feeder.

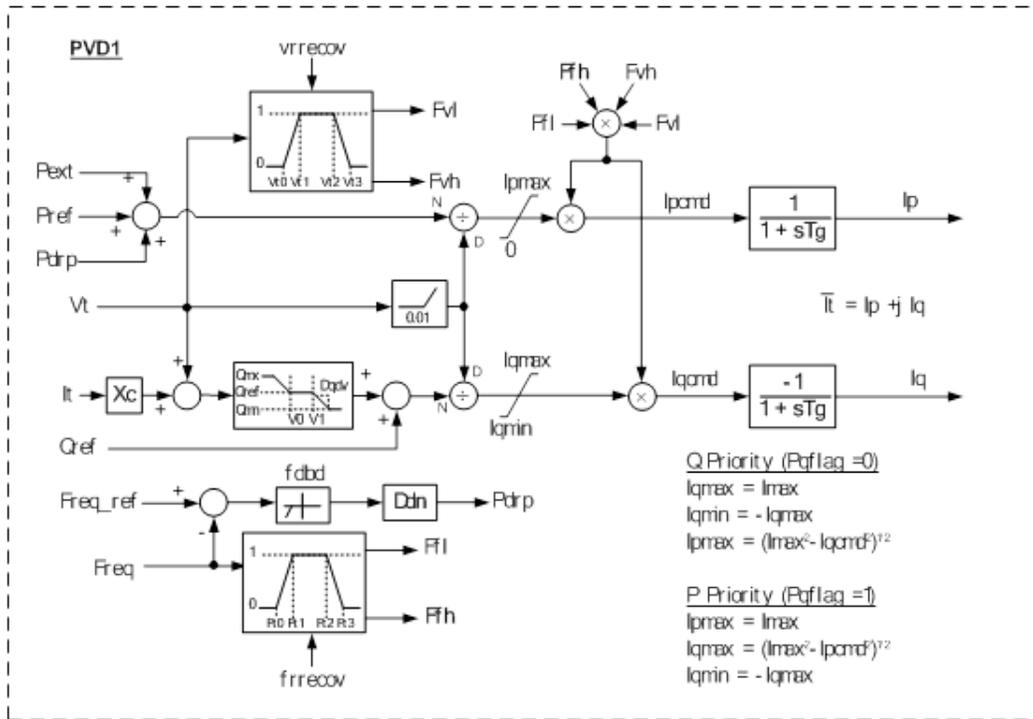


Figure 7 – Block Diagram Showing Different Modules of the WECC Generic Models

At its core, the PVD1 model is a simple current injection with the following basic functionality for reactive power control, active power control and protection.

4.3.2 Model call

The model call varies according to the software platform. Users must follow the instructions provided with the model documentation. The example described below is for the PSLF™ platform, using the simple test system shown in Figure 8. This example would be applicable to a single distribution-connected PV plant or multiple distribution-connected PV systems with total capacity of 25 MW, deployed in the vicinity of a transmission bus (bus 2) where generation and load is aggregated. In this case, the aggregated generation is modeled behind an equivalent substation unit transformer and feeder impedance.⁶

⁶ Consideration should also be given to modeling the load behind the transformer and equivalent impedance.

