PV SYSTEM MODELING FOR GRID PLANNING STUDIES

Ellis A.[1], Behnke, M.[2], and Barker, C.[3]
[1]Sandia National Laboratories, Albuquerque, NM, USA
[2]BEW Engineering, San Ramon, CA, USA
[3]SunPower Corporation, Richmond, CA, USA

ABSTRACT

Validated electrical performance models of power system components are required to support a range of power system planning studies, interconnection studies and plant design. This includes steady-state (power flow) models, detailed transient models for the study of electromagnetic interactions, dynamic models for the study of electromechanical phenomena, and short circuit models. Transmission and distribution simulation platforms commonly used by system planners do not presently have full-featured models for PV systems representation. Interest in positive-sequence power flow and dynamic models has increased recently due to the trend toward larger PV system plant sizes, both commissioning and interconnection applications, and interest in understanding the possible impacts of high PV penetration levels on grid performance. Compared to conventional generator models, PV system models are very much a work in progress. This paper describes advances in power flow and dynamic modeling of PV systems for grid planning studies based on on-going efforts by the Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force (REMTF). The goal of REMTF is to improve the adequacy, availability and accessibility of PV system models for grid planning and interconnection studies.

PV SYSTEM MODELS

In the past, most grid-connected PV deployment consisted of small isolated residential and commercial-scale installations on distribution systems. Concerns about safety and grid compatibility were addressed by adherence to IEEE 1547 standards and associated inverter certification. A formal evaluation involving technical studies and simulations was seldom required. Currently applicable interconnection procedures still allow for small PV systems to be installed with minimal technical evaluations when the systems are relatively small and the penetration level is relatively low. Today, many proposed PV installations are large enough to warrant a full interconnection study that involves power flow, dynamic and short-circuit simulations. A different set of standards and procedures apply, including those issued by the North American Electric Reliability Corporation (NERC) and the Federal Energy Regulatory Commission (FERC). Access to adequate PV system models for regional planning requirements and to process the growing queue of large utility scale PV interconnection applications needs to be improved.

Currently, standard library models for PV systems are not widely available. Interconnection studies are typically conducted with manufacturer-specific, user-written models that tend to be proprietary. These types of models are discouraged for the purposes of regional planning studies. Confidentiality issues complicate a study process that often involves multiple stakeholders. In addition, manufacturer-specific models are difficult to maintain, document and use, compared to standard library models. Even in the context of interconnection studies, the user-written models can become very difficult to work with in practice. In North America, there is growing interest in developing generic PV system models that will eventually be adopted as industry standards.

The Western Electricity Coordinating Council established the Renewable Energy Modeling Task Force (REMTF) to improve availability of adequate PV and wind system models for bulk system studies. The intent is to make industry standard models available for grid planning studies, similar to models available for conventional generators and other system components. This paper describes some of the progress that has been made, including recommendations for representation of PV systems and descriptions of proposed generic dynamic models. REMTF's scope includes development of technical specifications for PV system models, model validation, implementation in major simulation software packages, and model application guidelines.

POWER FLOW REPRESENTATION

PV systems should be represented in bulk system studies to the extent they can impact grid performance. Large central–station PV systems, as well as high-penetration distributed systems have the potential to affect grid performance. Transmission service providers apply guidelines and procedures established by NERC and Reliability Organizations (ROs). For example, the WECC Data Preparation Manual states that single generating units 10 MVA or higher, or aggregated capacity of 20 MVA connected to the transmission system (60kV and above) through a step-up transformer(s) should be modeled as distinct generators. It also states that collector-based system such as wind or solar plants connected to the transmission grid may be represented as a single-machine equivalent circuit consisting of an equivalent generator, low voltage to intermediate voltage transformer, equivalent collector circuit, and station transformer (Figure 1).

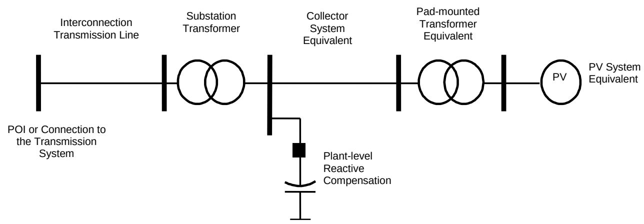

Figure 1 – PV system single-machine representation

Power flow representation of central-station and distributed PV systems at the bulk level should not add unnecessary overhead. The following sections describe recommendations for representation of central-station and distributed PV in power flow simulations.

Central-Station PV Plants

In general, central-station PV plants are built with a radial topology, with one or more feeders connected to a collector system station. Figure 2 shows a sample topology for a multi-MW PV plant.

