APPENDIX J
SCOPING STUDY TO ASSESS SOLAR GENERATION CHARACTERISTICS AND ITS IMPACTS ON LOAD MODELING

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1.0 INTRODUCTION

As concerns of climate change intensify, renewable energy technologies such as photovoltaic (PV) generation are being deployed in large scale within the electrical grid dominated by conventional electricity sources such as coal, natural gas, and nuclear generation. Solar power generation has been expanding rapidly year after year as illustrated in Fig. 1, which shows the cumulative growth in PV capacity since 1992 within selected countries that are members of International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS). This reported installed capacity represents an annual rate of growth of cumulative installed capacity in the IEA PVPS countries was 40 %, up from the 34 % recorded in 2006, [1].

Annual PV installations in the United States increased 42 % from 145 MW in 2006 to 206.5 MW in 2007. Most of the growth occurred in the grid-connected sector – to over 150 MW during 2007. At the State Government level, renewable portfolio standards (RPS) requiring electricity utilities or electricity providers to supply a certain quantity of their delivered energy from renewable energy sources such as PV have been adopted in 25 states and the District of Columbia. These requirements call for as much as 20 % to 30 % of electricity to come from renewable energy sources in the next 15 to 20 years [1].

In according to a utility solar assessment study, the solar contribution could be quite considerable, realistically reaching 10 percent of total U.S. electricity generation by 2025 by deploying a combination of solar photovoltaic (PV) and concentrating solar power (CSP), as shown in Table I [2].

More than 90% of the installed PV capacity is connected to national electric grids [3]. The increasing connection of distributed generation at distribution levels from a certain penetration level may not only influence the operation and design of distribution systems, but also affect to the operation and stability of transmission system as well. In impact studies for installing these generation systems, the transmission system is generally modeled as a strong – sometimes even as an infinite – voltage source. Thus, the weakening effect that comes with high penetrations of DG therefore has been neglected. Transmission systems in the future however will become weaker and the DG systems may affect significantly the behavior of underlying distribution systems and consequently transmission systems. While there have been some studies of the potential impacts of PV systems on the distribution systems [4], there are no significant works analyzing the impacts of those on transmission systems [5]. Investigation impacts of PV systems on power systems become more important as the penetration level increases.
TABLE I
U.S. Solar Installed Capacity (CSP and PV)

<table>
<thead>
<tr>
<th>Year</th>
<th>Cumulative Capacity CSP+PV (MW)</th>
<th>Total Annual Generation Combined PV and CSP (MWh)</th>
<th>Total Projected Annual U.S. Elec. Generation/Demand All Sources (MWh)</th>
<th>CSP and PV Share of Total U.S. Elec. Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>1,284</td>
<td>2,513,665</td>
<td>4,119,235,320</td>
<td>0.06%</td>
</tr>
<tr>
<td>2010</td>
<td>3,027</td>
<td>5,849,916</td>
<td>4,219,402,150</td>
<td>0.14%</td>
</tr>
<tr>
<td>2015</td>
<td>15,184</td>
<td>29,385,504</td>
<td>4,397,239,160</td>
<td>0.67%</td>
</tr>
<tr>
<td>2020</td>
<td>69,260</td>
<td>133,345,983</td>
<td>4,608,068,490</td>
<td>2.89%</td>
</tr>
<tr>
<td>2025</td>
<td>255,646</td>
<td>485,723,159</td>
<td>4,858,105,640</td>
<td>10.00%</td>
</tr>
</tbody>
</table>

In this report, a state of the art literature survey is conducted, with a goal to establish a simple and accurate empiric modeling of PV systems to complement load representations that are commonly in use for power system load flow and power system stability analysis studies.

