

# Guidelines for Large Photovoltaic System Integration

Silviu Darie, PhD(EE), PE(EE)

**Abstract-** The paper summarizes the result of a research project funded by the Department of Energy (DOE) in collaboration with the University of California at San Diego (UCSD), [1]. One presents a planning guideline and establishes interconnection criteria for integrating Photo Voltaic Generation (PVG) into the power systems (transmission and distribution). Some of the experiences/guidelines in the field of wind farm integration are used here since wind generation and PVG generation share many common power electronics devices used in their control schemes and both generation types are intermittent resources with similar degree of predictability and forecast methodology. Recommendations are given on the best practice promising standards for interconnecting large PV generation to power system.

**Index Terms-** Photovoltaics, photovoltaics generation, planning guideline, system integration.

## I. INTRODUCTION

The intent of this paper is to objectively discuss the issues and concerns related to the integration of PV generation into the utility power system. The outcome is a series of recommendations, all technically feasible and viable, for possible incorporation into broader standards for interconnecting PV plants to the utility system. The goal of any such standard will be to establish minimum technical requirements for connecting PV plants to the power systems at transmission and/or distribution levels. Such a standard will make no distinction as to the preferred technologies or types of PV generation equipment, but rather rely on the ingenuity of the PV plant developers, PV plant manufacturers and other power equipment manufacturers to come up with the most cost effective means of meeting and/or exceeding the technical established standards.

The paper also summarizes the experiences/findings of other researchers on integration of PVG generation into power systems and planning guidelines which have been adopted by many utilities, RTOs (Regional Transmission Operators), and ISOs (Independent System Operator) in the North America and elsewhere in the world. Some of the experiences/guidelines in the field of wind farm integration have been used since wind generation and PV generation share many common power electronics devices used in their control schemes and both generation types are intermittent resources

with similar degree of predictability and forecast methodology. Based on several studies, the salient points of interest are outlined below:

- Interest in PV generation has been growing rapidly in the past few years; one can say that PV is growing at approximately the same rate as Wind Power and is just 6 years behind; by the end of 2009 the cumulative PV power reached 22.8 GW, [2] and the PV forecast worldwide by the year 2014 is 30 GW, [2];
- Power converters have become the major players for renewable energy generation, energy storage, smart grid technologies;
- There has not been any mature planning and interconnection guidelines or standards related to PV generation. However, the existing wind integration standards and interconnection guides are to a large extent addressing similar concerns and needs as PV integration and interconnection. There are several other studies and organizations also researching and developing potential standards around the world for PV integration such including the US, Germany, Spain, etc.;
- Major concerns of large scale PV generation integration into power systems are related to variations in the PV active power output due to intermittency of solar irradiance and their impact on system reserve. Even though storage such as Battery Energy Storage Systems (BESS) are being considered for PV applications, this solution is still not economical for large scale PV plant implementations;
- In these early days of PV development and application for power, most PVs were designed to disconnect from the power system immediately following a system disturbance especially a system fault in the vicinity of the PV plant. This is due to small size PVGs that are connected at distribution levels. With large-scale PVG being connected to the transmission systems, this is no longer an acceptable response. Many utilities in the US and Europe, have made the requirement for a low voltage ride through (ZVRT/LVRT) capability mandatory. This requirement is similar to wind farm interconnection standards;
- Power quality requirements including voltage flicker, harmonics, as well as coordination of controls and protection are important part of the interconnection guideline. The power quality, control and protection requirements for PV should be adopted from the

---

This work was supported by the DOE/UCSD, High Solar PV Penetration. FOA-0000085 grant.

S. Darie is with Power Analytics Corporation, San Diego, USA (e-mail:sdarie@poweranalytics.com)

existing guidelines and standards such as IEEE Standard 1547, IEEE Standard 1547.5, IEEE 519, IEC 555, IEC 61000, and IEEE Std. 929-2000;

- The maximum size of PV plant that can be accommodated in a power system, in general, should be limited by the available short circuit capability at the point of common coupling (POI) of the PV plant to the power system. Ratio of available short circuit at POI to the PV plant size of less than five (5) will likely introduce voltage control problems;
- The maximum level of PV penetration into a power system (i.e., percentage of PV generation e.g. 10, 20, 30%, etc. versus total system generation mix) cannot be determined from a simple set of rules. This question has been asked by many of the power system planning/operation engineers in regard to wind farm penetration. An excellent example is EirGrid (independent electricity transmission system operator and market operator) in Ireland that has attempted to determine the maximum level of wind power penetration into Irish power system. The only successful solution EirGrid selected was to perform on-line (and near real-time) power system analysis to determine what is the maximum wind generation at any given time of the day and day of the year. It the belief of this project team as well that maximum level of PV penetration into a given power system should also follow the same solution, i.e. on-line or off-line analysis for a specific power system.

