| Document name | Guideline Template |
|---|---|
| Category | ( ) Regional Reliability Standard<br>( ) Regional Criteria<br>( ) Policy<br>(X) Guideline<br>( ) Report or other<br>( ) Charter |
| Document date | June 17, 2015 |
| Adopted/approved by | TSS |
| Date adopted/approved | |
| Custodian (entity responsible for maintenance and upkeep) | M&VWG |
| Stored/filed | Physical location:<br>Web URL: |
| Previous name/number | N/A |
| Status | (X) in effect<br>( ) usable, minor formatting/editing required<br>( ) modification needed<br>( ) superseded by ________________________<br>( ) other _________________________________<br>( ) obsolete/archived |

**WECC Guideline:**
**Central Station Photovoltaic Power Plant Model Validation Guideline**
**Date: June 17, 2015**

## Introduction

The scope of this document encompasses the representation of central station PV plants in both power flow and dynamic data sets for bulk system studies. Its primary purpose is to outline best practices for performing model validation of utility-scale PV systems (≥10 MW) connected to the transmission network (60 kV and above). Model validation is broadly defined as the process of estimating, or tuning, the parameters of a plant's dynamic model such that the simulated response of the system matches measured data. The extent to which measured and simulated responses should match is dictated by engineering judgment. Agreement to machine epsilon is neither practical nor attainable. For cases in which validation is performed using measurements made at the station, the dynamic response of the system will be partially dependent upon the power flow model. Hence, creating an accurate model of the station equipment and collector system is a prerequisite for performing plant-level model validation.

## Guideline Criteria

This is an original document which does not combine or supersede any previous versions. Although this guideline discusses the fundamental concepts of power flow and dynamic modeling for central station PV plants, it is not intended as a replacement for existing guidelines on those topics. Please see the end of this section for a list of applicable WECC guidelines. The intended audience for this guideline includes PV plant owners responsible for performing model validation of their plants and transmission planners responsible for verifying validation data submitted to them.

## Power Flow Modeling

The power flow representation of a central station PV plant includes:

- An explicit representation of the interconnection transmission line, if one exists.
- An explicit representation of all station transformers.
- An equivalent representation of the collector system.
- An equivalent generator step-up (GSU) transformer with a scaled MVA rating.
- An equivalent generator scaled to match the total capacity of the plant.

## Dynamic Modeling

The dynamic model of a central station PV plant includes:

- A generator/converter module representing the typical PV inverter in the plant, scaled-up to match the plant's aggregate nameplate rating.
- A local electrical control module which translates real and reactive power references into current commands.
- A plant-level control module which sends real and reactive power references to the local electrical controller, if plant-level control is implemented.

## Model Validation Procedure

The steps of a successful model validation procedure include:

- Gather available data from commissioning tests, field tests, and grid disturbances.
- Clearly define the mode of operation, or control mode, of the plant.
- Work with the inverter manufacturer, system integrator, and/or plant operator to determine as many model parameters as possible beforehand.
- Minimize the set of dynamic model parameters which are available for tuning or parameter estimation.
- Use an optimization routine or manual tuning to bring measured and simulated data into agreement.

## Please refer to the following guidelines and policies for more information:

- WECC PV Plant Power Flow Modeling Guide
- WECC Solar PV Dynamic Model Specification
- WECC Solar Plant Dynamic Modeling Guidelines
- WECC Generating Unit Model Validation Policy
- WECC Generating Facility Data, Testing, and Model Validation Requirements
- WECC Data Preparation Manual

## Approved By:

| Approving Committee, Entity, or Person | Date |
|---|---|
| WECC Renewable Energy Modeling Task Force | June 16, 2015 |
| WECC Modeling and Validation Work Group | June 17, 2015 |
| WECC Technical Studies Subcommittee | |

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## Western Electric Coordinating Council

### Background

The composition of the generation fleet in the Western Interconnection is undergoing rapid transformation. According to the Solar Energy Industry Association (SEIA), there are presently 2.6 GW of solar generation under construction and another 18.7 GW under development as of 2014. Ambitious Renewable Portfolio Standards (RPS) are contributing to increased demand for renewable energy. For example, California is committed to serving 33 percent of its load with renewable resources by 2020. Dramatic reductions in the manufacturing cost of solar cells are making investments in photovoltaic (PV) power plants increasingly attractive. The Department of Energy’s SunShot Initiative has set a goal of reducing the total installed cost of PV systems to $1 per Watt by 2020. The capacity of some PV plants has begun to reach levels previously reserved for synchronous generation facilities. For example, the Agua Caliente Solar Project completed in Arizona in 2014 has an installed capacity of 290 MW.

As renewable energy plants have increased in capacity, standards and policies have been developed to ensure they are accurately represented in power flow and dynamic data sets. In particular, NERC MOD-026 and MOD-027 apply to all generating facilities with an aggregate nameplate rating of 75 MVA or larger. The standards, which are subject to enforcement, require accurate representation of a generating facility’s reactive power response to system voltage variations, and its real power response to system frequency variations respectively. Although these NERC MOD standards currently only apply to generating facilities with an aggregate nameplate rating of 75 MVA or larger, WECC policy requires the submission of validated generating facility data for all plants connected to the transmission system (60 kV and above) with an aggregate nameplate rating of 20 MVA or larger. The WECC Generating Unit Model Validation Policy requires generating facility data to be updated at least once every 5 years.

As of 2014, there are approximately 2-3 GW of solar PV generation capacity installed in the Western Interconnection, which corresponds to roughly 1-2 percent of the non-coincident peak load. As the penetration of solar PV generation increases, the dynamic response of the system will change, in part due to a decline in inertia provided by thermal power plants. In order to conduct accurate planning studies and ensure the grid operates reliably, it is vital to model variable generation with the same care and attention to detail as synchronous generation. The intent is for time domain simulation of the system to match reality as closely as possible. Over the course of many years and with input from manufacturers, the WECC Renewable Energy Modeling Task Force (REMTF) has developed a suite of generic models for renewable energy plants. This document focuses on central station PV plants (≥10 MW), how to model them in bulk system planning studies, and how to estimate appropriate dynamic model parameters.

The central station PV plant models used in bulk system studies consist of two main parts: (1) a power flow model based on station equipment and an equivalent representation of the collector system, and (2) a dynamic model representing a scaled-up version of the typical PV inverter in the plant. In order to accurately capture the behavior of a PV plant, it is essential that both the power flow representation and dynamic model be configured correctly using sound engineering judgment and due diligence. For every central station PV plant, the power flow model submitted for use in planning studies must include an explicit representation of the station transformer(s) and an equivalent representation of the collector system. The impedance of the collector system and the generator step-up (GSU) transformer are non-negligible and should be included in the power flow model. Under no circumstances should an equivalent PV inverter be directly connected to a high-voltage bus or to the low-voltage side of a station transformer.

Over the timescales of interest for planning studies, the dynamic behavior of a utility-scale PV inverter is driven primarily by its software/firmware and application-specific control settings. A key simplifying assumption of the generic models created by the REMTF is that the dynamics associated with the dc side of the inverter are neglected. This was a conscious decision made with industry input. In many cases, the dynamics associated with the dc side of the inverter are dominated by high frequency content that is beyond the realm of interest for bulk system planning studies.

The dynamic model for a central station PV plant comprises 2 or 3 modules and contains between 45-75 unique parameters, depending on whether a plant controller is implemented. The resulting model has a high degree of flexibility and can be configured in over 30 unique modes of operation. With such a plethora of available control settings, it is essential to compile as much information about the system as possible before attempting to tune the model parameters. In particular, knowing the pertinent time constants and the mode of operation, i.e., control mode, of the plant are critical to achieving satisfactory model validation. In many cases, this will require engaging the inverter manufacturer, system integrator, and/or plant operator in the process. The number of parameters available for tuning should be minimized to prevent mathematical degeneracy, i.e., loss of uniqueness. The primary purpose of this document is to outline best practices for using measured data to estimate dynamic model parameters for central station PV plants.

**Note**: The generic models developed by the WECC REMTF and discussed in this document are applicable for systems with a short circuit ratio of 3 and higher at the point of interconnection (POI). These generic models are ***not*** intended for studying parts of the system with very low short-circuit levels. In such cases, detailed, vendor-specific models may be required. A brief overview of these concepts is presented in the Appendix.

# 1. POWER FLOW REPRESENTATION

For time domain simulation of the bulk power system, it is recommended that central station PV plants be represented with a single equivalent generator in power flow. This equivalent generator represents the typical, or “average”, inverter inside the plant with its capacity scaled such that it matches the plant’s aggregate nameplate rating. This paradigm for representing renewable energy plants simplifies the modeling of plant level controls and improves computational tractability. Incorporating the generator step-up (GSU) transformers and collector system into equivalent forms follows logically from the generator representation. For thorough documentation of the recommended practices for modeling central station PV plants in power flow, please see the WECC PV Plant Power Flow Modeling Guide.

Figure 1 depicts the complete one-line diagram of the recommended power flow representation for central station PV plants.

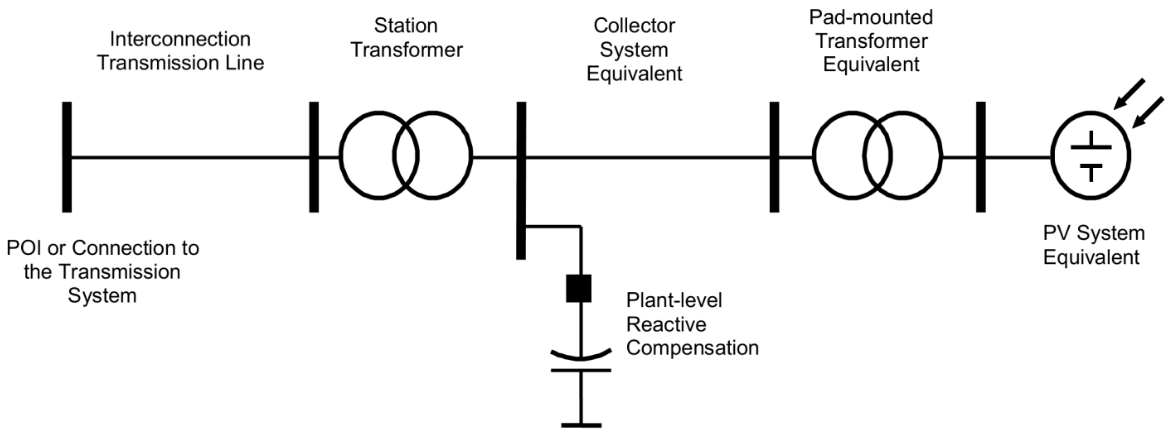


**Figure 1. One-line diagram of a central station PV plant.**

## 1.1 Common Mistakes

This section explains some of the common mistakes made when representing variable generation plants in power flow and how to rectify them.