Such a PV model may be used to analyze the impact of PV systems on the transmission systems and distribution systems. The desirable model will permit the representation of all PV systems installed in a distribution area as an equivalent active load by using the source aggregation techniques. To be sure, the model intended will depend on parameters such as installed power, penetration level, location of system, weather condition, rated electrical values etc.
A brief review of the current state of the art of PV system models is presented in Section II, followed by a discussion of issues and concerns related to PV modeling in Section III. Section IV presents the features of a candidate model, followed by a concluding summary in Section V.
2.0 PV System Models

A block diagram of a grid connected PV system is shown in Fig. 2. As may be observed from the block diagram, the properties and behavior of the system will be affected on the output I-V characteristics of photovoltaic array, a maximum power point tracking (MPPT) function generally incorporated in the DC-DC converters, and the DC-AC inverter, besides variations in the solar insolation.

![Block diagram of typical grid-connected PV system](image)

**Fig.2. Block diagram of typical grid-connected PV system**

There have been parallel efforts to develop models suitable to study their individual impact within the PV generation system and at the grid interface. These models may be classified into three groups: (a) model based on characteristics of PV array, (b) model based on characteristics of specific inverter structure and (c) overall PV system model. The last model is much convenient for interacting with the traditional power flow analysis to obtain steady-state operating status of power grid and PV system. The overall system models use the principle of instantaneous power balance and the principle of power electronic transformation [6,7]. Model development for study of single PV based generation devices have generally focused on developing tools that enable time-domain simulation using tools such as PSCAD, Matlab-Simulink, EMTP, etc. Reference [8] provides an excellent overview of the state of the art from this perspective.

On the other hand, among the models that are aimed at studying their collective behavior and investigate the effects of PVs on power systems, most of them are related to impacts on the distribution systems [9-10]. The few works related studying impacts on transmission systems [11-12], consider general DG technologies beyond PV systems, with machines such as synchronous and induction generators.

Most of the modeling studies of PV systems have generally been based on analytical methods. Although these models exhibit the behavior of PV systems with certain accuracy, they do not reflect the response of PV systems to variable conditions in irradiance, grid voltage, etc. While there are some studies which present experimental test results in grid-connected PV systems in order to show interaction between PV systems and power systems [4], they have not been considered in the model development, with the exception of [13]. In that paper, a model of PV generator capable of simulating its response to changes in irradiance and grid voltage is
established. However, the effect of variations in grid frequency has not been taken into consideration in the model.
3.0 PV System Modeling Issues

When modeling the PV systems in the electric power systems, major issues to be accounted may be grouped into two categories; steady state concerns and transient concerns, as discussed further in the following sub-sections.

3.1. Steady State Concerns

The main steady state issue concerning PV generation is the variation of power generation, which is affected by environmental factors such as location, weather, and climate. The single major parameter that affects the output power of PV generator is the irradiance. Since the irradiance is related to latitude, geographical location of PV systems is used to estimate the irradiance consequently output power.

![Graph showing direct and diffuse irradiance](image)

Fig. 3. A graph of measured direct and diffuse irradiance on (a) a summer day, and (b) a winter day (From [4])

For instance, it has been observed daily average irradiance values ranged from 5.0 to 7.5 kWh/m²/day from a measurement study in which the nineteen monitored systems are located at
geographically diverse sites from San Diego County in the South to Willits in the North [14]. Besides the location, the irradiance changes from hour to hour, day to day, or month to month, output of the PV system may vary with time. For selected summer and winter days, direct and diffuse irradiance measured in study is shown in Fig. 3, [4]. As shown from figure, irradiance changes not only during daytime, but also with season.

PV array power output varies depending on module temperature besides irradiance level. It means that PV array output consequently depends on the weather conditions such as ambient temperature and wind speed. Thus, alternative approaches based on weather rather than cell temperatures may be used to develop system capacity estimates [14].

The steady state irradiance at the location may be more readily integrated with the power system modeling tools. There are some data sources open to public related to PV generation. European Commission Photovoltaic Geographical Information System (PVGIS) has interactive maps for Europe and Africa [14]. National Renewable Energy Laboratory (NREL) has solar maps for USA [15]. These organizations have dynamic solar maps that calculate daily and monthly irradiance throughout the year. Using these data, it may be found the solar insolation for a given location and a specific time.