Technical problems can be addressed regardless of the type of PVG or vendor of the PVG system, provided proper analysis and design is performed at the onset of a project. As PVG technology advances they are becoming more and more economically viable and competitive compared to other alternate energy sources.

North American utilities evaluate interconnection requests including a PV plant proposal through a “**Feasibility and System Impact Study**”. In these studies, system performance is compared with and without the proposed PV plant under various system load/generation dispatches and considering a number of N-1, N-2 creditable contingencies. Generally a typical system interconnection study consists of, [1]:

- Transmission facilities over-load determination (thermal evaluation);
- Impact on transfer capability over the critical tie-lines/interfaces;
- Transient and voltage stability analysis and
- Impact on increased fault levels.

Power Analytics team has developed several steady state and dynamics models for various PV plants, [1]. This paper is primarily qualitative providing an overview of existing planning and interconnection criteria established by US utilities. Using the aforementioned resources, the paper addresses PV integration study, planning guideline, and acceptable level of penetration issues.

## A. Interconnection Guideline/Standards and Criteria (PVG less than 10 MVA)

### A1. Voltage Control (Automatic Voltage Regulation)

There is a requirement and need for automatic voltage regulation for PV plants. For PV plant technologies that use voltage source inverters, automatic regulators may be applied to regulate the reactive output, to maintain a certain voltage e.g. at the point of interconnection between the PV plant and power system. In other cases voltage regulation can come from a supervisory control system regulating the reactive resources throughout the PV plant. For larger PV installations, SVC or STATCOM coordinated together with a number of mechanically switched capacitors can provide the required voltage regulation. For smaller PV plants in distribution systems, DVAR or DSTATCOM can be utilized.

### A2. Frequency Control

Frequency control for PVG is possible but not to the same degree as frequency control with a governor on a classical generator. PV plants should not actively participate in primary frequency control during under-frequency.

Having a “governor like” control for a PV plant control scheme is a technical possibility and even desirable.

However, it is reasonable to recommend that a PV plant meet an off-nominal frequency operating condition similar to the appropriate operation standards (that is used by many utilities for wind farms and classical generating plants) – Table 1.

Table 1: Frequency range versus time

Frequency Range (Hz)	Time (seconds)
>61.7	0
61.6 to 61.7	30
60.6 to <61.6	180
>59.4 to <60.6	Continuous Operation
>58.4 to 59.4	180
>57.8 to 58.4	30

### A3. Low Voltage Ride-Through

Typically PV plants operate continuously between 90-110% of nominal voltage at the point of connection to power system. PV plants should be able to stay connected to the power system for voltage dips or voltage rises. Typically PVG will be required to ride-through voltages for the duration required to achieve fault clearing times of a normally cleared fault. The cost of achieving ride-through down to zero voltage (using a combination of battery storage system and voltage source inverter) can be significant and may only be reasonable for larger PV plants installations (greater than 10 MW), [1].

### A4. Reactive Power Capability

Reactive power capability requirements and power factor (PF) control for larger PV plants should be similar to those for wind generation. Reactive power compensation is desirable for PV

units. Reactive power capability is measured at the low voltage side of the PV substation. A PV plant at its full load, should be capable of 0.90 PF lagging and 0.95 PF leading. Automatic voltage regulation that is able to regulate the voltage at this point to a “desired” set-point to within +/-0.5%. The voltage regulation system should have adjustable gain, droop and a reference set-point. Voltage regulation should be provided to adequately control voltage at the point of interconnection throughout the range of power delivery of the PV plant and coordinated with other voltage regulating devices on the transmission system.

In cases where a good portion of reactive compensation is provided at the PV substation in the form of an SVC or STATCOM, such coordination is more easily achieved since it is done through a centralized control. Moreover, the device may be more easily used for voltage regulation even when the PV is disconnected since it is directly connected to the substation. Finally, based on general consensus it is believed that a power factor (PF) requirement of +/- 0.95 at the point of interconnection is a reasonable requirement.