1) Not representing the interconnection transmission line, if one exists.
2) Directly connecting the equivalent generator to the point of interconnection (POI) or another high voltage bus.
3) Connecting the equivalent generator to the low-voltage side of the station transformer, thereby neglecting the collector system.

These issues can be corrected by modeling all of the elements depicted in Figure 1 which pertain to a particular plant. For questions on how to calculate the equivalent impedance of the collector system or generator step-up transformer, please see the WECC PV Plant Power Flow Modeling Guide.

# 2. DYNAMIC MODELING

The WECC Renewable Energy Modeling Task Force (REMTF) has developed a set of dynamic models for renewable energy power plants using a modular approach. The way in which the modules are assembled dictates what type of plant is represented (Type 3 WTG, PV, etc.). Central station PV plants are represented using the generator converter module (REGC_A), the PV electrical control module (REEC_B), and the plant controller module (REPC_A). We recognize that some implementations will not feature plant-level control. In those cases, it is appropriate to omit the plant controller module. For systems with voltage or frequency ride-through capability, the optional LHVRT and/or LHFRT models may be incorporated. Figure 2 depicts the interconnection of the modules necessary to represent a central station PV plant with a plant-level controller.

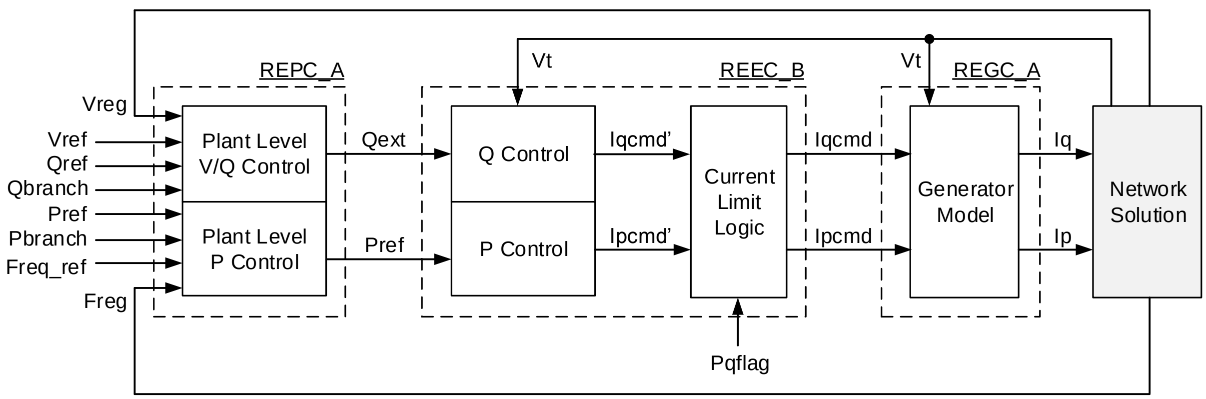


**Figure 2. Dynamic model interconnection diagram for a central station PV plant.**

## 2.1 Module Overview

This section provides a brief, high-level description of the functions carried out by the 3 primary modules used to represent central station PV plants. Block diagrams and parameter lists are included in the Appendix.

REGC_A – The generator converter module reconciles the current commands with the network boundary conditions to yield current injections.

REEC_B – The electrical control module translates real and reactive power references into current commands.

REPC_A – The plant controller module takes values from the network solution and produces real and reactive power references (optional).

For further information on the dynamic model structure and specification, please refer to the WECC Solar PV Dynamic Model Specification. Additionally, the WECC Solar Plant Dynamic Modeling Guidelines provide a helpful introduction to the PV system dynamic models and their applications.

# 3. MODEL VALIDATION

The overarching goal of the model validation process is to verify that the results of time domain simulation agree with measured data and hence, are consistent with actual system performance. In commercial software tools, the power system is simulated by integrating the differential equations of the dynamic models used to represent the system equipment. Many dynamic model inputs are values provided by the solution of the algebraic power flow equations. As such, computational simulation of the power system is dependent upon the fidelity of both the power flow and dynamic models. For central station PV plants, the power flow representation is dictated by physics. All of the necessary parameters are known or can be directly calculated with a high degree of certainty. Hence, the focus of this section will be on configuring the structure and selecting the parameter values of dynamic models for central station PV plants.

**Note**: A prerequisite for the model validation process is following the procedure outlined in the WECC PV Plant Power Flow Modeling Guide to generate an accurate power flow representation of the plant.

## 3.1 Data Collection

The types of data useful for model validation of PV plants can be roughly divided into two categories. The first corresponds to the system's response to repeatable tests, and the second corresponds to the system's to spontaneously occurring disturbances. Repeatable tests, such as performing a step-test with a switched capacitor, can be an effective method of characterizing a plant's response. The controlled nature of the test makes it easier to distinguish the plant's response from noise in the measurement channel. However, data collected during actual grid disturbances help demonstrate the accuracy of the model when subject to uncontrolled perturbations in a way that tests cannot. The intent is for the modeled and measured output to agree for contingencies that occur in the field.

To isolate the behavior of the typical inverter in the plant, measurements may be taken at either the terminals of the inverter or the generator step-up transformer. For plant-level model validation purposes, measurements may be taken at either the point of interconnection (POI) or the station. In the context of bulk system dynamics studies, the bandwidth of interest for the equipment models spans a range between approximately 0-5 Hz. Using a multiple of the Nyquist rate as a guide, the sample rate of measurements used for model validation should ideally be 30 Hz or greater. For phasor measurement units (PMUs), a sample rate of 60 Hz is preferred. In modern implementations, PMU measurements are typically taken at both the primary and secondary of the station transformer(s). Digital Fault Recorders (DFRs) and PMU-capable DFRs can capture valuable data for dynamic model validation as well.

## 3.2 Defining the Mode of Operation

With the generic models developed by the REMTF, a central station PV plant can be configured in over 30 unique modes of operation. Because there are a myriad of different ways the models can be configured, selecting the appropriate model structure is a vital first step in the parameter estimation process. Each unique model configuration corresponds to a particular control scheme. Possible control objectives include regulating the voltage at the point of interconnection (POI) or maintaining a constant power factor. Tables 1 and 2 provide a breakdown of commonly employed real and reactive power control options respectively. The REGC_A model is required for ***all*** central station PV plants regardless of control mode. For brevity, it was not listed in the "Required Models" column of the tables below.

The control functionality labeled "governor response" in Table 1 enables a plant to modulate its real power output to support system frequency and/or maintain a constant plant-level real power output. This control loop is experimental and primarily used for research purposes. Unless it is known with complete certainty that a plant employs this functionality, it should be disabled (set **frqflag** = 0). This control loop has not been tested extensively and should be used with extreme caution.

**Table 1. Real power control options.**

| Functionality | Required models | frqflag | ddn | dup |
|---|---|---|---|---|
| No governor response | REEC_B | 0 | N/A | N/A |
| Governor response, down regulation | REEC_B + REPC_A | 1 | >0 | 0 |
| Governor response, up and down | REEC_B + REPC_A | 1 | >0 | >0 |

**Table 2. Reactive power control options.**

| Functionality | Required models | pfflag | vflag | qflag | refflag |
|---|---|---|---|---|---|
| Constant local power factor control | REEC_B | 1 | N/A | 0 | N/A |
| Constant Q control | REEC_B | 0 | N/A | 0 | N/A |
| Local V control | REEC_B | 0 | 0 | 1 | N/A |
| Local coordinated Q/V 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 Q/V control | REEC_B + REPC_A | 0 | 1 | 1 | 0 |
| Plant level V control & Local coordinated Q/V control | REEC_B + REPC_A | 0 | 1 | 1 | 1 |

***Note**: The designation "N/A" in Table 2 means the parameter flag has no effect on the mode of operation and hence may be set to either 0 or 1. For instance, in constant local power factor control mode **vflag** has no effect because the REEC_B interior PI loops are bypassed.

### 3.2.1 Setting the REPC_A Model Flags

The plant controller module, REPC_A, has 4 flags. The reference flag, **refflag**, selects either plant-level voltage or reactive power control. If plant-level voltage control is selected, the voltage compensation flag, **vcmpflag**, selects either voltage droop or line drop compensation. The output flag, **outflag**, indicates whether the Qref Volt/VAR output of REPC_A corresponds to a voltage or reactive power reference. The real power reference flag, **frqflag**, determines whether the real power output of the plant is modulated to support system frequency and/or to maintain a constant plant-level real power output. Unless it is known with certainty that a plant employs this functionality, disable it by setting **frqflag** to zero.

1) Does the plant feature a plant-level controller?
   - If yes, move on to Step 2. Otherwise, do not include the REPC_A module in the dynamic model and skip ahead to Subsection 3.2.2.
2) Is plant-level voltage control implemented?
   - If yes, set **refflag** = 1. If plant-level reactive power control is implemented instead, set **refflag** = 0.
3) If plant-level voltage control is implemented, does it use line drop compensation?
   - If yes, set **vcmpflag** = 1. If voltage droop compensation is implemented instead, set **vcmpflag** = 0.
   - If the measured voltage is not compensated, set **vcmpflag** = 1 and the compensation resistance and reactance to zero, **rc** = 0 and **xc** = 0.
4) Does the plant modulate its real power output to support system frequency and/or maintain a constant plant-level real power output?
   - If yes, set **frqflag** = 1. Otherwise, set **frqflag** = 0.
   - If you set **frqflag** = 1, confirm that the plant being modeled actually employs this functionality. This control loop has not been tested extensively and should be used with extreme caution.
   - For most plants, the correct selection is **frqflag** = 0.
5) Does the plant controller's Qref Volt/VAR output correspond to reactive power?
   - If yes, set **outflag** = 0. If the Qref output instead corresponds to voltage, set **outflag** = 1. See Table 5 for more information.

### *3.2.2 Setting the REEC_B Model Flags*

The renewable energy electrical control model for PV systems, REEC_B, has 4 flags which allow the user to fine-tune its control structure and select real or reactive power priority. The combination of the power factor (**pfflag**), voltage (**vflag**), and reactive power (**qflag**) control flags dictates the reactive power control scheme of the plant. For information on how to map a given control scheme to a flag combination, please see Table 2.