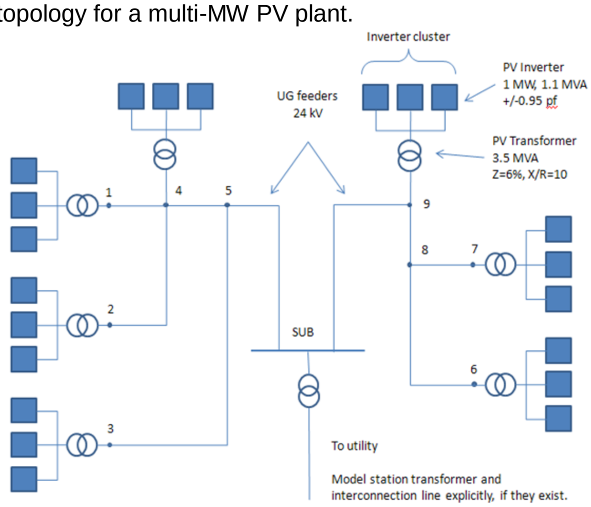

Figure 2 – Sample PV system topology

For bulk system studies, full representation of individual WTGs together with the associated detailed collector system is unnecessary and overly complicated. REMTF recommends that the single-machine equivalent model shown in Figure 1, be used. The reduction of a detailed collector system power flow model to a single-machine equivalent is referred to as "equivalencing"—see [1], [2]. Generally, the idea is to select appropriate equivalent power flow data for each of the components in the equivalent model such that the active and reactive power flow at the POI for the equivalent aggregated model is the same as for the detailed model, over the full plant operating range. In [1], a procedure is described to compute the parameters of the single-machine equivalent based on branch data. The impedance and admittance parameters of the equivalent collector system (Figure 1) can be computed as follows:

$$Z_{eq} = R_{eq} + jX_{eq} = \frac{\sum_{i=1}^{I} Z_i n_i^2}{N^2} \qquad (1)$$

$$B_{eq} = \sum_{i=1}^{I} B_i \qquad (2)$$

where I is total number of branches in the collector system, Z_i and n_i are the impedance ($R_i + jX_i$) for i-th branch, and N is the total number of inverters in the plant. The number of inverters is used as a weighting factor (in place of current). The equivalent collector system parameters capture total plant real and reactive losses and reproduce the terminal voltage at the "average inverter" in the plant. This calculation can be easily implemented in a spreadsheet. For the example in Figure 2, the computations are shown in Table 1.

From	To	R	X	B	n	R n^2	X n^2
1	4	0.03682	0.00701	0.000000691	3	0.33136	0.06307
2	4	0.02455	0.00467	0.000001036	3	0.22091	0.04205
4	5	0.02455	0.00467	0.000001036	9	1.98816	0.37843
3	5	0.02557	0.02116	0.000000235	3	0.23016	0.19042
5	**SUB**	**0.02557**	**0.02116**	**0.000000235**	**12**	**3.68251**	**3.04673**
6	8	0.03747	0.00868	0.000000561	3	0.33726	0.07809
7	8	0.02455	0.00467	0.000001036	3	0.22091	0.04205
8	9	0.02109	0.02501	0.000000199	6	0.75925	0.90025
9	**SUB**	**0.02109**	**0.02501**	**0.000000199**	**9**	**1.70831**	**2.02555**

Table 1 – Computation of equivalent collector system line parameters for the sample system in Figure 2.

The last two columns are added together to obtain the partial sum in the numerator of (1), which is then divided by N^2 ($21^2 = 121$ in this example) to compute R_{eq} and X_{eq}. For this example, the result is $R_i + jX_i = 0.0245 + j\,0.015$, in the same units as the branch data. According to (2), the values in the susceptance column of Table 1 are simply added together. For feasibility studies, reasonable estimated values could be used. The authors reviewed PV system designs for different plants and determined that a good estimate can be obtained based plant size, as shown in Figure 3 below.