#### A5. Power System Stabilizers

Power System Stabilizer (PSS), obviously, in the traditional sense, PSS does not apply to PV generation since they are essentially used for synchronous units. PV units are essentially decoupled from the system and do not really participate in electromechanical modes of rotor oscillation. The fundamental concept behind PSS tuning is to introduce a component of damping torque on the shaft of a generator in the range of frequencies associated with electromechanical modes of rotor oscillation. However, based on the generalization of concept of power system stabilizer, it may be possible to design stabilizer for a PV plant controller to modulate the output power to improve the damping of inter-area modes. Similar stabilizers have been proposed for SVC, STATCOM and HVDC. This, would be contingent on the location of the PV plant and thus the controllability of the mode from the PV plant location. To be fully effective, a PV plant needs to be on-line to obtain the full benefit of all stabilizers (the PV output and status are difficult to predict). Therefore, at this time, PSS application on the PV plant controllers it is not generally recommended.

The cost of implementing some of the recommended control functionalities described earlier may very well exceed the benefits. Since such PV size units may not significantly contribute to the bulk system performance (e.g. transmission connected PVs vs. distribution PVs). The benefits of this section become evident when applied to large PV plants (e.g. 50, 100 MW and larger) connected to a transmission system. Smaller PV systems (e.g. 5 to 10 MW), are less significant to the distribution system and have no net active power delivery into the transmission system. As such, these units may not significantly contribute to the overall system performance.

*Therefore, the operator should, at their discretion, reserve the right to override requirements where such requirements may not deliver any significant benefit to their system operation.*

However it is important to note that the distinction between distribution connected and transmission connected PV generation may be somewhat subjective when a number of

smaller (<10 MVA) distribution connected PVs make up a substantial power delivery to the transmission systems.

An easy way to make this distinction is to discuss the net amount of megawatt transfer. That is, if the megawatt output from a small distribution-connected PVs is being consumed locally at the distribution level such that a system disturbance that disconnects the PV plant from the system also disconnects the load (i.e. no net imbalance in system load generation) then, for example, the requirements for low-voltage ride-through and power limitation/curtailment may be doubtful for such a PV plant. However, if megawatts are being transported over the transmission system to remote loads then the loss of the generation following a disturbance would constitute load/generation imbalance and thus would not be acceptable in large amounts. In general we recommend adoption of the IEEE Std. 1547 Standard for Interconnection Distributed Resources with Electric Power Systems, and its applicable guides, for PV plants with an aggregated combined power output of 10 MVA or less. This standard was recently developed for distributed generation facilities of 10 MVA or less. The IEEE Std. 1547.5 under development for facilities with a combined capacity of more than 10 MVA.

#### B. Interconnection Guideline/Standards and Criteria (PVG greater than 10 MVA)

##### B1. Active Power Generation

- The system control center (transmission system operator - TSO), through telemetry, should have a means at all times to monitor the megawatt output of a PV plant and whether or not it is on or off-line due to solar irradiance;
- The 15 minutes average megawatt output of a PV plant must not at any time exceed the specified maximum output of each PV plant, [4, 5, 9];
- The system control center, through telemetry or other means of contact with the PV plant operator, must have a means of issuing a directive to reduce the megawatt output of the PV plant, or curtail the PV plant in the event of an emergency condition where the PV plant output is to be reduced to respect thermal limits on nearby transmission corridors or when otherwise generation far exceeds demand. Alternatively, the PV plant operator may intentionally disconnect blocks of PV modules in the plant to effect a reduction in generation. In any case, this should be done in a controlled fashion and at the specified rate by the operator (e.g. certain number of MW/minute);

All PV modules in a single PV plant must not start or stop simultaneously. This can be achieved through sequencing of the start-up and shutdown controls of the PV modules in a plant.

##### B2. Zero/Low Voltage Ride Through

PV plants should be able to ride through faults taking place at the high side (transmission voltage level) of the substation transformer. This requirement does not apply to a radial PV

plant connection. In such cases, the PV plant should be able to ride through any normally cleared faults external to the radial line feeding the plant. This requirement would translate to the PV plant being required to ride-through a 3-phase fault (normally the most severe fault) close to the point of interconnection which means PV plant should “survive” near zero voltage for duration of approximately 100 ms, [9,10].

In FERC (Federal Energy Regulatory Commission) discussions, it is suggested that zero/low voltage ride through may still be a relatively new development and still requires further development. What cannot be tolerated is to have a single disturbance that results in the loss of multiple generating plants. In the future as the technology improves (and PV penetration increases) then a fault ride-through strategy may be adopted. The recommendation here is to slowly transition to requiring that the PV plant be able to ride-through fault external to the plant for the normal fault clearing durations. For system disturbances with longer durations, where the system voltage does not recover for an extended period of time, the PV plant must be tripped by under voltage protection. Also, any shunt capacitors that are used for power factor correction must disconnect from the system to prevent overvoltage conditions when the system recovers after fault is cleared.

