Generic Photovoltaic System Models for WECC – A Status Report

WECC Renewable Energy Modeling Task Force

***Abstract* – This paper describes generic models of photovoltaic (PV) systems developed for implementation in Western Electric Coordinating Council (WECC) base cases. The scope encompasses both transmission-connected, central station PV plants and distributed PV systems. These models were added to the WECC Approved Dynamic Model Library in March of 2014.**

***Index Terms* – Distributed generation, dynamic models, photovoltaic generation (PV), wind turbine generator (WTG).**

I. INTRODUCTION

Over the course of several years, the Renewable Energy Modeling Task Force† (REMTF) within the Western Electric Coordinating Council (WECC) has developed a suite of dynamic models for renewable energy plants using a modular approach [1]. At a high-level, the manner 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 two or three modules depending on whether the plant-level control is implemented [2]. For distribution-connected PV systems, a simpler modeling paradigm is employed featuring a single dynamic model.

The development of these dynamic models was necessitated by growth in both the scale and number of installed and projected PV systems. According to the Solar Energy Industry Association (SEIA), there are presently 1.8 GW of solar generation installed in the Western Interconnection and another 2.7 GW under construction [3]. Without taking proposed projects into account, the 4.5 GW of aggregate nameplate capacity already installed or under construction corresponds to roughly three percent of the non-coincident peak load in the Western Interconnection [4].

Significant reductions in the cost of manufacturing photovoltaic solar cells combined with ambitious Renewable Portfolio Standards (RPS) contribute to a favorable outlook for the growth of PV generation [5], [6]. The mission of the Department of Energy's SunShot Initiative is to reduce the total cost of PV systems to one dollar per Watt by 2020 [5]. Progress toward this goal is making PV generation an increasingly attractive investment for states looking to meet RPS requirements. California has committed to serving 33 percent of its retail electricity demand with renewable resources by 2020 [6]. Not coincidentally, the amount of proposed solar generation currently under development in California exceeds 12 GW [3].

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The generation mix in the Western Interconnection is clearly undergoing rapid transformation. In light of this, the accuracy of system-wide power flow and dynamics cases depends upon accurate representation of variable generation. Since this modeling effort began, the REMTF has released several guidelines on the topic of representing PV systems in power flow and dynamic data sets. In [7], the task force presents a set of best practices for representing PV systems in large-scale power flow cases. The advocated approach involves using a single equivalent generator to represent the typical or "average" inverter within a plant. A detailed specification covering the dynamic models for both central station PV plants and distribution-connected systems is provided in [2]. A general introduction to the dynamic models for PV systems and their applications is presented in [8].

This paper is organized as follows. Section II provides a discussion of the modules used to represent central station PV plants. The dynamic model developed for distribution-connected PV systems is discussed in Section III. The model testing and validation efforts being conducted are highlighted in Section IV. Conclusions are provided in Section V.

II. CENTRAL STATION PV PLANT MODELS

The initial development of this modular approach was done by the task force in the development of the generic wind turbine models [1]. Since type 4 wind turbine generators (WTGs) and PV systems are both inverter-coupled energy sources, it became apparent to the task force that the modules used for type 4 WTGs can also be used for modeling PV. Thus, the model structure of a central station PV plant is presented in Figure 1. The names of the modules are: Renewable Energy Generator/Converter (regc_a), Renewable Energy Electrical Control (reec_b), and Renewable Energy Plant-Level Control (repc_a). The two modules regc_a and repc_a are identical to those used in [1] for WTG modeling. The reec_b is based on the reec_a module developed in [1] for WTGs, but further simplified to remove components that are more WTG specific.

The role of the plant controller is to produce real and reactive power references for the electrical control using values from the network solution. The electrical control then translates the real and reactive power references into current commands for the converter. Finally, the generator/converter model re-conciles the current commands with boundary conditions imposed by the network solution to yield current injections.

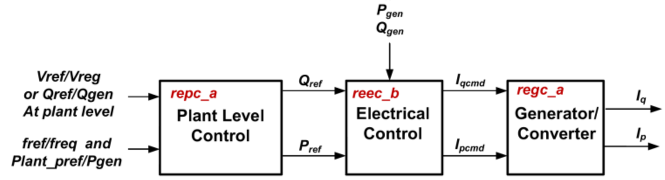

Figure 1. Central station PV plant model interconnection diagram.