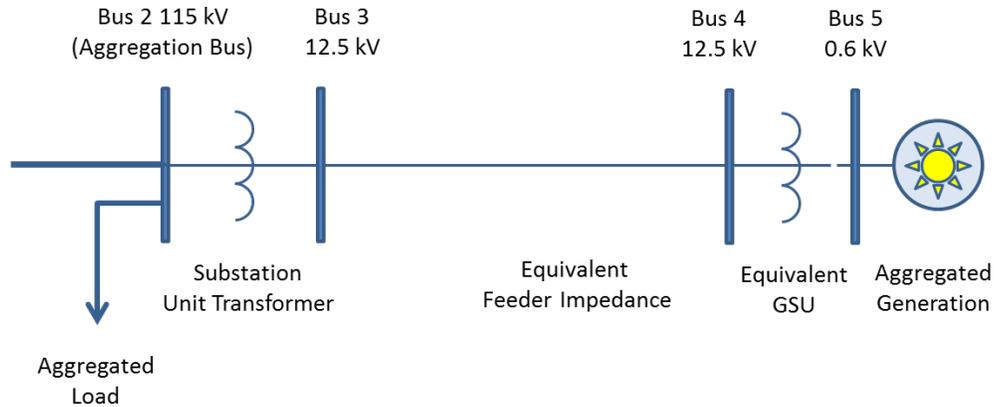


Figure 8 – Test system for PVD1 model

```
pvd1 5 "Test" 0.6 "1" " : #1 mvab=28. "pqflag" 1. "xc" 0. "qmx" 0. "qmn" 0.
"v0" 0.9 "v1" 1.1 "dqdv" 0. "fdbd" -99. "ddn" 0. "imax" 1.1 "vt0" 0.88 "vt1"
0.9 "vt2" 1.1 "vt3" 1.2 "vrflag" 1. "ft0" 59.5 "ft1" 59.7 "ft2" 60.3 "ft3"
60.5 "frflag" 0. "tg" 0.02 "tf" 0.05 "vtmax" 1.2 "lvpnt1" 0.8 "lvpnt0" 0.4
"qmin" -1.3 "accel" 0.7
```

The parameters shown are intended for model testing only, and do not represent the performance of any particular case.

4.3.3 Scaling for the PV plant size and reactive capability

To scale the dynamic model to the size of the aggregated PV generation, the generator MVA base MVA (*mvab* parameter in the example above) must be adjusted. In this case, fixed power factor was emulated by setting the reactive limits (*qmin* and *qmax* in the example above) to zero.

4.3.4 Volt/Var Controls

The model allows two basic reactive power control modes, listed below.

- Constant reactive power, based on generator output in the solved power flow case
- Volt/var control at the generator terminals, with user-defined Q versus V characteristic and optional line drop compensation

In the example above, volt/var control is disabled by setting the reactive range (*Qmx* and *Qmn*) to zero.

4.3.5 Active Power Controls

The model allows two basic active power control modes, listed below.

- Constant active power, based on generator output in the solved power flow case
- Over-frequency response, with user-defined dead band and droop

In the example above, frequency response is disabled by setting the droop gain parameter (*Dbn*) to zero; thus, the plant operates in constant active power mode.

Similar to the large-scale PV plant model, the user can specify whether active or reactive power takes precedence, by setting the *Pqflag* parameter.

4.3.6 Generation tripping

The model allows for tripping of all or a portion of the generation based on over- and under-voltage and frequency monitored at the equivalent generator terminals. The user can set the voltage and frequency dead bands (*vt1* to *vt2* and *ft1* to *ft2*, respectively), how much generation trips, and what fraction of the generation is restored as the disturbance subsides. In the example above, generation would disconnect outside the 0.9 to 1.1 pu voltage range, with all generation assumed to be disconnected when voltage goes below 0.88 or above 1.2 pu. Similarly, generation would disconnect when frequency is outside the range 59.7 Hz to 60.3 Hz, with all generation assumed to be disconnected when frequency goes below 50.5 Hz or above 60.5 Hz. In the example shown above, the parameters *vfflag* and *frflag* (labeled *vr_recov* and *fr_recov* in Figure 7) are set to 1 and 0, respectively. This means that, as voltage and frequency recover within the dead band, all of the generation disconnected on voltage reconnects, but none of the generation disconnected on frequency would reconnect.

Partial tripping is relevant when the equivalent generator represents distributed generation systems, each of which would experience a transmission-level disturbance very differently depending on the electrical distance to the bus where they are aggregated⁷.

It should be noted that trip thresholds in this model are not time-dependent. If this functionality is desired, a standard generator protection model can be used.

4.3.7 Sample simulation results

Figure 9 shows the results of a PV plant response to a 3-cycle fault bus 2, using the hypothetical test system and model parameters shown in Section 4.3.2. Transformer and equivalent generator parameters are as follows:

- GSU: R = 0.0 pu, X = 0.05 pu on 50 MVA base
- Station transformer: R = 0.0 pu, X = 0.1 pu on 50 MVA base
- Equivalent collector system: R = 0.015 pu, X = 0.025 pu, B = 0.01 pu on 50 MVA and 12.5 kV base

⁷ At present, applicable interconnection requirements emphasize tripping requirements for off-nominal frequency and voltage, as opposed to fault ride-through capability. The REMTF is integrating distributed generation model into the existing WECC composite load model (CMPLDW), which would provide a better indication of conditions that distributed generation experience. This topic falls outside of this document.