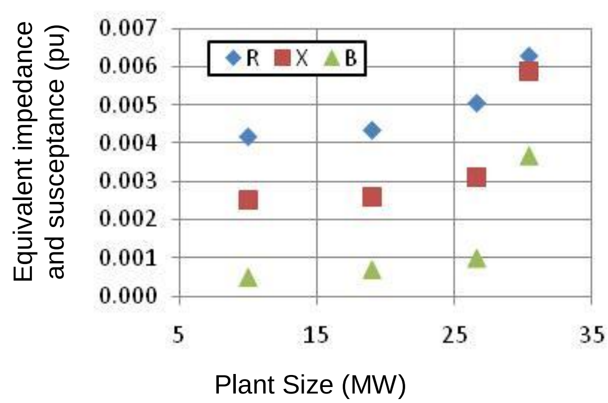

Figure 3 – Sample equivalent collector system data (R, X, B) in per unit on 100 MVA, 34.5kV base, as a function of plant size

A large PV plant has several pad-mounted transformers, each connected to one or more PV inverters. Assuming that all step-up transformers are identical, and each connects to the same number of inverters, the per-unit equivalent impedance (Z_{Teq}) and the equivalent MVA rating (MVA_{Teq}) can be computed as follows:

$$
\begin{aligned}
Z_{Teq} &= Z_T \\
MVA_{Teq} &= N \times MVA_T
\end{aligned}
\qquad (3)
$$

In these equations, Z_T is the impedance of one transformer on its own MVA base (MVA_T). For the example system discussed above, the equivalent transformer impedance would be 6% on a 21 MVA base (7 X 3 MVA), with an X/R ratio of 10. Step-up transformers for utility-scale PV plants are in the range of 500 kVA to 2 MVA, and have impedance of approximately 6% on the transformer MVA base. The X/R ratio is approximately 8.

The equivalent PV generator in Figure 1 would be represented as an ordinary generator in power flow, with specified active power level and reactive power capability. The active power level assumptions depend on the purpose of the study. In an interconnection study, a PV plant would be modeled at full active power output. For other studies, PV plants may be modeled at partial active power output or zero output, depending on the study scenario. For instance, WECC off-peak cases correspond to night-time periods, when PV output is zero. Heavy summer scenarios typically correspond to mid afternoon peak load periods, when PV can be assumed to be at or near rated output. For regional transmission planning studies, it is recommended that the power level be established based on the average expected output level during the time frame of interest. Representation of reactive power capability also requires care. Reactive power range at the assumed active power level (Q_{min} and Q_{max}) and control capability, should be represented in power flow. Interconnection requirements addressing reactive power capability are still evolving. However, utility-scale PV systems are normally deployed with inverter-based reactive power capability. Considering that inverters are current-limited and four-quadrant devices, actual reactive power capability is a function of active power level. It should be noted that inverter current and terminal voltage design limits may reduce the available reactive capability. When terminal voltage has reached maximum design voltage (typically 110% of nominal), the inverter may not be able to inject rated reactive power into the grid. Technically, PV inverters could be designed to provide reactive support even at zero power output (e.g., at night); however, this feature is not normally deployed. Possible control options to be represented in power flow model are voltage control (closed loop or droop) and power factor or reactive power control.

As an example, let us assume that the equivalent generator for the sample system shown in Figure 2 operates at rated power (21 x 1 MW = 21 MW). The nameplate reactive range is +/-0.95 power factor. If plant participates in voltage control, then Q_{min} and Q_{max} should be set to -6.9 MVAr and +6.9 MVAr, respectively. If the plant actually operates at a fixed power factor, then the equivalent generator should have $Q_{min} = Q_{max}$ according to the power level.

Distribution-Connected PV Plants

Distribution networks are not typically represented in bulk system models. Load (and embedded distributed generation) is usually lumped at the transmission or sub-transmission load buses. There is increasing industry consensus that distributed generation should be represented more explicitly in scenarios where the penetration level is sufficiently high to affect bulk system performance. Some ROs guidelines address this issue. For example, the WECC Data Preparation Manual states that, when the aggregated generation capacity exceeds 10 MVA at any load bus, that generation should be represented explicitly as a generator in power flow. Further, the WECC Data Preparation Manual states that embedded generation should not be load-netted if it exceeds five percent of the area total generation.

REMTF recommends that power flow models be extended as shown in Figure 5 to represent distribution-connected PV in high penetration scenarios. The model has an equivalent LTC transformer and equivalent series impedance representing the impedance of the feeder, service transformer, and secondary network.