On the other hand, the properties of the PV generation system itself are more difficult to aggregate. The immediate variability conditions of the generation system will depend on the type of solar array, orientation of the solar array, aging of the solar array, dust, dirt, and snow build up on the solar array, microlimate conditions such as local cloud-cover, etc.

3.2. Transient Concerns

The properties of the components that comprise the PV generation system contribute to the transient issues that affect the behavior of the generation system in the electric grid. The transient concerns that would to be considered in developing the model may be conveniently represented by the voltage and frequency sensitivity PV array properties, MPPT dynamics, DC-DC converter dynamics, overall power conversion efficiency, anti-islanding protection and decoupling protection which inverters for PV systems should comply with, etc.

3.2.1. Frequency and Voltage Sensitivity

Determining the real power and reactive power sensitivity with respect to grid voltage and frequency is required to model PV system accurately. The response of a commercial PV generator to grid voltage change has been studied in laboratory conditions as reported in [13]. Fig.4 illustrates the variation of system output real power to voltage variations at the grid connections. In this study, the effect of frequency change has not been considered. While the power factor (PF) of the PV system is typically 1.0 in residential applications, central power stations can be produced reactive power to realize local voltage regulation. The need and impact of such operational variations have not been definitively established and hence a study of the system with respect to voltage and frequency is in order.
3.2.2. MPPT Dynamics

A field survey of 387 different models of PV generation systems below 10 kW reported in [17], found that all the units contain a MPPT module. Furthermore, the results of experiments carried out with three different inverters have indicated that the response time of PV generating units is significantly affected by MPPT module dynamics and efficiency [13]. Therefore MPPT dynamics of inverters that form the aggregate representation should be accounted appropriately in the system level models.

3.2.3. Efficiency and derating

While a typical PV system may be rated at a particular power level, equipment dynamics can have drastic impact on output of the system. Power conversion efficiency of the PV system and the de-rating factor of the design together may affect the output power of the system when grid voltage and frequency have variations. The de-rating factors and conversion efficiency may be in 0.1-0.96 ranges, while efficiency may be in the 0.7-0.98 ranges depending on the operating conditions and design cases. Therefore incorporating the collective behavior among these factors are also important in developing an appropriate system level model.

3.2.4. Array properties

The solar array of the PV system may vary depending on the crystal used in solar cells; monocrystalline, polycrystalline and amorphous. Since solar cells produced from these
materials have different levels of efficiency and aging behavior, consequently efficiencies and behaviors of PV arrays composed various solar cells also show variety.

### 3.2.5. Protection set points

Islanding is a condition that occurs when a portion of the utility system is disconnected from the reminder of the utility system but remains energized by the distributed resource (DR). Due to concerns associated with islanded system such as safety issues for service personnel and asynchronous reclose which can cause equipments to damage, the islanding is not usually desired [18, 19]. Thus behavior of the anti-island function of the PV inverter should be considered in terms of its behavior during utility disconnection and disturbances.

Furthermore, compliance settings related to standards for distributed energy resources such as IEEE-1547, UL-1741 require decoupling protection requirements besides other regulations. For instance, a survey of the voltage tolerance curves presented in [19] which investigate 9 commercial PV inverters in the range of about 0.2 to 4 kW reports that all inverters except one are highly sensitive to voltage sags. None of them are capable of withstanding any voltage sag deeper than 50%, lasting longer than 40 ms, as illustrated in Fig. 5. Furthermore, voltage rise may also occur at the point of interconnection to the grid. Since interconnection requirements require disconnection during abnormal voltages, PV systems would disconnect themselves from the power systems under such conditions subject to their protection settings, and variable dynamics in response time. Therefore, it is important to consider and include these aspects in the PV system model representation to ensure faithful predictions from the studies.