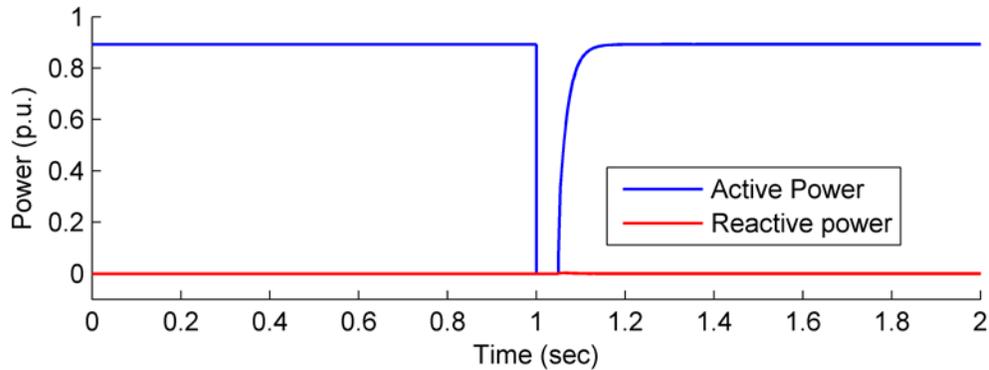


Figure 9 – Dynamic response of the sample aggregated, distribution-connected PV plant from Section 4.3.2 to a 3-cycle bolted fault at Bus 2 (P and Q measured at Bus 2).

5 Summary

The PV plant generic models described in this document are intended for general bulk system planning studies. The general guidelines discussed in this document should be used in conjunction with the model documentation provided as part of the relevant simulation platform. Selection of appropriate model parameters requires consultation with inverter manufacturer and plant operator. PV plant dynamic modeling is an area of active research. As with any other model, the WECC generic PV plant models will evolve based on industry experience and technology evolution.