The purpose of the current limit logic is to allow the plant to properly allocate its current capacity upon saturation. Priority is given to either the active or reactive current command depending on the value of the current limit logic priority flag (**pqflag**). The first priority command is bounded only by the current rating of the converter. Hence, the second priority command is bounded by whatever capacity is leftover after generating the first priority command.

The instructions for how to set the REEC_B module flags are broken down into two sections, one for plants with strictly local control (i.e., no plant controller) and one for plants with plant-level control. Be careful to follow the correct procedure for the plant being modeled.

#### *Strictly Local Control – No REPC_A Module*

1) Does the plant regulate its output to maintain a constant local power factor?
   - If yes, set **pfflag** = 1, **vflag** = 1, **qflag** = 0. Skip to Step 5.
   - If no, set **pfflag** = 0. Go to Step 2.
2) Does the plant regulate its output to maintain a constant reactive power level (constant reactive power control)?
   - If yes, set **vflag** = 1 and **qflag** = 0. Skip to Step 5.
3) Does the plant regulate voltage at the terminal bus (local voltage control)?
   - If yes, set **vflag** = 0 and **qflag** = 1. Skip to Step 5.
4) Does the plant operate in local coordinated Q/V control using the series PI loops depicted in Figure 11?
   - If yes, set **vflag** = 1 and **qflag** = 1.
5) Does the plant operate in real or reactive power priority mode?
   - For real power priority, set **pqflag** = 1. For reactive power priority, set **pqflag** = 0.

The remainder of Subsection 3.2.2 describes how to set the REEC_B parameter flags for central station PV plants with plant-level control (i.e., the REPC_A module is included). This procedure is different because the mode of operation and flag settings must be compatible across the REEC_B and REPC_A modules.

*Plant-Level Control – Model Includes REPC_A Module*

1) Set **pfflag** = 0. Local power factor control should not be used with the plant controller module.
2) Does the Qref Volt/VAR output of the plant controller correspond to a voltage reference?
   - If yes, set **vflag** = 0 and **qflag** = 1. Skip to Step 6.
3) Does the Qref Volt/VAR output of the plant controller correspond to a reactive power reference?
   - If yes, set **vflag** = 1. Go to Step 4.
4) Does the plant employ local coordinated Q/V control using the series PI loops depicted in Figure 11?
   - If yes, set **qflag** = 1. Skip to Step 6.
5) Does the plant compute a reactive current command by dividing the reactive power reference by a voltage?
   - If yes, set **qflag** = 0. In this configuration, the series PI loops depicted in Figure 11 are bypassed.
6) Does the plant operate in real or reactive power priority mode?
   - For real power priority, set **pqflag** = 1. For reactive power priority, set **pqflag** = 0.

### *3.2.3 Setting the REGC_A Model Flags*

The generator converter module, REGC_A, has 1 flag which enables or disables the Low Voltage Power Logic (LVPL) feature. The **lvplsw** flag indicates whether the limit on the inverter's active current is voltage-dependent. For more information, please consult the WECC Solar PV Dynamic Model Specification or the relevant software user guide.

1) Is the limit on the inverter's active current voltage-dependent?
   - If yes, set **lvplsw** = 1. Otherwise, set **lvplsw** = 0.

**Note**: After setting the model parameter flags as described in this section, check Section 3.3 to ensure that the selected flag combination corresponds to a valid mode of operation.

## 3.3 Valid Model Parameter Flag Combinations

### *3.3.1 Strictly Local Control – No REPC_A Module*

This section discusses the possible flag combinations for plants with strictly local control. The distinguishing feature of strictly local control is that the plant has no plant-level controller. Hence, the overall dynamic model consists only of the REGC_A and REEC_B modules. Table 3 lists the possible flag combinations for plants with strictly local control and indicates whether each combination is valid or invalid. Only valid flag combinations are permissible for model data submissions.

The choice of real or reactive power priority via the **pqflag** does not influence whether a particular flag combination corresponds to a valid control mode. Hence, the **pqflag** may be set to either 0 or 1 for any case.

**Table 3. List of flag combinations for local control.**

| REEC_B | | | Notes |
|---|---|---|---|
| **pfflag** | **vflag** | **qflag** | **No.** |
| 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 2 |
| 0 | 1 | 0 | 3 |
| 0 | 1 | 1 | 4 |
| 1 | 0 | 0 | 5 |
| 1 | 0 | 1 | 6 |
| 1 | 1 | 0 | 7 |
| 1 | 1 | 1 | 8 |

| Key |
|---|
| Valid |
| Invalid |

Notes

1.) Valid – Constant reactive power control (equivalent to Combination #3).
2.) Valid – Local voltage control.
3.) Valid – Constant reactive power control (equivalent to Combination #1).
4.) Valid – Local coordinated Q/V control.
5.) Valid – Constant local power factor control (equivalent to Combination #7).
6.) Invalid – Local power factor control is incompatible with the interior PI loops.
7.) Valid – Constant local power factor control (equivalent to Combination #5).
8.) Invalid – Local power factor control is incompatible with the interior PI loops.

Key Points

- The **pqflag** value does not affect whether a parameter flag combination corresponds to a valid control mode.

### *3.3.2 Plant-Level Control – Model Includes REPC_A Module*

This section discusses the possible flag combinations for plant-level control. Only valid flag combinations are permissible for model data submissions. The overall plant model comprises 3 modules: REGC_A, REEC_B, and REPC_A. The plant controller module contains 4 parameter flags: **refflag**, **vcmpflag**, **frqflag**, and **outflag**. A brief description of the REPC_A flags follows:

**refflag** — Determines whether the plant-level Volt/VAR control loop regulates voltage (=1) or reactive power (=0)

**vcmpflag** — Determines whether the plant controller employs line drop compensation (=1) or voltage droop (=0) when **refflag** = 1

**frqflag** — Determines whether the real power control functionality of the plant controller is enabled (=1) or disabled (=0)

**outflag** — Indicates whether the Qref Volt/VAR output corresponds to a voltage (=1) or reactive power (=0) reference

The position of the voltage compensation flag, **vcmpflag**, only has an impact when the plant-level Volt/VAR control loop is regulating voltage (i.e., when **refflag** = 1). Although the value of **vcmpflag** does not affect the validity of a flag combination, care must be taken to coordinate its setting with the plant's mode of operation and the REPC_A model invocation.

The output indicator flag, **outflag**, denotes whether the output of the plant-level Volt/VAR control loop corresponds to a voltage or reactive power reference. It should be set in accordance with Table 5. For PV plants, the REPC_A Qref output must be consistent with the REEC_B settings.

The plant-level real power control loop is experimental and primarily used for research purposes. The function of this control loop is to modulate the real power output of the plant to support system frequency and/or maintain a constant real power output. Because this feature has not been tested extensively, it should be used with extreme caution. It may require further enhancements in the future.

<u>Key Points</u>

- Set **frqflag** = 0 unless the plant modulates its real power output to support system frequency and/or maintain a constant plant-level real power output.
- The **vcmpflag** setting does not affect whether a parameter flag combination corresponds to a valid control mode. It is only used when **refflag** = 1.
- Make sure the **outflag** setting is consistent with the selected control mode by setting it in accordance with Table 5.

**Table 4. List of flag combinations for plant-level control.**

| REEC_B | | | REPC_A | Notes |
|---|---|---|---|---|
| pfflag | vflag | qflag | refflag | No. |
| 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 2 |
| 0 | 0 | 1 | 0 | 3 |
| 0 | 0 | 1 | 1 | 4 |
| 0 | 1 | 0 | 0 | 5 |
| 0 | 1 | 0 | 1 | 6 |
| 0 | 1 | 1 | 0 | 7 |
| 0 | 1 | 1 | 1 | 8 |
| 1 | 0 | 0 | 0 | 9 |
| 1 | 0 | 0 | 1 | 10 |
| 1 | 0 | 1 | 0 | 11 |
| 1 | 0 | 1 | 1 | 12 |
| 1 | 1 | 0 | 0 | 13 |
| 1 | 1 | 0 | 1 | 14 |
| 1 | 1 | 1 | 0 | 15 |
| 1 | 1 | 1 | 1 | 16 |

| Key |
|---|
| Valid |
| Invalid |

Notes

1.) Valid – Plant-level reactive power control (equivalent to Combination #5).
2.) Valid – Plant-level voltage control (equivalent to Combination #6).
3.) Valid – The REPC_A Qref output is a voltage reference.
4.) Valid – The REPC_A Qref output is a voltage reference.
5.) Valid – Plant-level reactive power control (equivalent to Combination #1).
6.) Valid – Plant-level voltage control (equivalent to Combination #2).
7.) Valid – Plant-level reactive power control and local coordinated Q/V control.
8.) Valid – Plant-level voltage control and local coordinated Q/V control.
9.) Invalid – REPC_A is not used for constant local power factor control.
10.) Invalid – REPC_A is not used for constant local power factor control.
11.) Invalid – Power factor control is incompatible with the REEC_B PI loops.
12.) Invalid – Power factor control is incompatible with the REEC_B PI loops.
13.) Invalid – REPC_A is not used for constant local power factor control.
14.) Invalid – REPC_A is not used for constant local power factor control.
15.) Invalid – Power factor control is incompatible with the REEC_B PI loops.
16.) Invalid – Power factor control is incompatible with the REEC_B PI loops.

*Setting the Output Type Indicator Flag*

The purpose of the output type indicator flag, **outflag,** is to indicate whether the REPC_A Qref output corresponds to a voltage or reactive power reference. The **outflag** setting must be consistent with the REEC_B configuration and vice versa. When the REPC_A Qref output corresponds to a voltage reference, **vflag** in REEC_B must be set to zero. Otherwise, the electrical control module would interpret the voltage reference from the plant controller as a reactive power reference. To ensure compatibility across model settings, select the mode of operation first and set **outflag** in accordance with Table 5.