**Fig. 5. Voltage tolerance curves of 9 commercial PV inverters (From [19])**
3.2.6. *Penetration and census*

Because the effects on the power systems vary with levels of PV penetration and type of PV generation system from among different commercial manufacturers and vendors, these aspects will have to be accounted appropriately in developing the system model.
4.0 Candidate System Model

Within the context of power system studies, system components such as power sources, loads, transformers and interconnections are widely modeled in an aggregate manner. In this mix, considering the PV system as an active load that injects energy into power system may provide more convenience, since they have not internal inertia. However, establishing the representative analytical model that presents accurately the characteristic of grid-connected PV systems is particularly challenging in light of the discussions presented above. Alternatively, empirical model may be a more practical solution, based on laboratory scale experimental results and data from the real field measurements [13,14,17,20]. Such load modeling approach in power systems is among the preferred approaches in developing and validating modeling tools [21].

It should be mentioned that detailed component-level models (such as those including models of PV array, MPPT part, power electronic converter, etc.) are suitable for analysis of specific PV unit or grid-independent PV system. But the precision of such modeling is generally lost in grid-level studies, where wide aggregations are made of large number PV units (such as residential area installed PV units). Therefore grid-level models that reasonably represent of PV units on the power systems should be main motivation of this study. Towards this aim, an appropriate aggregation method similar to that applied in the load aggregation may be used in order to represent the combined effect of the PV systems installed in a distribution area [22-23].

With such an approach, a simple, practical and faithful PV system model for electrical power systems may be established. The approach should also use an aggregated representation of distribution systems with dynamic and static loads as well as PV systems that is adequate enough for system level studies. Fig. 6 illustrates a candidate representation for PV installations within the distribution system by including a ‘PV load model’ to exist the load model structure.

![Diagram](image)

**Fig. 6. Structure of a candidate PV system model to be incorporated within the framework of load modeling**

The heart of the candidate model is the behavioral representation of the inverter component including the various dynamics such as efficiency, MPPT and protection functions. In order to
develop this, detailed tests may be carried out using several commercial PV inverters found in
the market. The objective of these tests is to investigate the inverter dynamics performance
during some events typically found in the grid such as voltage, and frequency fluctuations and
oscillations. Additionally, transient response tests may also be carried out. For instance, a
switching transient test may be used to determine the time delay when suddenly the inverter is
connected to grid. Inverter anti-island test, short circuit test, rapid power fluctuation test, etc,
will provide complementary data to develop a faithful system representation. Based on test data
from an array of tests on a variety of inverters, an aggregate representation that provides a
weighted average of model parameters depending on the distribution of different devices
among the population within the distribution system.

The development of a practical model with a user-friendly interface will be a challenging task,
even given all the representative test data. The results from the test data would be classified and
correlated for similarities, and differentiated for variations and an appropriate model
representation to accurately represent the bulk behavior will need to be developed. On the other
hand, based on the model it would be very easy to obtain results needed by entering some
parameters, such as installed power, penetration level, population distribution among different
manufacturers’ inverters as appropriate, location of system, weather conditions, rated electrical
values, into the appropriate program interface.
5.0 Conclusions

In this report, various issues related to PV generation system representation in power system studies have been discussed. A survey of the state of the art has been presented, highlighting the particular limitations and useful approaches in the literature. A summary conclusion may be stated as, “Though there are several PV modeling studies, none of them are suitable for power flow analysis at the grid-level studies in which wide aggregations are made of large number PV generation sources”. Various parametric and sensitivity aspects of PV generation sources have been identified and discussed on the basis of the literature in the field, and a candidate modeling approach has been presented. The immediate step in developing the approach further is initiating, conducting and completing comprehensive tests on commercial PV generation inverters in laboratories capable of providing grid emulation. It is learned that Southern California Edison is initiating such tests in concert with the National Renewable Energy Labs [25].

On the basis of the results from the tests, an aggregation and representation method may be developed as a follow on activity. Such an approach will lead to useful and practical tools for studying and preparing for high penetration of PV in the electric grid.
6.0 References