Appendix – Detailed Model Description

5.1 REGC_A – Renewable Energy Generator/Converter Model

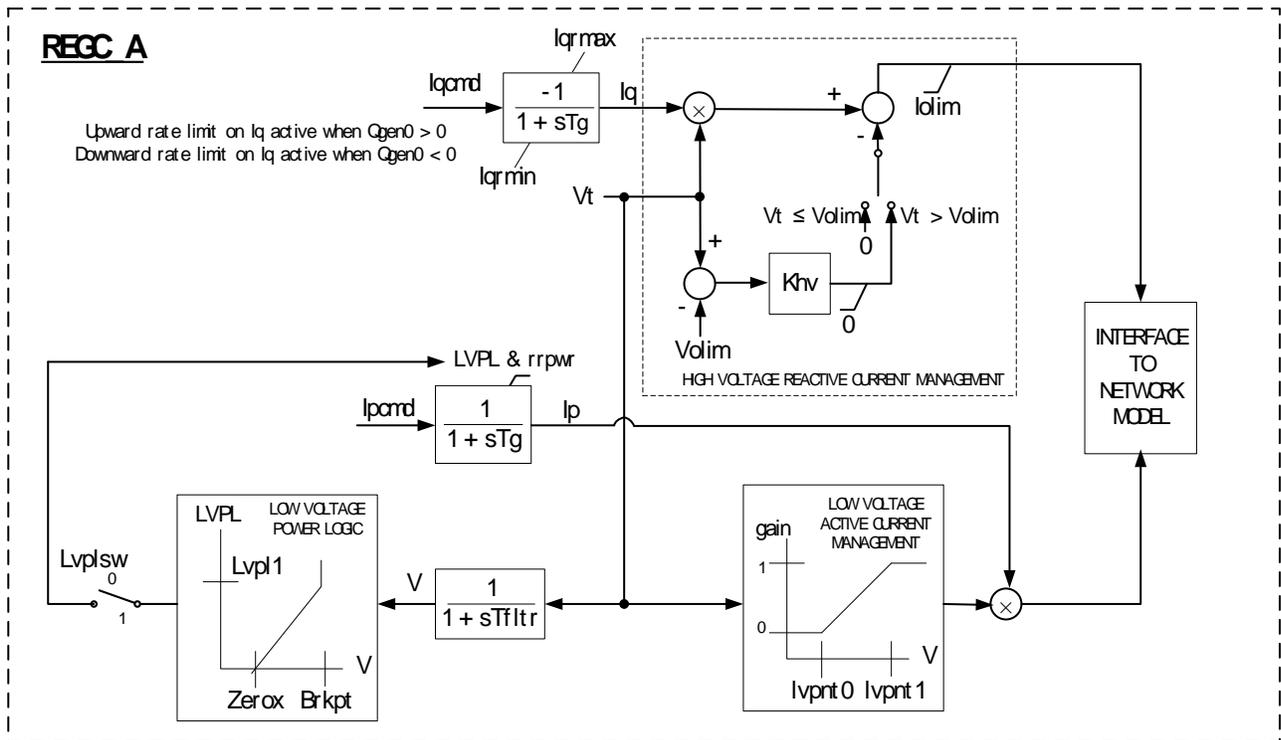
Description

The model incorporates a high bandwidth current regulator that injects real and reactive components of inverter current into the external network during the network solution in response to real and reactive current commands. Current injection includes the following capabilities:

- User settable reactive current management during high voltage events at the generator (inverter) terminal bus
- Active current management during low voltage events to approximate the response of the inverter PLL controls during voltage dips
- Power logic during low voltage events to allow for a controlled response of active current during and immediately following voltage dips

The current injection model is identical to that which the WECC REMTF is proposing to utilize for the Type 3 and Type 4 generic wind turbine models.

Block Diagram



Parameters and Default Settings

REGC_A Input Parameters		
Name	Description	Typical Values
Tfltr	Terminal voltage filter (for LVPL) time constant (s)	0.01 to 0.02
Lvpl1	LVPL gain breakpoint (pu current on mbase / pu voltage)	1.1 to 1.3
Zerox	LVPL zero crossing (pu voltage)	0.4
Brkpt	LVPL breakpoint (pu voltage)	0.9
Lvplsw	Enable (1) or disable (0) low voltage power logic	-
rrpwr	Active current up-ramp rate limit on voltage recovery (pu/s)	10.0
Tg	Inverter current regulator lag time constant (s)	0.02
Volim	Voltage limit for high voltage clamp logic (pu)	1.2
Iolim	Current limit for high voltage clamp logic (pu on mbase)	-1.0 to -1.5
Khv	High voltage clamp logic acceleration factor	0.7
lvpnt0	Low voltage active current management breakpoint (pu)	0.4
lvpnt1	Low voltage active current management breakpoint (pu)	0.8
Iqrmax	Maximum rate-of-change of reactive current (pu/s)	999.9
Iqrmin	Minimum rate-of-change of reactive current (pu/s)	-999.9

Internal Variables and Output Channels

REGC_A Internal Variables	
Name	Description
Vt	Raw terminal voltage (pu, from network solution)
V	Filtered terminal voltage (pu)
LVPL	Active current limit from LVPL logic (pu on mbase)
Iqcmd	Desired reactive current (pu on mbase)
Ipcmd	Desired active current (pu on mbase)
Iq	Actual reactive current (pu on mbase)