**Table 5. Correct settings for the REPC_A outflag parameter.**

| REEC_B | | | REPC_A | |
|---|---|---|---|---|
| **pfflag** | **vflag** | **qflag** | **refflag** | **outflag** |
| 0 | 0 | 0 | 0 | 0 (Q) |
| 0 | 0 | 0 | 1 | 0 (Q) |
| 0 | 0 | 1 | 0 | 1 (V) |
| 0 | 0 | 1 | 1 | 1 (V) |
| 0 | 1 | 0 | 0 | 0 (Q) |
| 0 | 1 | 0 | 1 | 0 (Q) |
| 0 | 1 | 1 | 0 | 0 (Q) |
| 0 | 1 | 1 | 1 | 0 (Q) |

## 3.4 Dynamic Model Invocation Considerations

This section discusses important things to consider when selecting the correct dynamic model invocation for a PV plant. A dynamic model invocation is an entry or series of entries in a dynamic data file that specifies which modules will be employed to represent a plant and what their respective parameters are. Model invocation conventions vary somewhat between software platforms, so consult the appropriate user manual for guidance. For PV plant model invocation examples in specific software formats, please refer to the WECC Solar Plant Dynamic Modeling Guidelines.

The precise details of the model invocation can affect the operation of the modules. For example, the manner in which the plant controller module is invoked specifies which bus is regulated and which branch is monitored. It is crucial to consider not only how the parameters of the REPC_A module are populated, but how the model itself is invoked.

### *3.4.1 REPC_A Module Invocation Considerations*

In the REPC_A module invocation, the user specifies which bus is regulated by the plant. In addition to declaring which bus is regulated, the user has the option of specifying a monitored branch. For central station PV plants, this branch is typically selected such that it reflects the total output of the plant as measured on either side of the collector system equivalent.

The Ibranch, Pbranch, and Qbranch inputs to REPC_A seen in Figure 12 are determined from the flows on this branch. Hence, in order to model real and/or reactive power control at the plant-level, a monitored branch must be specified. Notice that for plant-level voltage control, line drop compensation is performed using the current magnitude on this branch and the user-specified compensation resistance and reactance.

Key Points

- Define the terminal bus to which the equivalent generator/converter is connected.
- Define the bus that is regulated by the plant, if other than the terminal bus.
- Define the monitored branch from which the Ibranch, Pbranch, and Qbranch inputs to REPC_A are derived. See Figure 12. REPC_A block diagram.Figure 12 for further information.

### 3.5 Identifying Tunable Parameters

The dynamic model for a central station PV plant comprises 2 or 3 modules and contains between 45-75 unique parameters, depending on whether a plant controller is implemented. As such, it is essential to fix as many parameter values as possible before beginning a parameter estimation procedure. The aim of this section is to describe how to set the fixed parameter values, and how to identify the tunable parameters. Fixed parameters are known, and tunable parameters are unknown. Section 3.6 presents additional information and background on parameter estimation.

Before the tunable parameters can be identified, it is essential to complete three key prerequisites:

- Create a power flow representation of the plant as described in the WECC PV Plant Power Flow Modeling Guide and Section 1 of this document.
- Define the mode of operation for the plant as discussed in Sections 3.2 and 3.3.
- Determine the correct dynamic model invocation for the plant based on the mode of operation, the regulated bus, and the monitored branch as described in Section 3.4.

Unless these three prerequisites are successfully completed, the correct parameter values will still not yield the desired model behavior.

After the power flow representation for the plant and the proper dynamic model invocation have been established, it is time to begin populating the parameters of the dynamic model. Please refer to the WECC Second Generation Wind Turbine Model Specification for a description of the algorithms employed in the “high-voltage reactive current management” and “low-voltage active current management” blocks.

Table 10 provides typical values for the REGC_A generator/converter module parameters. Likewise, Tables 11 and 12 provide typical value ranges for the REEC_B and REPC_A modules respectively. These typical values and ranges are not set in stone. It may be entirely appropriate to deviate from the listed values, provided that it is done with sound reasoning and engineering judgment. The typical values included here are intended to serve as starting points.

The set of parameters available for tuning is dependent upon a plant’s mode of operation and whether a plant controller is implemented. The mode of operation and its matching parameter flag combination are important because they dictate the structure of the dynamic model. Furthermore, the structure of the dynamic model determines which parameters influence model behavior. One of the most valuable features of the generic dynamic models developed by the REMTF is their flexibility. Certain control features, such as proportional control of terminal voltage in REEC_B, can be enabled or disabled through appropriate selection of control gains. As with Sections 3.2 and 3.3, the procedure for identifying tunable parameters is divided into two subsections: one for strictly local control and one for plant-level control. Be careful to follow the appropriate procedure that applies to the plant being modeled.

### *3.5.1 Strictly Local Control – No REPC_A Module*

This subsection discusses how to identify tunable parameters for plants with strictly local control (i.e., no plant controller). A plant's mode of operation determines which parameters have an impact on its model behavior. The REMTF recommends that only control gains be used as tunable parameters. The basis for this recommendation is that the uniqueness of the solution may be compromised by expanding the tunable parameter set. That is, if the set is expanded to include other parameters, such as time constants, there is a high likelihood that multiple parameterizations could yield near identical model output for a given input data set. Therefore, to help prevent the problem from becoming underdetermined, the tunable parameter set is restricted to control gains. Table 6 summarizes the parameters available for tuning for each of the valid local control modes. Notice that all of the tunable parameters listed in the table belong to the electrical control module (REEC_B).

**Table 6. Recommended tunable parameters for strictly local control.**

| REEC_B | | | Tunable Parameters |
|---|---|---|---|
| **pfflag** | **vflag** | **qflag** | **Local** |
| 0 | 0 | 0 | Kqv |
| 0 | 0 | 1 | Kqv, Kvp, Kvi |
| 0 | 1 | 0 | Kqv |
| 0 | 1 | 1 | Kqv, Kqp, Kqi, Kvp, Kvi |
| 1 | 0 | 0 | Kqv |
| 1 | 1 | 0 | Kqv |

### *3.5.2 Plant-Level Control – Model Includes REPC_A Module*

This subsection discusses how to identify the tunable parameters for model implementations featuring a plant controller. A plant's mode of operation determines which parameters have an impact on its model behavior. Table 7 summarizes the parameters available for tuning in each of the valid plant control modes. Notice that the tunable parameters are arranged in columns according to those that belong to the plant controller (REPC_A) and those that belong to the electrical control module (REEC_B). See the note below the table for information about the plant-level real power control loop and its parameters.

**Table 7. Recommended tunable parameters for plant-level control.**

| REEC_B | | | REPC_A | Tunable Parameters | |
|---|---|---|---|---|---|
| **pfflag** | **vflag** | **qflag** | **refflag** | **Local** | **Plant** |
| 0 | 0 | 0 | 0 | Kqv | Kp, Ki |
| 0 | 0 | 0 | 1 | Kqv | Kp, Ki |
| 0 | 0 | 1 | 0 | Kqv, Kvp, Kvi | Kp, Ki |
| 0 | 0 | 1 | 1 | Kqv, Kvp, Kvi | Kp, Ki |
| 0 | 1 | 0 | 0 | Kqv | Kp, Ki |
| 0 | 1 | 0 | 1 | Kqv | Kp, Ki |
| 0 | 1 | 1 | 0 | Kqv, Kqp, Kqi, Kvp, Kvi | Kp, Ki |
| 0 | 1 | 1 | 1 | Kqv, Kqp, Kqi, Kvp, Kvi | Kp, Ki |

**Note**: The real power control functionality of the plant controller is experimental and primarily used for research purposes. This control loop has not been tested extensively and should be used with extreme caution. If this functionality is enabled, then **Kpg** and **Kig** of the plant controller are candidates for inclusion in the set of tunable parameters. Correspondingly, if this control loop is used to support system frequency, **Ddn** and **Dup** determine how sensitive the plant controller is to over and under frequency conditions respectively.

Although the REPC_A voltage droop gain **Kc** can be viewed as a control gain, it should be treated as a fixed parameter. This gain only affects the model behavior when voltage is regulated at the plant level and voltage droop is employed (**vcmpflag** = 0). If the plant is configured this way, set the **Kc** parameter value according to how the compensation was designed.

## 3.6 Parameter Estimation or Tuning

In general, the purpose of a parameter estimation routine is to identify the set of parameters for which the model output matches measured data as well as possible. As with most problems in engineering, we begin with sets of known and unknown variables. In this case, the measured data and fixed parameters are known, and the tunable parameters are unknown. Section 3.1 describes what type of data is required to perform model validation for a central station PV plant. The overall plant model includes both the power flow representation and the dynamic model implementation of the plant. Although all parameters recommended for tuning belong to the dynamic model, establishing an accurate power flow representation of the plant is essential. For more information on representing PV plants in power flow, see the WECC PV Plant Power Flow Modeling Guide and Section 1 of this document.

### *3.6.1 Dynamic Model Parameter Sensitivity*

In most circumstances, the control loops which affect a plant's real and reactive power response are independent of one another. As a result, a majority of the tunable parameters directly influence either the real or reactive current command, but not both. An example of where this clear delineation breaks down is when the converter's output approaches its current rating. Under saturation, the REEC_B current limit logic engages, and the active and reactive current commands are allocated according to the limit scheme and the priority selection made with **pqflag**. However, the real and reactive power responses can generally be tuned independently.

Out of about 75 parameters distributed across the 3 modules for a central station PV plant, there are 11 control gains which are suitable for tuning. Table 8 categorizes those parameters according to whether they affect real or reactive power. The columns of the table indicate whether a parameter belongs to the electrical control module (REEC_B) or the plant controller (REPC_A). Very few, if any, implementations should require all of these gains as tunable parameters. In particular, most implementations will not use the real power control loop in the plant controller, reducing the size of the tunable parameter set. Tables 6 and 7 in Section 3.5 indicate which of the tunable parameters are applicable for each of the possible modes of operation.

**Table 8. Parameter sensitivity to real and reactive power response.**

| Real Power | | Reactive Power | |
|---|---|---|---|
| REEC_B | REPC_A | REEC_B | REPC_A |
| - | Kpg | Kqv | Kp |
| - | Kig | Kqp | Ki |
| - | Ddn | Kqi | - |
| - | Dup | Kvp | - |
| - | - | Kvi | - |

A plant's dynamic response can be roughly divided into four components which characterize its real and reactive power response to voltage and frequency variations respectively. The following section aims to explain the key factors which influence each of those four elements. Along the way, we will attempt to highlight the role of important model parameters.

*Real Power Response to Voltage Variations*

In the REEC_B electrical control module, the active current command is generated by dividing the real power reference by the terminal voltage of the equivalent converter. This operation will cause the real power response of the plant to be sensitive to voltage. The ability to tune this response within REEC_B is somewhat limited; however, one does have the ability to select the time constant (**trv**) corresponding to the voltage transducer. The key factors influencing a plant's real power response to voltage variations are the low voltage power logic and low voltage active current management in the REGC_A module. These features are not easily integrated into a parameter estimation routine and should be set according to how a particular plant's active current output is limited in response to terminal voltage variations.