Additional modules may be employed if voltage or frequency ride-through capabilities are represented. Standard modules for emulating voltage and frequency ride-through already exist in the major commercial software platforms.

Central station PV system models with plant-level control can be configured in over 50 unique modes of operation. Available control objectives include regulating voltage at the point of interconnection (POI) and maintaining a constant power factor. Some of the flexibility in the model is conferred by the modular design approach. The choice to break the overall model into its constituent parts was made early on to enable interoperability with dynamic models for other types of converter-coupled generation, such as WTGs, and in anticipation of future changes (e.g., modeling energy storage, adding other modules for additional functionality, etc.). Constructing the overall model from a collection of building blocks also facilitates the process of integrating new feature sets into the components as variable generation technology evolves.

A. Renewable energy generator/converter module

The generator/converter module depicted in Figure 2 represents an inverter with a high-bandwidth current regulator. As displayed in Figure 1, the converter model injects real and reactive current into the external network in response to current commands generated by the electrical control. The algorithms within the generator/converter module are an emulation of fast controls. The control capabilities of this module include:

- User-settable reactive current management during high voltage events at the generator (inverter) terminal bus
- Active current management during low voltage events to emulate the response of the inverter phased-lock loop (PLL) 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 "low voltage power logic" (LVPL) enables the user to specify a voltage-dependent active current limit characteristic. The relationship between the active current limit and terminal voltage is piecewise linear, and its form is specified in Figure 2. Note that this capability is optional and can be connected or disconnected through the model parameters. Additionally, there is a user-settable limit on the ramp-rate of the active current which is independent of the limit imposed by the low voltage power logic.

The "high voltage reactive power logic" limits the reactive current injection of the inverter such that the terminal voltage of the machine does not exceed a given limit. The ability to meet this objective is constrained by the current rating of the converter. The "low voltage active power logic" is designed to capture the effect of terminal bus voltage variation on active power output. These two blocks are implemented through an iterative numerical procedure. Their primary function is to alleviate numerical issues that arise from modeling a high-bandwidth hardware component with a simple model.

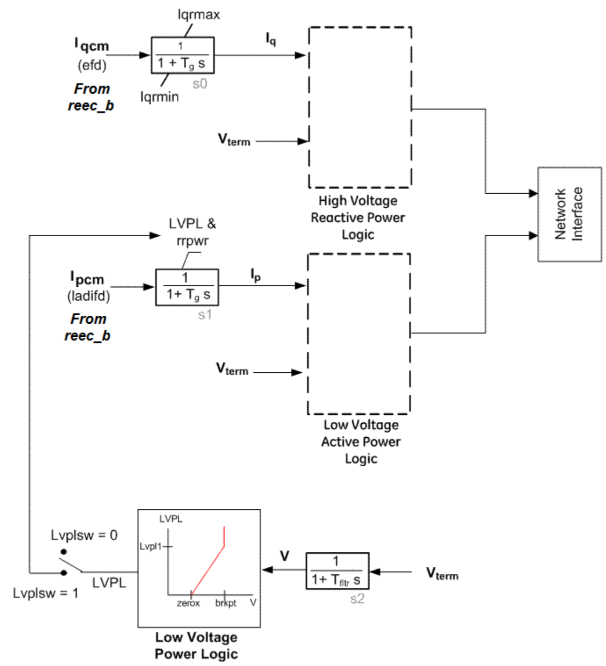

Figure 2. Renewable energy generator/converter module.

B. Renewable energy electrical control module

The renewable energy electrical control module is presented in Figure 3. This module is responsible for translating real and reactive power references, typically produced by the plant controller, into inverter current commands. Depending on the mode of operation of the plant controller, the reactive power reference *Qref* may correspond to either reactive power or voltage. If the model of a plant does not require a plant-level control module, then the real and reactive power references are held fixed according to the values in the initial power flow solution.