5.2 REEC_B – Renewable Energy Electrical Control Model for PV Plants

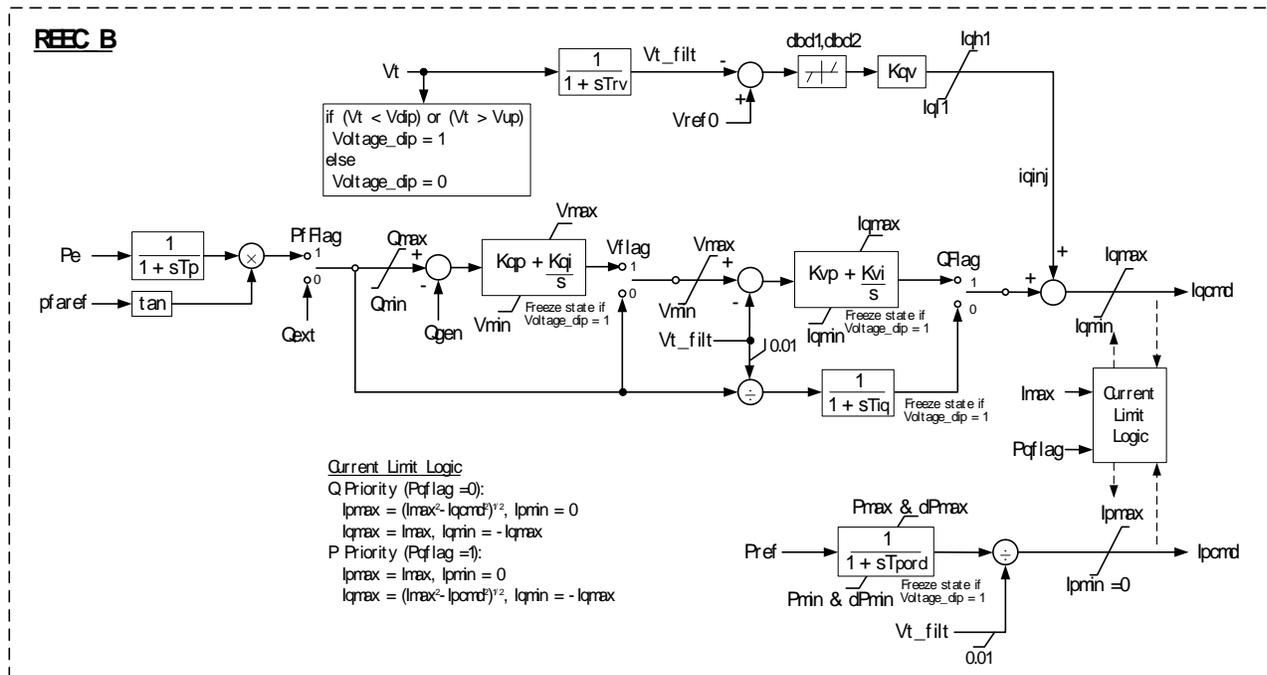
Description

The active power control subsystem provides the active current command to the current injection model. The active current command is subject to current limiting, with user-selectable priority between active and reactive current. The active current command is derived from a reference active power and the inverter terminal voltage determined in the network solution. The reference active power is the initial active power from the solved power flow case; or, in the case where a plant controller model (REPC_A) is included, from the plant controller. The reactive power control subsystem provides the reactive current command to the current injection model. The reactive current command is subject to current limiting, with user-selectable priority between active and reactive current. The following reactive power control modes are accommodated:

- Constant power factor, based on the inverter power factor in the solved power flow case
- Constant reactive power, based either on the inverter absolute reactive power in the solved power flow case or, in the case where a plant controller model (REPC_A) is included, from the plant controller.

The option to process the reactive power command via a cascaded set of PI regulators for local reactive power and terminal voltage control (refer to Figure 3), or to bypass these regulators and directly derive a reactive current command from the inverter terminal voltage, shall be provided. In addition, a supplementary, fast-acting reactive current response to abnormally high or low terminal voltages (again, refer to Figure 3) shall be provided.

Block Diagram



Parameters and sample settings

REEC_B Input Parameters		
Name	Description	Typical Values
Pfflag	Constant Q (0) or PF (1) local control	-
Vflag	Local Q (0) or voltage control (1)	-
Qflag	Bypass (0) or engage (1) inner voltage regulator loop	-
Pqflag	Priority to reactive current (0) or active current (1)	-
Trv	Terminal bus voltage filter time constant (s)	0.01 to 0.02
Vdip	Low voltage condition trigger voltage (pu)	0.0 to 0.9
Vup	High voltage condition trigger voltage (pu)	1.1 to 1.3
Vref0	Reference voltage for reactive current injection (pu)	0.95 to 1.05
dbd1	Overvoltage deadband for reactive current injection (pu)	-0.1 to 0.0
dbd2	Undervoltage deadband for reactive current injection (pu)	0.0 to 0.1
Kqv	Reactive current injection gain (pu/pu)	0.0 to 10.0
Iqhl	Maximum reactive current injection (pu on mbase)	1.0 to 1.1
Iqll	Minimum reactive current injection (pu on mbase)	-1.1 to -1.0
Tp	Active power filter time constant (s)	0.01 to 0.02
Qmax	Maximum reactive power when Vflag = 1 (pu on mbase)	-
Qmin	Minimum reactive power when Vflag = 1 (pu on mbase)	-
Kqp	Local Q regulator proportional gain (pu/pu)	-
Kqi	Local Q regulator integral gain (pu/pu-s)	-
Vmax	Maximum voltage at inverter terminal bus (pu)	1.05 to 1.15
Vmin	Minimum voltage at inverter terminal bus (pu)	0.85 to 0.95
Kvp	Local voltage regulator proportional gain (pu/pu)	-
Kvi	Local voltage regulator integral gain (pu/pu-s)	-
Tiq	Reactive current regulator lag time constant (s)	0.01 to 0.02
Tpord	Inverter power order lag time constant (s)	-
Pmax	Maximum active power (pu on mbase)	1.0
Pmin	Minimum active power (pu on mbase)	0.0
dPmax	Active power up-ramp limit (pu/s on mbase)	-
dPmin	Active power down-ramp limit (pu/s on mbase)	-
Imax	Maximum apparent current (pu on mbase)	1.0 to 1.3