Key parameters: **lvplsw, zerox, brkpt, lvpl1, lvpnt0, lvpnt1** (REGC_A)

*Real Power Response to Frequency Variations*

In general, PV inverters are designed such that their real power output is insensitive to system frequency variations. Unlike synchronous machines, there is no electromechanical relationship that couples real power to frequency. In the REPC_A plant controller module, there is a normally disabled control loop that modulates real power to support system frequency and/or maintain a constant plant-level real power output. This control loop is experimental and primarily used for research purposes. Unless it is known with complete certainty that a plant employs this functionality, it should be disabled (set **frqflag** = 0). This control loop has not been tested extensively and should be used with extreme caution.

Key parameters: **frqflag, kpg, kig, ddn, dup** (REPC_A)

*Reactive Power Response to Voltage Variations*

The plant-level reactive power control loop and the majority of the REEC_B electrical control module are dedicated to shaping a plant's reactive power response to system voltage variations. Everything discussed in Sections 3.2 to 3.4 about a plant's mode of operation and its dynamic model invocation will affect the relationship between reactive power and voltage. For further information, please see the WECC Solar PV Dynamic Model Specification.

Key parameters: **kp, ki, kqv, kqp, kqi, kvp, kvi** (REPC_A and REEC_B)

*Reactive Power Response to Frequency Variations*

As with real power, PV inverters are designed such that their reactive power output is insensitive to system frequency variations. Furthermore, there is no supplemental control loop which modulates reactive power in response to frequency error. Hence, there are no key control features or parameters that impact this element of a plant's response.

Key parameters: Not applicable

### *3.6.2 Parameter Estimation Example*

This section presents an example of a successful parameter estimation procedure. This case was constructed using simulated data for purposes of demonstration. As such, the model data and plant response are not associated with any specific PV plant. The necessary preliminaries discussed in Section 3.5 were executed prior to beginning the parameter estimation procedure. Figure 3 presents the one-line diagram corresponding to the plant's power flow representation. The plant was configured to control voltage at the plant level and employ local coordinated Q/V control. Hence, both interior PI loops of the REEC_B module were utilized.

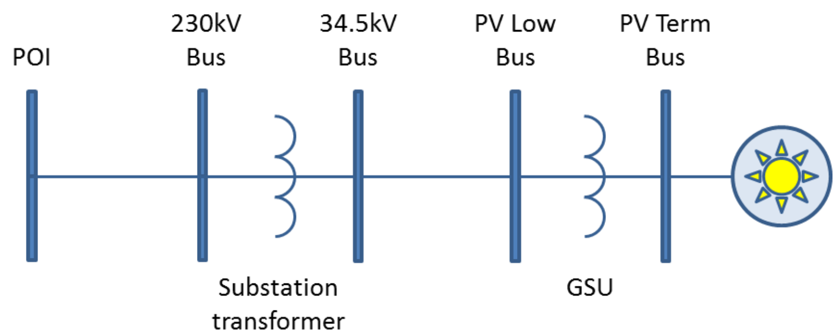


**Figure 3. One-line diagram for the parameter estimation example.**

The aim of the procedure described here was to characterize the plant's real and reactive power response to system voltage variations. A 6-cycle fault was simulated on the grid side using the playback feature in PSLF. Although this data was simulated, field measurements can be played in using this approach as well. During the fault, the voltage at the POI was depressed to approximately 50% of its pre-disturbance level. Data was recorded to simulate PMU measurements taken on the primary and secondary of the substation transformer. Figure 4 shows the voltage measurements taken on the primary (high-voltage side) of the substation transformer during the fault. These signals served as the inputs to the PV plant model. Figure 5 shows the real and reactive power output of the plant as measured at the station. These signals served as the outputs. The tunable parameters of the model were adjusted such that the output matched the measurements displayed in Figure 5 for the inputs displayed in Figure 4.

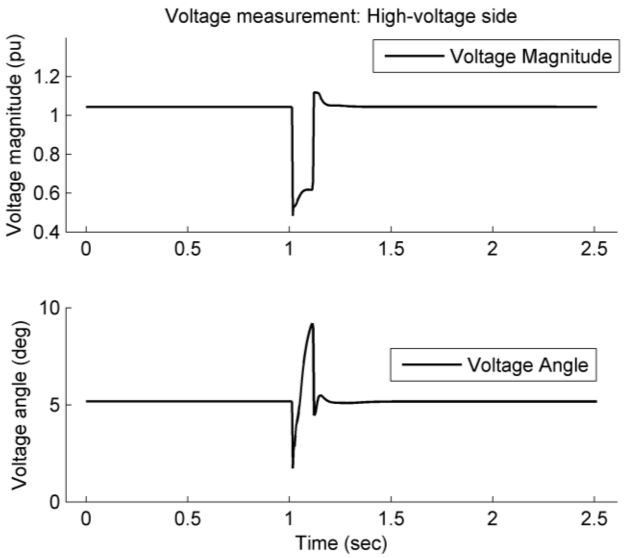


Figure 4. Inputs – Station voltage measurements.

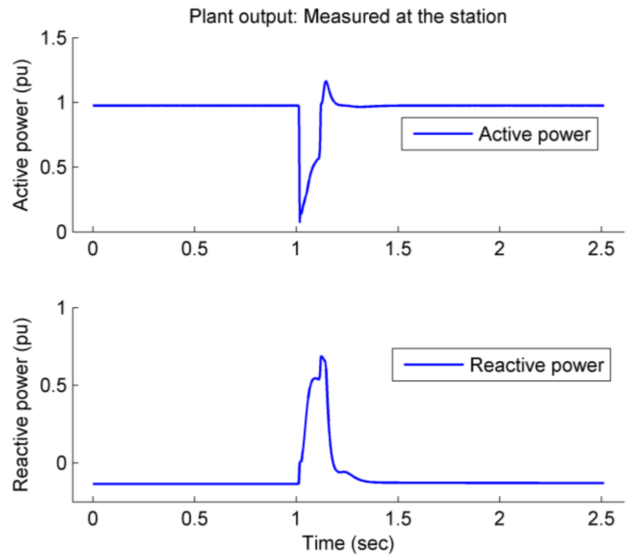


Figure 5. Outputs – Plant real and reactive power.

For this plant, the selected mode of operation was plant-level voltage control with local coordinated Q/V control. The parameter flag combination for this control mode, as shown in Table 2, is:

**pfflag** = 0, **vflag** = 1, **qflag** = 1, **refflag** = 1

Because this is a control mode that requires a plant controller, Table 7 was used to identify the set of tunable parameters for the estimation procedure. This set included:

**Kp, Ki, Kqv, Kqp, Kqi, Kvp, Kvi**

For the purposes of the example, the actual parameters used to generate the simulated data depicted in Figure 4 were effectively erased. That is, the parameter estimation routine was stripped of all information about their values. Although the tunable parameters of the dynamic model were unknown, it was necessary to postulate an initial guess about their values to seed the parameter estimation routine. The initial guess for the unknown parameters was used to produce the preliminary model output depicted in Figure 6. In contrast to Figure 5 which shows the plant output at the POI, Figure 6 shows the real and reactive power output measured at the generator step-up (GSU) transformer. These signals represent the output of the equivalent generator/converter. Notice that the modeled response does not match the measured data particularly well for the initial guess. This is to be expected because the control gains were not known with certainty.

For this example, the parameters were estimated using an optimization algorithm called the Nelder-Mead method. The algorithm yielded a set of estimated (or optimized) parameters and the modeled plant output generated with those parameters. Table 9 presents the estimated parameters, and Figure 7 shows the final model output.

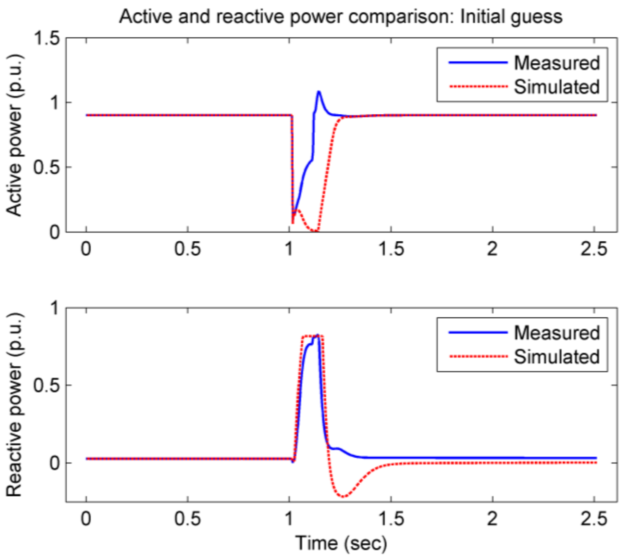


**Figure 6. Initial guess output comparison.**

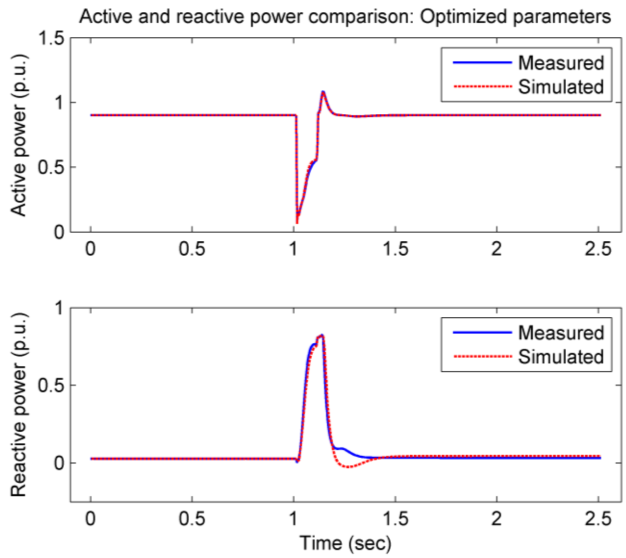


**Figure 7. Optimized parameter output comparison.**

The results of the parameter estimation routine are summarized in Table 9. The table presents the initial guess at the tunable parameter values, the actual values used to generate the data, and the estimated (or optimized) parameter values. Because this example was created in simulation for demonstration purposes, the actual parameter values are known with certainty. This allows us to assess how well the actual and estimated parameters agree. For real-world scenarios, there is no master parameter set which represents the "true" solution.