The structure of the electrical control module can be broken down into two parts corresponding to the active and reactive current control loops. The active current control scheme is straightforward. The real power reference is passed through a first-order low-pass filter and divided by the terminal voltage to yield the active current command. The active power reference is also subject to upper and lower bounds, and up and down ramp rates. The ramp rates and time constant are irrelevant in the case where the active power reference is fixed.

The reactive power control structure is more flexible and capable of being configured in numerous unique modes of operation. The uppermost loop depicted in Figure 3 allows for proportional control of the terminal voltage with a user-settable deadband. This loop generates one of the two components of the reactive current command. The other component comes from either a PI loop or a division of the reactive power reference by the terminal voltage. The two PI loops in the center of the Figure 3 allow for either local voltage control, or local coordinated Q/V control depending on how the flags are set. Under coordinated control, the first PI loop generates a voltage reference (and error) that the second PI loop translates into a reactive current command.

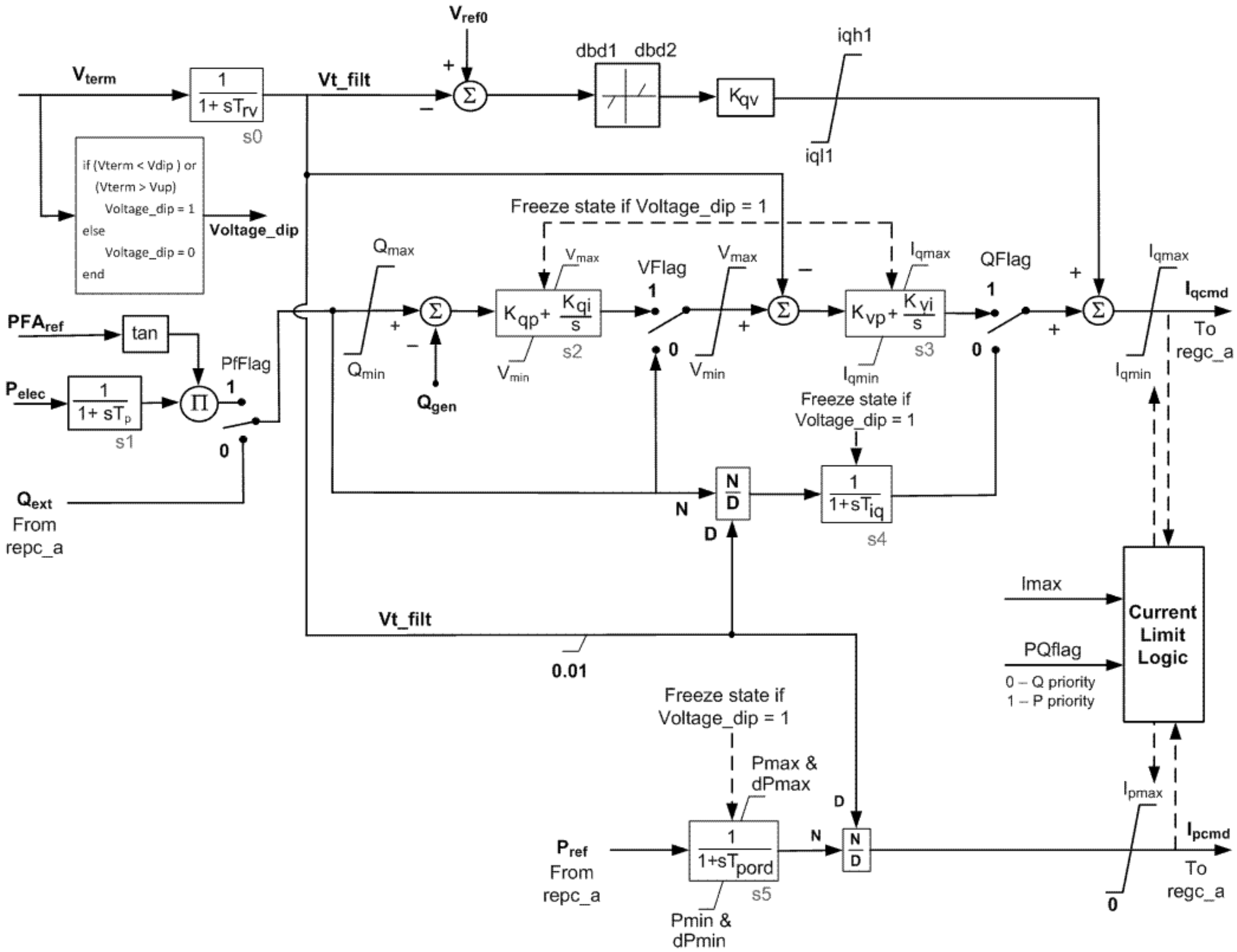

Figure 3. Renewable energy electrical control module for PV plants.