Internal variables and Output Channels

REEC_B Internal Variables	
Name	Description
Vt	Raw terminal voltage (pu, from network solution)
Vt_filt	Filtered terminal voltage (pu)
Voltage_dip	Low/high voltage ride-through condition (0 = normal, VRT = 1)
Pe	Inverter active power (pu on mbase)
Pref	Inverter active power reference (pu on mbase, from power flow solution or from plant controller model)
Pfaref	Inverter initial power factor angle (from power flow solution)

Qgen	Inverter reactive power (pu on mbase)
Qext	Inverter reactive power reference (pu on mbase, from power flow solution or from plant controller model)
Iqinj	Supplementary reactive current injection during VRT event (pu on mbase)
Ipmax	Maximum dynamic active current (pu on mbase)
Ipmin	Minimum active current (0)
Iqmax	Maximum dynamic reactive current (pu on mbase)
Iqmin	Minimum dynamic reactive current (pu on mbase, = -iqmax)
Ipcmd	Desired active current (pu on mbase)
Iqcmd	Desired reactive current (pu on mbase)

5.3 REPC_A - Renewable Energy Plant Control Model

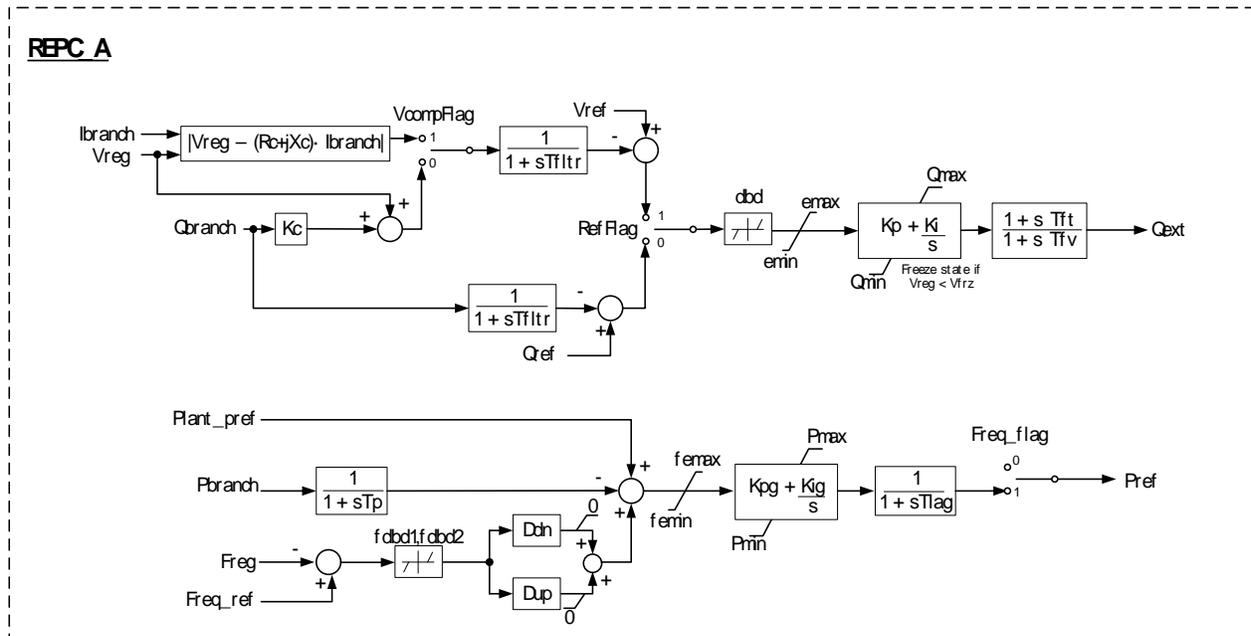
Description

The plant controller model is an optional model used when plant-level control of active and/or reactive power is desired. The model incorporates the following:

- Closed loop voltage regulation at a user-designated bus. The voltage feedback signal has provisions for line drop compensation, voltage droop response and a user-settable dead band on the voltage error signal.
- Closed loop reactive power regulation on a user-designated branch with a user-settable dead band on the reactive power error signal.
- A plant-level governor response signal derived from frequency deviation at a user-designated bus. The frequency droop response is applied to active power flow on a user-designated branch. Frequency droop control is capable of being activated in both over and under frequency conditions. The frequency deviation applied to the droop gain is subject to a user-settable dead band.