**Table 9. Initial, actual, and optimized model parameters.**

| Model | Param. | Initial guess | Actual | Estimated |
|---|---|---|---|---|
| **REPC_A** | Kp | 15.0 | 10.0 | 10.9 |
| | Ki | 1.0 | 5.0 | 4.3 |
| **REEC_B** | Kqv | 0.0 | 0.0 | 0.0 |
| | Kqp | 0.0 | 0.1 | 0.0 |
| | Kqi | 0.0 | 0.1 | 0.0 |
| | Kvp | 12.0 | 5.0 | 4.1 |
| | Kvi | 2.0 | 1.0 | 1.2 |

The extent to which the modeled output matches the measured data in Figure 7 is representative of what is achievable using field data. The modeled output does not exhibit any significant bias error, and it tracks the data well during the disturbance. While the aim of a parameter estimation routine is to make the modeled output match measured data as well as possible, it is unrealistic to expect an exact fit. If the modeled output matched the measured data exactly, that would be an indication of overfitting. The intention is to track the physical response of the plant and disregard the process noise.

In the case of model validation for PV plants, the criterion by which parameterizations are judged is difficult to codify. Mathematical norms, such as the sum of squared error or the Euclidean norm, can serve as useful metrics for describing how well the modeled output matches measured data. That said, it is the opinion of the REMTF that it is counterproductive to attempt to reduce the model validation criteria to a rigid mathematical definition. Model validation for power systems is as much an art as a science, and engineering judgment plays a significant role in the process. As such, this document does not prescribe any tests of goodness of fit which neatly separate "good" model parameter sets from "bad."

### 3.6.3 Importance of Power Flow Representation

The importance of a plant's power flow representation was discussed in Section 1. To elaborate on the subject, the figures below illustrate that a plant's response is based on both its power flow representation and its dynamic model. Figure 8 shows the case in which the dynamic model parameters and power flow representation match the master data precisely. Figure 9 shows the case in which the dynamic model parameters match exactly, but the impedance of the collector system equivalent is incorrect. This type of result could lead one to believe that the dynamic model parameters are incorrect, when in reality it is the power flow representation that is deficient.

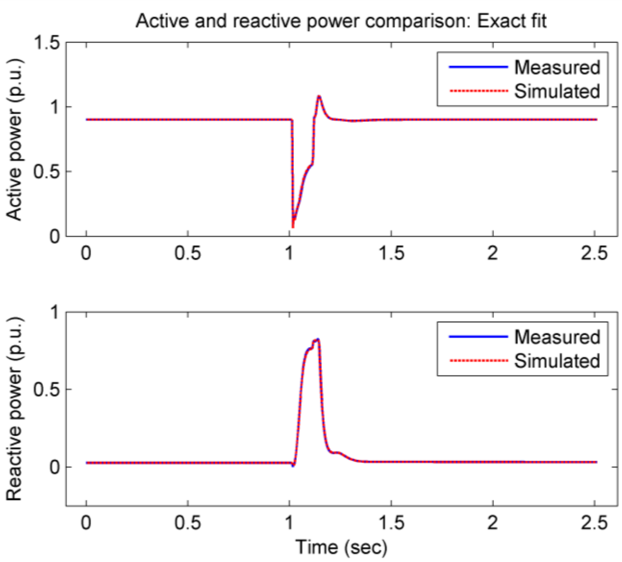


**Figure 8. Exact fit output comparison.**

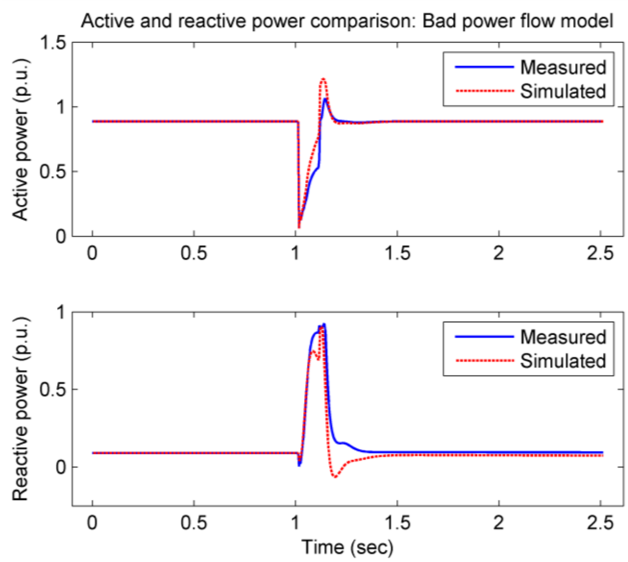


**Figure 9. Bad power flow model output comparison.**

### 3.6.4 Model Performance for Various Disturbances

A satisfactory PV plant model produces simulated output that matches measured data for an array of different disturbances and power output levels, not just a select data set used to train the model. A good practice is to reserve certain data sets and use them for model evaluation only, meaning they are not used to tune the model parameters. When performing model validation using multiple data sets, one must confirm that the plant's mode of operation and control settings are consistent across the different cases.

# 4. FINAL WORDS

This guideline is intended to clarify the goals and requirements of the model validation process rather than to serve as a rigid procedure. There are many different ways to arrive at a satisfactory model parameterization for a central station PV plant; however, all successful approaches have certain characteristics in common. Modeling a central station PV plant begins with establishing an accurate power flow representation of the plant. Without one, it is very difficult to accurately assess the performance of the dynamic model. Next, the plant's mode of operation is defined and the corresponding dynamic model invocation is specified. The generic models developed by the REMTF possess tremendous flexibility, and the control structure must be configured in a way that is consistent across the various modules. Because the dynamic model for a PV plant contains between 45-75 parameters, it is critical to minimize the set of tunable parameters by holding fixed as many of them as possible. Then, and only then is it appropriate to adjust the parameters of the dynamic model to bring the modeled and measured output into agreement. Irrespective of the method used to estimate the unknown parameters, sound engineering judgment is required to discern a satisfactory dynamic model representation.

# Appendix

## Short-Circuit Ratio Fundamentals

The ac system strength at a central station PV plant's point of interconnection (POI) has a significant impact on the interaction between the plant and the grid. For inverter-coupled renewable generation plants, the most common measure of ac system strength is the Short-Circuit Ratio (SCR). One component of this measure is the three-phase apparent power delivered to a short circuit at the POI[1]. This quantity is given by,

$$SC_{sys}(MVA) \stackrel{\text{def}}{=} ac\ system\ short\ circuit\ MVA$$

$$V_{ac} \stackrel{\text{def}}{=} ac\ voltage\ at\ plant\ rated\ power$$

$$Z_{th} \stackrel{\text{def}}{=} ac\ system\ Thevenin\ equiv.impedance$$

$$SC_{sys}(MVA) = \frac{V_{ac}^2}{Z_{th}} \qquad \textbf{(Eq. 1)}$$

The short-circuit MVA is an indicator of the Thevenin equivalent impedance looking into the grid at the POI[2]. The short-circuit ratio is calculated by dividing the short-circuit MVA, defined in (Eq. 1), by the plant's rated (maximum) real power output. Voltages on systems with a low SCR are more sensitive to fluctuations in reactive power than those with a high SCR. Plants with a low SCR (<3) tend to experience voltage stability problems, including, but not limited to: high dynamic overvoltages, harmonic resonance, and voltage flicker. Reactive compensation in the form of synchronous condensers or static VAR compensators (SVC) can help alleviate some of these problems.

$$P_{rated}\ (MW) \stackrel{\text{def}}{=} plant\ max\ rated\ MW\ output$$

$$SCR = \frac{SC_{sys}(MVA)}{P_{rated}\ (MW)} \qquad \textbf{(Eq. 2)}$$

The generic models developed by the WECC REMTF and discussed in this document are applicable for systems with a short circuit ratio of 3 and higher at the point of interconnection (POI). These generic models are not intended to represent plants with very low short-circuit levels. In such cases, detailed vendor-specific models may be required.

[1] North American Electric Reliability Corporation (NERC), "Interconnection Requirements for Variable Generation," *Special Assessment*, September 2012.

[2] P. Kundur, *Power System Stability and Control*, pp. 528-533, New York: McGraw-Hill, 1994.

## Dynamic Model Invocation in GE PSLF

This section describes how to properly invoke the dynamic models for a central station PV plant in GE PSLF. For a discussion of model invocation in Siemens PSS/E and PowerWorld Simulator, please refer to the WECC Solar Plant Dynamic Modeling Guidelines. In PSLF, the dynamic models are invoked and their parameters are declared in the dynamic data file (DYD). All dynamic model invocations for central station PV plants must lead with the REGC_A module. The REEC_B module comes next in the sequence, and if a plant controller is required, REPC_A is listed last.

### *Strictly Local Control – No REPC_A Module*

This subsection presents a dynamic model invocation template and example for central station PV plants with strictly local control (i.e., no plant controller). Note that the parameters listed here are purely for example, and are not intended to represent any particular plant. Any resemblance to actual generating facilities is purely coincidental.

Template:

```
regc_a [<n>] {<name> <kv>} <id> : #<rl> {mva=<value>}

reec_b [<n>] {<name> <kv>} <id> : #<rl>
```

Example:

```
regc_a 5 "PV TERM " 0.600 "1 " : #9 mva=111.0 "lvplsw" 1. "rrpwr" 10.00 /
    "brkpt" 0.90 "zerox" 0.40 "lvpl1" 1.22 "vtmax" 1.20 "lvpnt1" 0.80 /
    "lvpnt0" 0.40 "qmin" -1.30 "accel" 0.70 "tg" 0.02 "tfltr" 0.02 /
    "iqrmax" 999.00 "iqrmin" -999.00 "xe" 0.00

reec_b 5 "PV TERM " 0.600 "1 " : #9 "mvab" 0.00 "vdip" -999.00 "vup" 999.00 /
    "trv" 0.02 "dbd1" -0.02 "dbd2" 0.02 "kqv" 0.00 "iqh1" 1.05 "iql1" -1.05 /
    "vref0" 1.00 "tp" 0.02 "qmax" 0.40 "qmin" -0.40 "vmax" 1.10 "vmin" 0.90 /
    "kqp" 0.10 "kqi" 0.10 "kvp" 5.00 "kvi" 1.00 "tiq" 0.02 "dpmax" 999.00 /
    "dpmin" -999.00 "pmax" 1.00 "pmin" 0.00 "imax" 1.25 "tpord" 0.02 /
    "pfflag" 1. "vflag" 1. "qflag" 0. "pqflag" 1.
```

The model names are directly followed by the number of the terminal bus to which the plant's equivalent generator/converter is attached. Neither of the modules required for strictly local control require the specification of a "to-bus" in the model invocation. Note that the generator variables are in per unit on the generator MVA base. As such, it is recommended that the MVA base be specified in the dynamic data file (DYD) as in the example above. If the REEC_B **mvab** parameter is set less than or equal to zero, it inherits the base used by REGC_A.