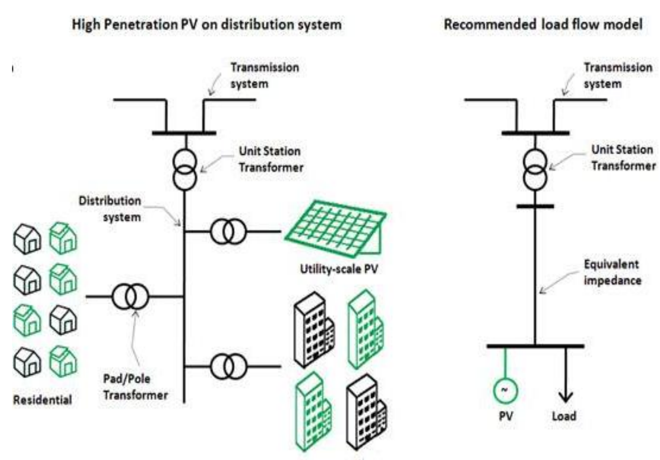

Figure 5 – Power flow representation of distributed PV systems at the bulk system level

Note that the load was moved to the low voltage bus as well. Representation of series impedance and voltage dependency for loads has been shown to be of critical importance [5]. Typical load flow data for the equivalent distribution feeder is shown in Table 2. Transformer impedances are on the transformer self-cooled MVA base and the feeder impedance is on 100 MVA, 12.5 kV base.

Table 2 - Suggested data for distribution system equivalent (station transformer and feeder impedance)

	R, pu	X, pu
Substation transformer impedance, pu on transformer self-cooled MVA base	0	0.1
Equivalent feeder, service transformer and secondary impedance, pu on 100 MVA, 12.5 kV base	0.1	0.1

DYNAMIC MODELS

Transient stability simulations require accurate positive-sequence dynamic models to represent the phasor domain response of the power system to major disturbances such as transmission system short circuits or sudden loss of generation or load. From a transmission service provider's perspective, desirable features for dynamics models include:

- **Non-propriety:** Models should not be proprietary to any specific equipment manufacturer confidentiality concerns regarding proprietary information are avoided. Models should allow for representation of a wide range of manufacturers' specific equipment through user configurable gains, time constants and feature switches.
- **Numerical stability:** Models should be numerically stable over simulation time steps from one millisecond to ½ a line cycle.
- **Cross-platform portability and compatibility:** Models should not be restricted to, or proprietary to, a particular simulation platform. Further, the models should have the same basic functionality and input parameter sets as implemented in different simulation platforms.
- **Self-initializing capability:** Models should initialize properly from a saved power flow case without significant user intervention.
- **Full documentation:** Models should be provided with full documentation, including block diagrams, description of all major control functions, and default parameter sets.
- **Validity:** Models, when fitted with specific input parameter sets, should have been validated through field tests, factory tests or against higher order (electromagnetic transient) models that have been validated themselves against test data.

As previously noted, current industry practice utilizes manufacturer-specific models, which do not provide for all of these desirable features. The WECC REMTF is working to develop two varieties of generic PV dynamic models, one for representation of centralized PV power plants, and a second for representation of distributed PV systems as part of a composite load model.

Central Station PV Plants

From a modeling perspective, central station PV plants are those that meet the regional RO capacity and interconnection voltage criteria for explicit representation in transient stability simulations. A central station PV plant will generally be expected to meet the same reliability criteria as central power plants using other energy resources. The grid interface characteristics of a central station PV plant have many similarities to a central station wind plant consisting of full-conversion wind turbine generators. Thus, the generic dynamic models previously developed by the WECC REMTF for the full conversion, or Type 4, wind turbine generator (see [3] and [4]) provides a good starting point for a generic central station PV model.

Figure 6 depicts a simplified block diagram of such a model. The inverter control, reactive power control and grid protection subsystem models are substantially the same as the corresponding generator and electrical control models in the WECC Type 4 wind turbine mode, except that the aerodynamic and pitch (governor) control subsystems of the wind turbine model are not needed for PV. The protection module would contain voltage and frequency tolerance characteristics, which sometimes are based in grid connection requirements.

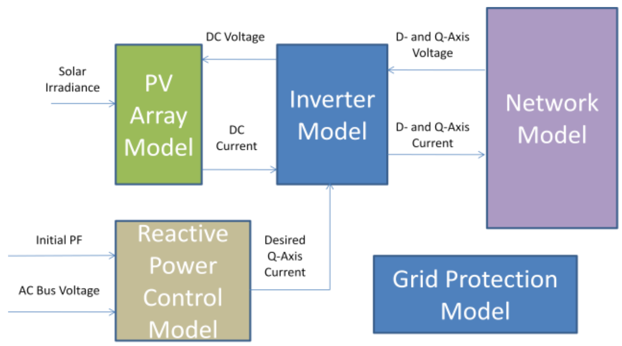

Figure 6 – Block Diagram of Generic Central Station PV Plant Dynamic Model

WECC REMTF is in the process of developing detailed technical specifications for central-station PV. Proper representation of the DC dynamics associated with the PV array inverter control interaction, as well as the impacts of the short-term variability of the solar resource on the PV array model, are current topics of discussion. Generally speaking, it is not necessary to model DC dynamics for the application space of generic positive-sequence models. This means that the PV array may not need to be explicitly represented. REMTF is collaborating with several software developers to implement the models in software commonly used in planning and interconnection studies. Model validation and development of data sets are part of the overall WECC effort.