The plant controller model is identical to that which the WECC REMTF is proposing to utilize for the Type 3 and Type 4 generic wind turbine models.

Block Diagram



Parameters and sample settings

REPC_A Input Parameters		
Name	Description	Typical Values
RefFlag	Plant level reactive power (0) or voltage control (1)	-
VcompFlag	Reactive droop (0) or line drop compensation (1)	-
Freq_flag	Governor response disable (0) or enable (1)	0
Tfltr	Voltage and reactive power filter time constant (s)	0.01 to 0.02
Vbus	Monitored bus number	-
FromBus	Monitored branch “from” bus number	-
ToBus	Monitored branch “to” bus number	-
Ckt	Monitored branch circuit designation	-
Rc	Line drop compensation resistance (pu on mbase)	-
Xc	Line drop compensation reactance (pu on mbase) when VcompFlag = 1	-
Kc	Reactive droop (pu on mbase) when VcompFlag = 0	-
dbd	Reactive power deadband (pu on mbase) when RefFlag = 0; Voltage deadband (pu) when RefFlag = 1	-
emax	Maximum Volt/VAR error (pu)	-
emin	Minimum Volt/VAR error (pu)	-
Kp	Volt/VAR regulator proportional gain (pu/pu)m	-
Kq	Volt/VAR regulator integral gain (pu/pu-s)	-
Qmax	Maximum plant reactive power command (pu on mbase)	-
Qmin	Minimum plant reactive power command (pu on mbase)	-
Vfrz	Voltage for freezing Volt/VAR regulator integrator (pu)	0.0 to 0.9
Tft	Plant controller Q output lead time constant (s)	-
Tfv	Plant controller Q output lag time constant (s)	0.15 to 5.0
fdbd1	Overfrequency deadband for governor response (pu)	0.01
fdbd2	Underfrequency deadband for governor response (pu)	-0.01
Ddn	Down regulation droop (pu power/pu freq on mbase)	20.0 to 33.3
Dup	Up regulation droop (pu power/pu freq on mbase)	0.0
Tp	Active power filter time constant (s)	0.01 to 0.02
femax	Maximum power error in droop regulator (pu on mbase)	-
femin	Minimum power error in droop regulator (pu on mbase)	-
Kpg	Droop regulator proportional gain (pu/pu)	-
Kig	Droop regulator integral gain (pu/pu-s)	-
Pmax	Maximum plant active power command (pu on mbase)	1.0
Pmin	Minimum plant active power command (pu on mbase)	0.0
Tlag	Plant controller P output lag time constant (s)	0.15 to 5.0

Internal Variables and Output Channels

REPC_A Internal Variables	
Name	Description
Vreg	Regulated bus voltage (pu, from network solution)
Vref	Regulated bus initial voltage (pu, from power flow solution)
Ibranch	Branch current for line drop compensation (pu on mbase)
Qbranch	Branch reactive power flow for plant Q regulation (pu on mbase)
Qref	Regulated branch initial reactive power flow (pu, from power flow solution)
Qext	Reactive power command from plant controller (pu on mbase)
Pbranch	Branch active power flow for plant P regulation (pu on mbase)
Plant_pref	Initial branch active power flow (pu on mbase, from power flow solution)
Freq	Frequency deviation (pu, from network solution)
Freq_ref	Initial frequency deviation (0)
Pref	Active power command from plant controller (pu on mbase)

Document Version Control

- March 10, 2014 – Original draft by Sandia National Laboratories (Ellis, Elliott)
- March 21, 2014 – Added reference link to folder containing model specifications in Section 1.1. Added caveat in Section 3.1 regarding voltage spikes. (Ellis)
- April 8, 2014 – Editorial changes from Pourbeik (EPRI) and Tacke (MID)
- April 9, 2014 – Model calls added for PSSE and PowerWorld platforms (Karlson, Weber, Senthil)