The slash character at the end of a line indicates that the parameters for the model extend to the next row of text. Note that the last parameter for each dynamic model is ***not*** followed by a slash.

### *Plant-Level Control – Model Includes REPC_A Module*

This subsection presents a dynamic model invocation template and example for central station PV plants with plant-level control. The distinguishing feature of this configuration is that the overall dynamic model includes a plant controller. If REPC_A is included in the implementation, the manner in which it is invoked specifies which bus is regulated and which branch is monitored. It is crucial to consider not only how the parameters of the plant controller module are populated, but how the model itself is invoked.

In the REPC_A model invocation, the user specifies the terminal bus to which the equivalent generator/converter is connected as the "from-bus." The from-bus number is listed directly after the name of the model. If a "to-bus" is specified, it follows the from-bus and the to-bus is regulated.

In addition to declaring which bus is regulated, the user has the option of specifying a monitored branch by listing the buses at its endpoints (**mon_i** and **mon_j**) and a circuit number. For central station PV plants, this branch is typically selected such that it reflects the total output of the plant, as measured on either side of the collector system equivalent. The Ibranch, Pbranch, and Qbranch inputs to REPC_A seen in Figure 12 are determined from the flows on this branch. If either **mon_i** or **mon_j** are absent from the model invocation, then Ibranch, Pbranch, and Qbranch are set to zero. Hence, in order to model real and/or reactive power control at the plant-level, a monitored branch must be specified. Notice that for plant-level voltage control, line drop compensation is performed using the current magnitude on this branch and the user-specified compensation resistance and reactance.

<u>Template:</u>

```
regc_a [<n>] {<name> <kv>} <id> : #<rl> {mva=<value>}

reec_b [<n>] {<name> <kv>} <id> : #<rl>

repc_a [<n>] {<name> <kv>} <id> [<nr>] {<namer> <kvr>} ! !
       [<mon_i>] {<namei> <kvi>}[<mon_j>] {<namej> <kvj> <ck> : #<rl>
```

<u>Plant Controller Invocation Variations:</u>

```
Regulate the terminal bus (bus 5):
repc_a 5 "PV TERM " 0.600 "1 " : #9 / etc.

Regulate the to-bus (bus 2):
repc_a 5 "PV TERM " 0.600 "1 " 2 "PV HIGH " 230.00 : #9 / etc.

Regulate the point defined by |Vmon_i - (rc + jxc)*Ibranch|:
repc_a 5 "PV TERM ″ 0.600 "1 " !  !  !  !  ! 5 "PV TERM " 0.600 4 "PV LOW2 "
      34.5 "1 " : #9 / etc.
```

In the first variant listed above, the terminal bus is regulated. In the second, the user-specified to-bus is regulated, which in this case represents the high-voltage side of the station transformer. Finally, in the third variant the generator step-up transformer is specified as the monitored branch. If plant-level voltage control with line drop compensation were employed with this invocation, a point partway into the generator step-up transformer would be regulated. Alternatively, the last variant could also be used in conjunction with plant-level reactive power control.

Example:

```
regc_a 5 "PV TERM " 0.600 "1 " : #9 mva=111. "lvplsw" 1. "rrpwr" 10.00 /
    "brkpt" 0.90 "zerox" 0.40 "lvpl1" 1.22 "vtmax" 1.20 "lvpnt1" 0.80 /
    "lvpnt0" 0.40 "qmin" -1.30 "accel" 0.70 "tg" 0.02 "tfltr" 0.02 /
    "iqrmax" 999.00 "iqrmin" -999.00 "xe" 0.00

reec_b 5 "PV TERM " 0.600 "1 " : #9 "mvab" 0.00 "vdip" -999.00 "vup" 999.00 /
    "trv" 0.02 "dbd1" -0.02 "dbd2" 0.02 "kqv" 0.00 "iqh1" 1.05 "iql1" -1.05 /
    "vref0" 0.00 "tp" 0.02 "qmax" 0.40 "qmin" -0.40 "vmax" 1.10 "vmin" 0.90 /
    "kqp" 0.00 "kqi" 0.10 "kvp" 0.00 "kvi" 40.00 "tiq" 0.02 "dpmax" 999.00 /
    "dpmin" -999.00 "pmax" 1.00 "pmin" 0.00 "imax" 1.25 "tpord" 0.02 /
    "pfflag" 0. "vflag" 1. "qflag" 1. "pqflag" 0.

repc_a 5 "PV TERM " 0.600 "1 " 2 "PV HIGH " 230.00 : #9 "mvab" 0.00 /
    "tfltr" 0.02 "kp" 18.00 "ki" 5.00 "tft" 0.00 "tfv" 0.10 "refflag" 1. /
    "vfrz" -999.00 "rc" 0.00 "xc" 0.00 "kc" 0.02 "vcmpflag" 1. "emax" 0.10 /
    "emin" -0.10 "dbd" 0.00 "qmax" 0.40 "qmin" -0.40 "kpg" 0.10 "kig" 0.05 /
    "tp" 0.02 "fdbd1" 0.00 "fdbd2" 0.00 "femax" 999.00 "femin" -999.00 /
    "pmax" 999.00 "pmin" -999.00 "tlag" 0.10 "ddn" 0.0 "dup" 0.0 "frqflag" 0.
```

The model names are directly followed by the number of the terminal bus to which the plant’s equivalent generator/converter is connected (Bus 5). Neither REPC_A nor REEC_B require the specification of a “to-bus” in the model invocation. Note that the generator variables are in per unit on the generator MVA base. As such, it is recommended that the MVA base be specified in the dynamic data file (DYD) as in the example above. If the **mvab** parameter for REEC_B or REPC_A is set less than or equal to zero, the module will inherit the MVA base from REGC_A.

The model invocation example listed here uses the plant controller variation in which the to-bus is regulated and no monitored branch is specified. As such the Ibranch, Pbranch, and Qbranch REPC_A inputs in Figure 12 would be set to zero. Using this invocation, the voltage at Bus 2 would be regulated; however, it would not be possible to model line drop compensation or voltage droop. In order to capture these features, it is necessary to specify a monitored branch in the model invocation.

## REGC_A Block Diagram and Model Parameters

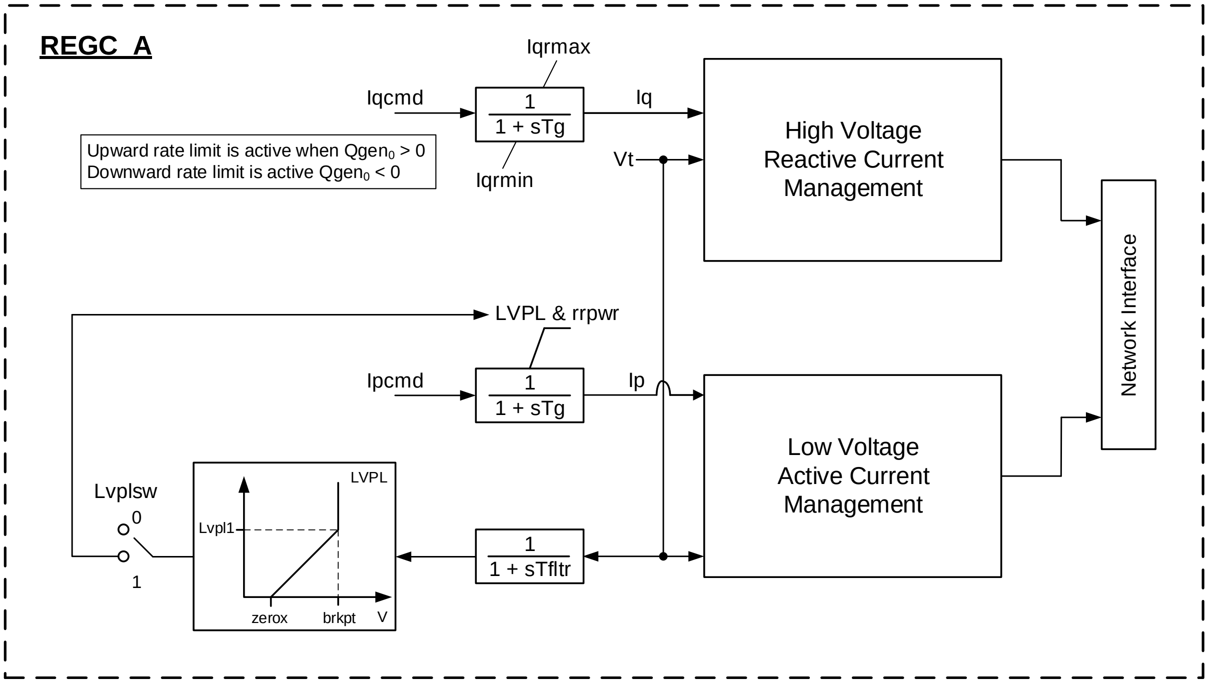


**Figure 10. REGC_A block diagram.**

Please refer to the WECC Second Generation Wind Turbine Model Specification for a description of the algorithms employed in the "high-voltage reactive current management" and "low-voltage active current management" blocks.