Distribution-Connected PV Plants

In the current low PV penetration scenario, distribution-connected PV is "hidden" as negative load within transmission planning models. High PV penetration scenarios on the distribution network will require a more explicit representation of PV within the composite transmission network load for transient stability analysis.

PV inverters will respond to voltage and frequency transients differently than other components of the composite load, with unique impacts on transient stability.

WECC-approved composite load models already capture the differing dynamic characteristics of the various components of load that may be aggregated on a transmission bus in a power flow model (see Figure 7). REMTF is proposing to modify these existing models to include a distributed PV component so that the dynamic characteristics of the PV inverters are not "lost" as penetration levels on the distribution system increase.

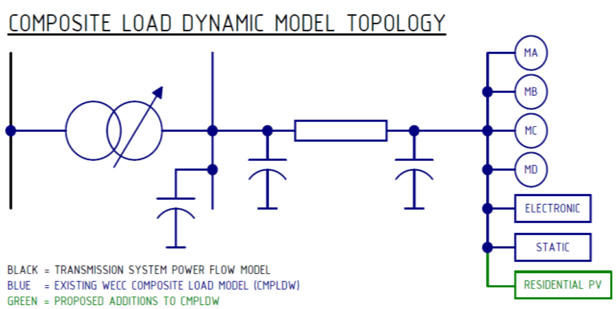

Figure 7 – Composite Load Model with PV Component

Figure 8 shows REMTF's proposed dynamic model structure for distribution-connected PV. The model is much simpler compared to the proposed dynamic model for central-station PV systems, due to the fact that it is meant to represent the aggregate behavior of many smaller PV systems.

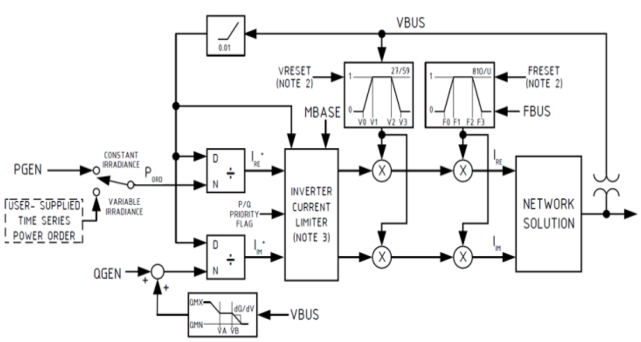

Figure 8 – Proposed model structure for distribution-connected PV

CONCLUSIONS

Better models to represent PV systems in grid performance simulations are needed. This paper discussed contributions by the WECC REMTF on power flow representation and generic positive-sequence dynamic stability models for use in interconnection and planning studies. This effort covers representation of both central-station and distributed PV, from the point of view of the bulk system. The dynamic generic models are designed to become part of the standard model library in commercial simulation software.

ACKNOWLEDGEMENTS

This work is being conducted by the WECC REMTF, funded in part by the Department of Energy. Sandia National Laboratories is the REMTF coordinator.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

REFERENCES

[1] WECC REMTF, "WECC Power Flow Modeling Guide for PV Systems", November 2010

[2] E. Muljadi, C.P. Butterfield, A. Ellis, J. Mechenbier, J. Hocheimer, R. Young, N. Miller, R. Delmerico, R. Zavadil, J.C. Smith, "Equivalencing the Collector System of a Large Wind Power Plant", presented at the IEEE Power Engineering Society, Annual Conference, Montreal, Quebec, June 12-16, 2006.

[3] A. Ellis, W. Price, R. Zavadil, Y. Kazachkov, E. Muljadi, R. Wilson, C. Quist, J. Kehler, J. Seabrook, J. Dunlop,"Generic Wind Plant Models for Power System Studies" , presented at the Windpower 2006 Conference, Pittsburgh, June 4-7, 2006

[4] WECC Wind Power Plant Dynamic Modeling Guide, Prepared by the WECC REMTF, August 2010 (www.wecc.biz).

[5] Kosterev, D.; Meklin, A, "Load Modeling in WECC", Power Systems Conference and Exposition, 2006. IEEE PSCE 2006, Atlanta, GA, October 29 – November 1, 2006