There are eight distinct reactive power control options in the electrical control model that correspond to unique flag combinations. The flags are parameters set by the user in the dynamic model invocation. Available reactive power control options include maintaining a constant power factor and regulating the voltage at a user-selected bus, such as the point of interconnection. The mode of operation of the electrical control is dependent not only on its own flags, but also on the plant controller settings. Hence, it is important to make sure the settings are compatible across the plant-level control and electrical control modules. For a complete rundown of the active and reactive power control options for central station PV plants, see [2]. Mapping the desired control options to a particular combination of flags is the first step in configuring the modules. An exhaustive test procedure was carried out for the electrical control module in which simulations were performed for every mode of operation.

The current limit logic allows for the selection of either active or reactive power priority. The first priority current command is bounded only by the current rating of the converter, specified by the *Imax* parameter. The second priority command is then bounded by the capacity that remains after the first priority command has been generated. This scheme ensures that the vector formed by the complex current resides within a semicircle with a radius of *Imax*.

C. Renewable energy plant-level control module

The renewable energy plant-level control module (repc_a) is depicted in Figure 4. This module features two independent control loops which generate real and reactive power references respectively. As mentioned in Section II.B, the reactive power reference produced by the plant controller may correspond to either reactive power or voltage. The inputs to this module are values from the network solution, such as voltages and branch power flows. For central station PV plants without a plant-level controller, this module may be omitted from the overall model structure (see Figure 1).

In the reactive power control loop, the user selects between plant-level voltage and reactive power control using the *refflg* parameter. If the module is configured in plant-level voltage control mode, the user has the choice of implementing line drop compensation or voltage droop via the *vcmpflg* parameter. The voltage compensation feature may be disabled by adjusting the model invocation in the dynamic data file such that the branch flow inputs to the plant controller are set to zero. The control error is passed through a deadband and limiter to the input of a PI controller. Finally, the reactive power reference is sent to the electrical control module through a first-order lead-lag compensator. For more information and a set of test parameters, see [1] or [8].