**Table 10. REGC_A input parameters.**

| REGC_A Input Parameters | | |
|---|---|---|
| **Name** | **Description** | **Typical Values** |
| lvplsw | Enable (=1) or disable (=0) Low Voltage Power Logic, LVPL | - |
| rrpwr | Active current up-ramp rate limit on voltage recovery, p.u./sec. | 10.00 |
| brkpt | LVPL breakpoint, p.u. | 0.90 |
| zerox | LVPL zero crossing, p.u. | 0.40 |
| lvpl1 | LVPL gain breakpoint, p.u. | 1.22 |
| vtmax | Voltage limit in the high voltage reactive current, p.u. | 1.20 |
| lvpnt1 | High voltage point for low voltage active current management, p.u. | 0.80 |
| lvpnt0 | Low voltage point for low voltage active current management, p.u. | 0.40 |
| qmin | Limit in the high voltage reactive current management, p.u. | -1.30 |
| accel | High voltage reactive current management acceleration factor, p.u. | 0.70 |
| tg | Inverter current regulator lag time constant, sec. | 0.02 |
| tfltr | Terminal voltage filter (for LVPL) time constant, sec. | 0.02 |
| iqrmax | Maximum rate-of-change of reactive current, p.u./sec. | 999.00 |
| iqrmin | Minimum rate-of-change of reactive current, p.u./sec. | -999.00 |
| xe | Generator effective reactance, p.u. | 0.00 |

## REEC_B Block Diagram and Model Parameters

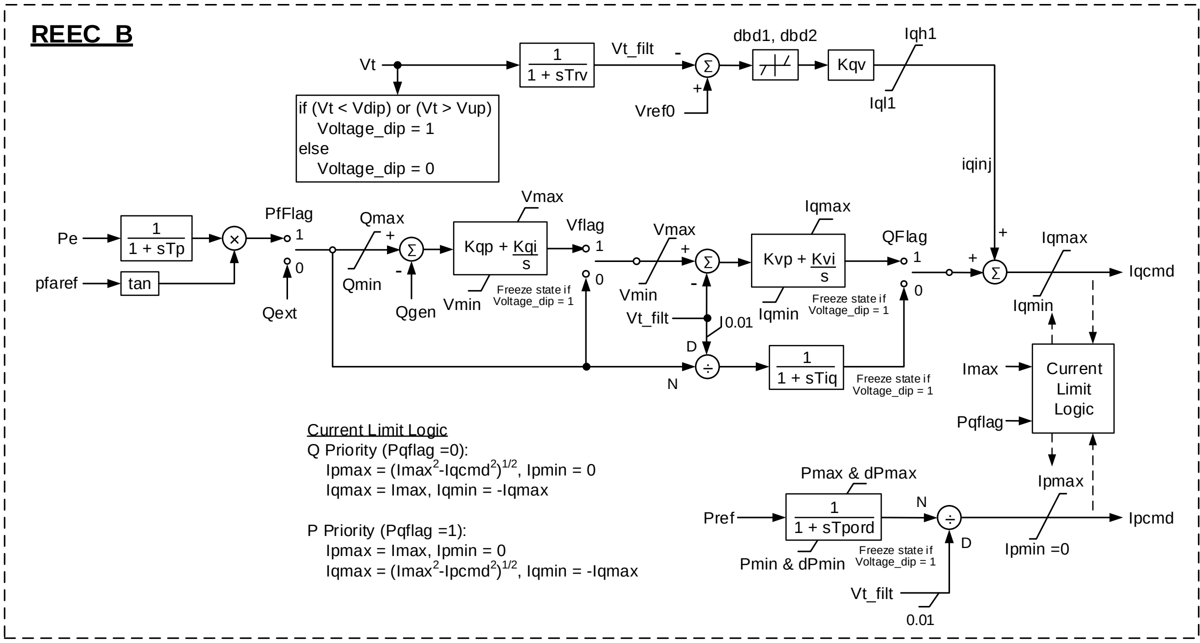


**Figure 11. REEC_B block diagram.**

**Table 11. REEC_B input parameters.**

| REEC_B Input Parameters | | |
|---|---|---|
| **Name** | **Description** | **Typical Values** |
| mvab | If mvab is less than or equal to zero, then the base used by regc_a is also used in reec_b | 0.0 |
| vdip | Low voltage condition trigger voltage, p.u. | [0.00, 0.90] |
| vup | High voltage condition trigger voltage, p.u. | [1.10, 1.30] |
| trv | Terminal bus voltage filter time constant, sec. | [0.02, 0.05] |
| dbd1 | Overvoltage deadband for reactive current injection, p.u. | [-0.10, 0.00] |
| dbd2 | Undervoltage deadband for reactive current injection, p.u. | [0.00, 0.10] |
| kqv | Reactive current injection gain, p.u. | - |
| iqh1 | Maximum reactive current injection, p.u. | [0.00, 1.10] |
| iql1 | Minimum reactive current injection, p.u. | [-1.10, 0.00] |
| vref0 | Reference voltage for reactive current injection, p.u. | [0.95, 1.05] |
| tp | Active power filter time constant, sec. | [0.02, 0.05] |
| qmax | Maximum reactive power when vflag = 1, p.u. | [0.00, 0.43] |
| qmin | Minimum reactive power when vflag = 1, p.u. | [-0.43, 0.00] |
| vmax | Maximum voltage at inverter terminal bus, p.u. | [1.05, 1.15] |
| vmin | Minimum voltage at inverter terminal bus, p.u. | [0.85, 0.95] |
| kqp | Local Q regulator proportional gain, p.u. | - |
| kqi | Local Q regulator integral gain, p.u. | - |
| kvp | Local voltage regulator proportional gain, p.u. | - |

| | | |
|---|---|---|
| kvi | Local voltage regulator integral gain, p.u. | - |
| tiq | Reactive current regulator lag time constant, sec. | [0.02, 0.05] |
| dpmax | Active power up-ramp limit, p.u./sec. | 999.00 |
| dpmin | Active power down-ramp limit, p.u./sec. | -999.00 |
| pmax | Maximum active power, p.u. | 1.00 |
| pmin | Minimum active power, p.u. | 0.00 |
| imax | Maximum apparent current, p.u. | [1.00, 1.70] |
| tpord | Inverter power order lag time constant (s) | [0.02, 0.05] |
| pfflag | Constant Q (=0) or local power factor (=1) 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) | - |

## REPC_A Block Diagram and Model Parameters

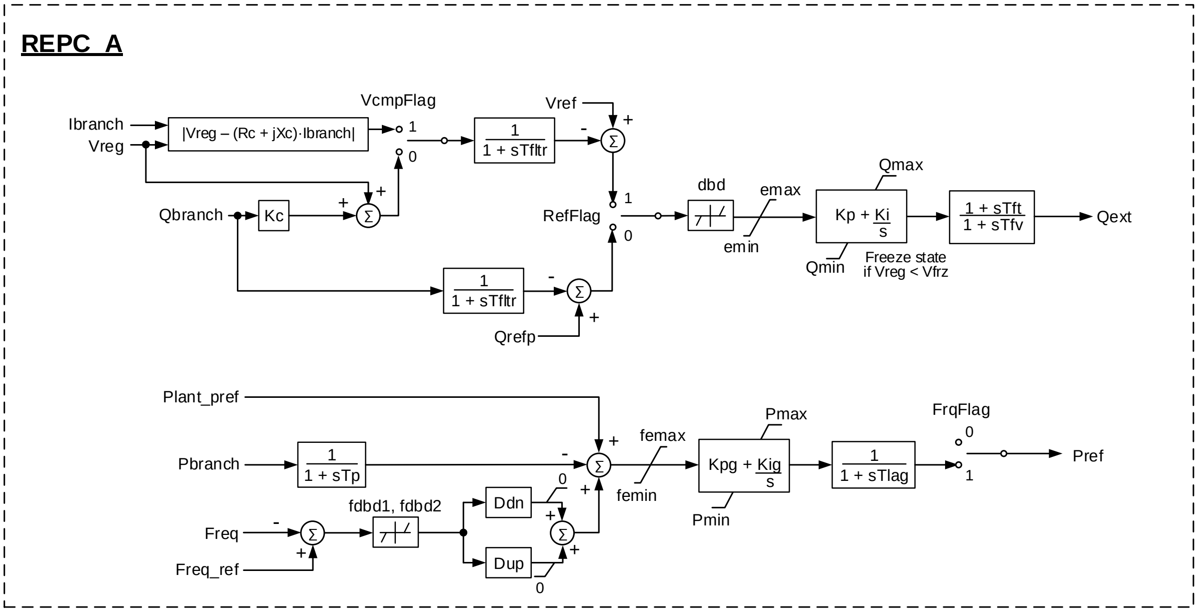


**Figure 12. REPC_A block diagram.**

**Table 12. REPC_A input parameters.**

| REPC_A Input Parameters | | |
|---|---|---|
| **Name** | **Description** | **Typical Values** |
| mvab | MVA base. If mvab is less than or equal to zero, then the base used by regc_a is also used in repc_a, MVA | 0.0 |
| tfltr | Voltage and reactive power filter time constant, sec. | [0.02, 0.05] |
| kp | Volt/VAR regulator proportional gain, p.u. | - |
| ki | Volt/VAR regulator integral gain, p.u. | - |
| tft | Plant controller Q output lead time constant, sec. | 0.00 |
| tfv | Plant controller Q output lag time constant, sec. | [0.02, 0.15] |
| refflag | Plant level reactive power (=0) or voltage control (=1) | - |
| vfrz | Voltage for freezing Volt/VAR regulator integrator, p.u. | [0.00, 0.90] |
| rc | Line drop compensation resistance, p.u. | ≥ 0.0 |
| xc | Line drop compensation reactance, p.u. | ≥ 0.0 |
| kc | Reactive droop gain, p.u. | - |
| vcmpflag | Reactive droop (=0) or line drop compensation (=1) | - |
| emax | Maximum Volt/VAR error, p.u. | -999.00 |
| emin | Minimum Volt/VAR error, p.u. | 999.00 |
| dbd | Reactive power deadband when refflag = 0, p.u.<br>Voltage deadband when refflag = 1, p.u. | [0.00, 0.10] |
| qmax | Maximum plant reactive power command, p.u. | [0.00, 0.43] |
| qmin | Minimum plant reactive power command, p.u. | [-0.43, 0.00] |
| kpg | Real power control proportional gain, p.u. | - |
| kig | Real power control integral gain, p.u. | - |
| tp | Active power filter time constant, sec. | [0.02, 0.05] |
| fdbd1 | Frequency deadband downside, p.u. | [-0.01, 0.00] |
| fdbd2 | Frequency deadband upside, p.u. | [0.00, 0.01] |
| femax | Maximum power error in droop regulator, p.u. | -999.00 |
| femin | Minimum power error in droop regulator, p.u. | 999.00 |
| pmax | Maximum plant active power command, p.u. | 1.00 |
| pmin | Minimum plant active power command, p.u. | 0.00 |
| tlag | Plant controller P output lag time constant, sec. | [0.02, 0.15] |
| ddn | Down regulation droop, p.u. | [0.00, 33.33] |
| dup | Up regulation droop, p.u. | 0.00 |
| frqflag | Governor response disable (=0) or enable (=1) | - |
| outflag | Flag for output selection, reactive power (=0) or voltage (=1) | - |