### B3. Voltage/Frequency Operating Limits

For steady state, transient voltage conditions, and for off-nominal frequency operation, PV plants should be expected to meet the existing criteria of the respective utilities. The table below shows a typical example of the off-nominal voltage performance. Clearly, all PV plants must operate continuously at and between  $\pm 10\%$  of nominal system voltage and  $\pm 0.5$  HZ of nominal system frequency.

Any single or multiple contingencies as defined by NERC (North American Electric Reliability Corporation, i.e. categories A, B, C, and D) with PV plant interconnections and operated at full output should not cause transient voltage and/or frequency violations as specified in below table WECC/NERC.

### B4. Power Quality

PV plants should be expected to meet the power quality requirements of their respective operator. This is in line with IEEE Std 519. PV plants owners should be responsible for performing studies where necessary to ensure that they avoid low-order harmonic resonance phenomenon on their system due to shunt capacitors (or cable charging) and power electronics. PV voltage/power variation due to variation in the solar irradiance may also cause voltage flicker. The PV plants owners should take steps to minimize flicker problems from their generation. The standards for voltage fluctuations at the point of connection of the PV plant facility to the power system should, for example, follow the requirement outlined in Table 2.

Table 2: Suggested Voltage Fluctuations Limits, [9, 10]

Voltage Change	Maximum Rate of Occurrence
+/-3% of normal level	once per hour
+5/-6% of normal level	once per 8-hour
Exceeding +5/-6%	As agreed by utility

Voltage and current harmonics can cause telecommunication interference and thermal heating in transformers; that can disable solid-state equipment and create resonant over-voltages. In order to protect and mitigate the PV plant equipment (power electronic interface) should not cause voltage and current harmonics on the power system and adhere to IEEE Standard 519.

### B5. Reactive Power Requirements

Based on standard industry practice it is recommended that PV plant facilities be able to operate with 0.90 PF lagging and 0.95 PF leading power factor (when generating its peak megawatt output) at the point of interconnection. This point is defined as the high voltage side of the substation transformer. This reactive capability should also be in the appropriate ratio of discrete (mechanically switched shunt capacitors) and dynamic (SVC, STATCOM, etc.) to ensure both steady state and transient stability during and after a disturbance. Studies may of course determine that the actual reactive needs are higher or lower depending on the size and location of the PV plant.

### B6. Protection Requirements

The PV plant operator:

- Is responsible to implement adequate protection to safeguard all PV generation equipment within the PV plant. The system protection, however, must properly be coordinated with other controls and the protection of the utility power system in its vicinity;
- Should design and implement the appropriate protection;
- In special cases, the plant developer may be required to perform specialized analysis such as:

*Electromagnetic transient/harmonic analysis such as switching including the energizing of transformer, capacitor banks, etc.;*

*Controls interaction studies, if the PV plant is being placed in-service in close vicinity to an existing power plant or HVDC system, etc.*

### B7. Modeling Requirements and Field/Simulation Verification

- The PV plant developer should be responsible to provide adequate steady state and dynamics models of the PV plant to utility where PV plant will be interconnected;
- The models should be updated when commissioning the PV plant if any model structures or parameters

are substantially changed between the planning and commissioning phase of the plant;

- Field verification tests or studies should be performed to demonstrate that the PV plant meets all of the requirements set forth by interconnection policy of the utility. In particular, the low-voltage ride-through capability of the PV should be demonstrated either through detailed modeling of the PV controls, or by field/ factory tests.

#### *B8. Automatic Voltage Regulators*

The concept of automatic voltage regulators (AVR) is not necessarily directly applicable to PV generation technologies. However, it is important to note that the voltage at the point of interconnection between the PV plant and the transmission network should be automatically controlled/regulated. The manner in which this requirement is achieved can be left at the discretion of the PV plant operator/developer.

#### *B9. Disturbance Monitoring System*

For the purpose of continued understanding of PV plant operation and control, utility may consider requiring that each PV plant be equipped with a disturbance monitor. As a minimum (monitor the interconnection point):

- Voltage and current;
- Active power transfer;
- Reactive power transfer;
- System frequency.

#### *B10. Telemetry*

A PV plant should make the following information available:

- Active and reactive power output at the PV plant;
- Status of circuit breakers on substation transformer and all shunt compensation devices located at the PV plant substation;
- Meteorological data including average solar irradiance at the site, as required to facilitate the use of the forecasting models;
- Tap position of the PV plant substation transformer if it is equipped with on-load tap-changers;
- Telemetry between PV plant (or PV plant operator) and the system control center to allow for curtailment;
- Telemetry between PV plant and the system control center operator to facilitate specifying voltage regulation set-points for the point of interconnection between the PV plant and the network.