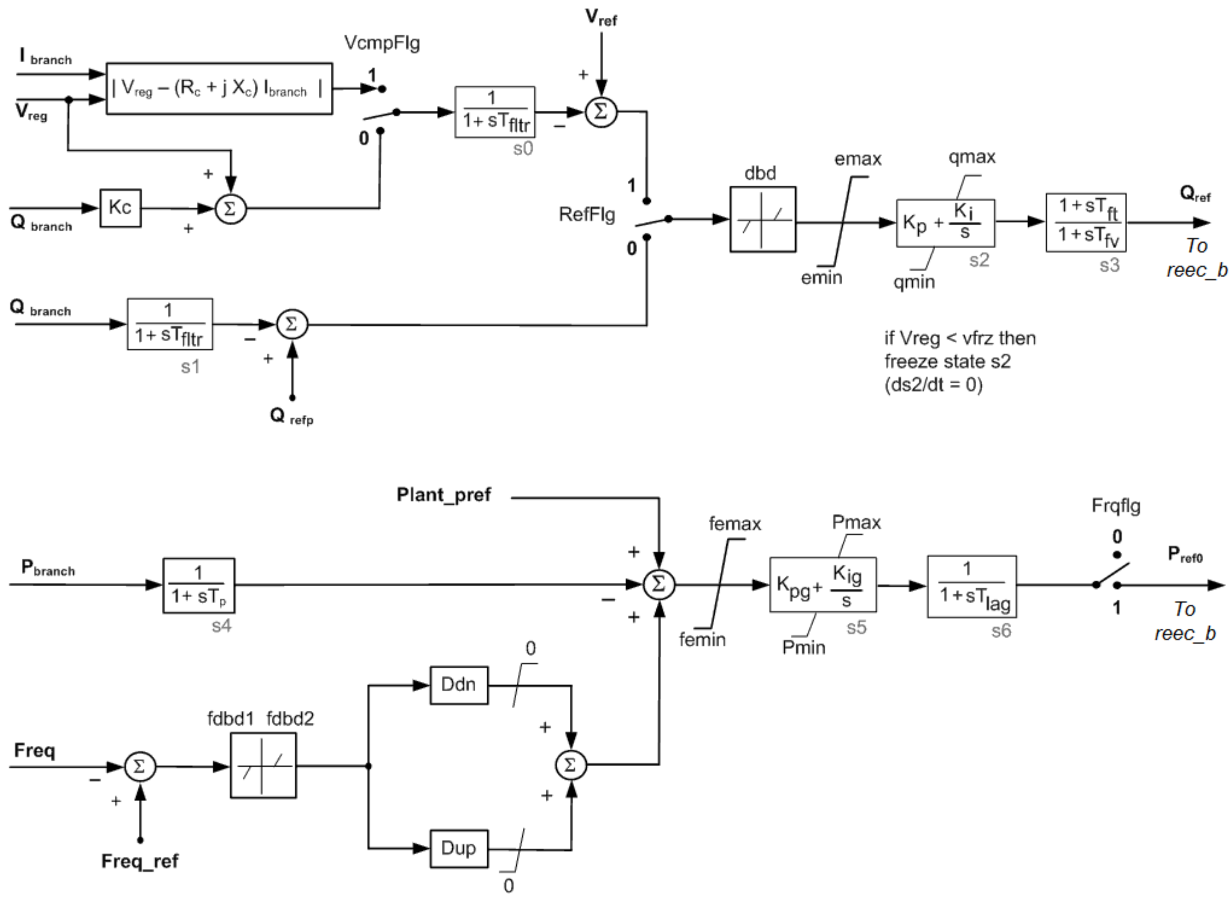

Figure 4. Renewable energy plant-level control module.

The real power control functionality within the plant controller module is experimental and primarily used for research purposes. It was introduced mainly for use with WTGs [1]. 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 at the plant level. Currently, many of the major manufacturers of WTGs do provide the ability for primary frequency regulation for WTG power plants; however, this comes at the expense of "spilling wind." Nonetheless, very few wind plants in North America, and no PV plants to our knowledge, currently have this feature installed in the field. Because this feature has not been tested extensively, it should be used with extreme caution. It may require further enhancements in the future.

The plant controller module discussed here is designed to interface with a single electrical control model, and hence one aggregated PV inverter. This approach is a result of the prevailing power flow modeling paradigm for central station PV plants. Currently, variable generation plants are represented by a single equivalent generator in WECC base cases [7]. The REMTF is presently considering the development of an augmented plant controller module with the ability to control multiple equivalent generators and/or reactive support devices behind a single point of inter-connection.

III. MODEL TESTING AND VALIDATION

The dynamic models described here have been implemented by multiple commercial software vendors including GE PSLF™, Siemens PTI PSS®E, and PowerWorld Simulator. The plot displayed in Figure 5 shows the modeled versus measured response of a 50 kW PV inverter to a 75 percent voltage dip during a controlled test performed at Sandia National Laboratories. In addition, working with a PV vendor, EPRI has performed several validation cases of a greater than 100kW PV inverter and shown very good agreement between simulations and measured response.

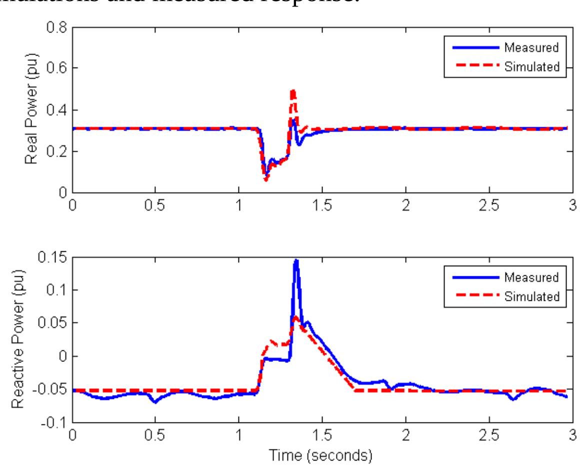

Figure 5. Model validation example for a PV inverter.

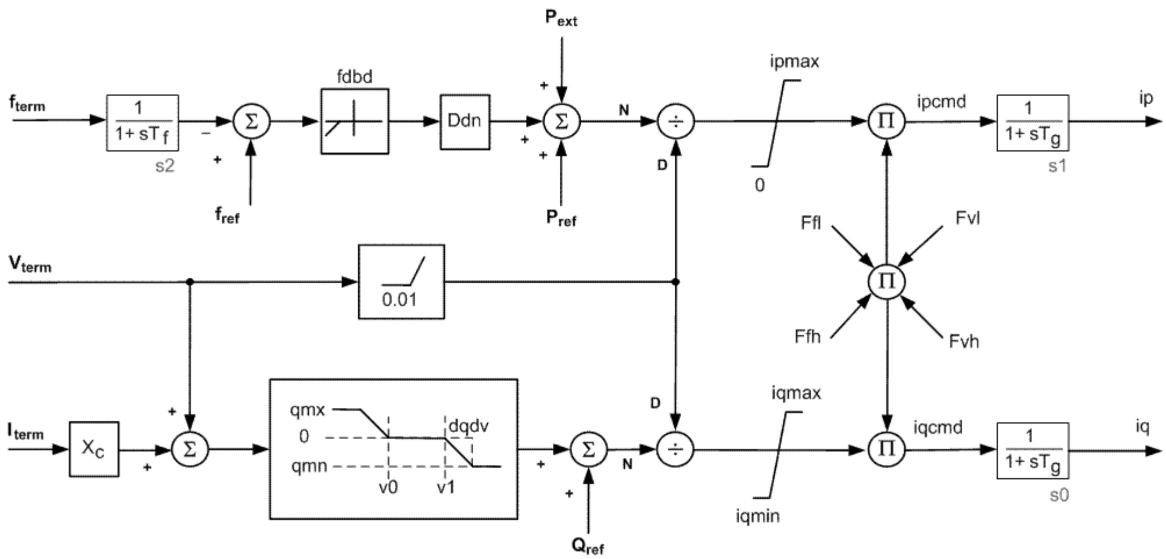

Figure 6. Distributed PV system model.

IV. DISTRIBUTED PV SYSTEM MODEL

The distributed PV system model (pvd1) is depicted in Figure 6. Sections I-III pertain to modules for central station PV plants connected at voltages of 60 kV or above. The pvd1 model is designed to represent distribution-connected systems that are smaller in scale. In contrast to the modular design approach discussed in Section II, the distributed PV system model integrates multiple subsystems into a single dynamic model. These subsystems include active power control, reactive power control, and protective functions. The REMTF and Load Modeling Task Force are currently considering integrating a distributed generation component, based on pvd1, into the WECC composite load model [9].

Reliability and interconnection requirements for distributed PV systems vary from state to state, but tend to reflect the criteria laid out in IEEE Standard 1547 [2]. Typically, PV inverters deployed in distribution systems operate in either constant power factor or constant reactive power control modes. At the time of this writing, they normally do not participate in steady state voltage regulation. There are on-going efforts by various research entities to look at the issues of voltage and frequency ride-through related to distributed PV, but such discussions are beyond the scope of this paper.

V. CONCLUSIONS

A modeling framework for representing central station and distributed PV systems in bulk system studies is presented. The main features of each model are highlighted. A brief description of some of the model testing and validation efforts being conducted follows. The models presented here were designed to be “generic,” i.e., capable of representing a wide array of equipment produced by different manufacturers. Generic models, by definition, do not require or include any proprietary information. The evidence continues to demonstrate that generic models can be successfully employed in power system studies without significant loss of fidelity. As the PV industry evolves, the generic models will be modified as needed to keep pace with technology.

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