Some of the above data may be used for forecasting purposes and so the data format and quality should be in a format that is suitable for such use.

## **Conclusions**

Photovoltaic (PV) generation is an attractive source of renewable energy due to their relatively small size and operation. Major advantages of the photovoltaic power are:

- Static structure with no moving parts;
- High power density per unit of weight;
- Short lead time to design, install, and start up;
- Highly modular structure, so plant economics are not just a function of size;
- Power output matches well with peak load;
- Expected longer life with low maintenance;
- Highly mobile.

The paper presents a summary of the experience with PV generation in North America and Europe. In addition, one uses the existing surveys on interconnection standards adopted by utilities for integrating classical generators, alternate sources of power generation including wind and PV into the power system to provide guidelines for PV plants. Based on background information obtained and the project team's experience with PV studies, recommendations are given on the best practices and emerging standards for interconnecting large PV plants to power system, [1]. The intent of this summary paper is to objectively discuss the issues and concerns related to the integration of PV generation into the utility power system. The outcome is a series of recommendations, all technically feasible and viable, for possible incorporation into broader standards for interconnecting PV plants to the utility system. The goal of any such standard will be to establish minimum technical requirements for connecting PV plants to the power systems at transmission and/or distribution levels. Such a standard will make no distinction as to the preferred technologies or types of PV generation equipment, but rather rely on the ingenuity of the PV plant developers, PV plant manufacturers and other power equipment manufacturers to come up with the most cost effective means of meeting and/or exceeding the technical established standards.

The salient issues of the PV plant interconnection are outlined below:

- Reactive power capability;
- Power factor and voltage regulation;
- Low voltage ride through capability;
- Frequency control;
- PV plant modeling for conducting power system studies to establish:
  - Thermal limits;
  - Voltage violations;
  - Frequency stability;
  - Transient response- dynamic response;
  - Post disturbance steady state.

Potential technical problems can be addressed regardless of the type or manufacturer of the PV generation system, provided proper analysis and design is performed at early

stages. As PV generation technology advances the use of PV plants is becoming more and more economically viable and competitive compared to other more traditional energy sources – this in the end will help to ensure greater utilization of our natural renewable resources helping to safe guard our environment.

## II. REFERENCES

- [1] Darie, S., Zhang, W., Pan, J “Improved Modeling Tools Development for High Penetration Solar”, Power Analytics Corporation, San Diego, CA, Tech. Rep. TR-DE-FOA-0000085, 2010.
- [2] Teodorescu, R., Liserre, M., Rodriguez, P., Grid Converters for Photovoltaic and Wind Power Systems. John Willey & Sons, Ltd., 2011, p.31
- [3] EPIA “Global market Outlook for Photovoltaics until 2011. May 2010. Available:[http://www.epia.org/fileadmin/EPIA-docs/public/Global\\_Market\\_outlook\\_for\\_Photovoltaics\\_until\\_2014.pdf](http://www.epia.org/fileadmin/EPIA-docs/public/Global_Market_outlook_for_Photovoltaics_until_2014.pdf)
- [4] WECC “Minimum Operating Reliability Criteria”, April 6, 2005, WECC
- [5] WECC “Coordinated Off-Nominal Frequency Load Shedding and Restoration Requirements”, WECC.
- [6] WECC “Under Voltage Load Shedding Guidelines”, Western Systems Coordinating Council, July 1999
- [7] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Standard 519, Aug. 1992.
- [8] IEEE Standard Definition, Specification and Analysis of Systems Used for Supervisory Control, Data Acquisition and Automatic Control, IEEE Std. C37.1, 2005
- [9] American Wind Energy Association “Standardizing Generator Interconnection Agreements and procedures”, AWEA, No. RM02-1-001. Available at [www.ferc.gov](http://www.ferc.gov)
- [10] WECC “Generator Electrical grid fault Ride through Capability”, WECC October, 2004.

## Biography:

**Silviu I. Darie** was born in Pitesti, Romania on January 10, 1945. He graduated from the Cluj Technical University, Romania in 1967. PhD from Technical University of Bucharest, 1973.



**Employment experience:** Professor at Technical University of Cluj Napoca, Romania (1968 – 1990); Award Professor at University of Cape Town, South Africa (1991-1996), Senior Consultant at DesignPower, New Zealand, (1996-1998), Senior Consultant at Compusoft, Saudi Arabia, (2002 – 2005), Vice President at Power Analytics Corporation, San Diego, CA, USA (2005 to present).

Author-co-author of 33 technical books and student manuals, 109 published papers, 173 research project and contracts and 18 prototypes designed for mass production. Holder of 3 registered patents.