DISTRIBUTION NETWORK IMPACTS OF HIGH PENETRATION OF DISTRIBUTED PHOTOVOLTAIC SYSTEMS

Johan H.R. ENSLIN, PhD, PrEng
Petra Solar, USA
Johan.Enslin@petrasolar.com

Hussam ALATRASH, PhD
Petra Solar, USA
Hussam.Alatrash@petrasolar.com

ABSTRACT

Grid impacts of PV power plants are associated with fluctuating voltage profiles, high electrical losses, poor power factor management, limited capacity, poor power quality, poor power balancing, difficult system operations and malfunction of protection schemes. Currently utility-scale solar PV plants have nominal capacities that are compatible with distribution substation MVA ratings e.g., between 2 MVA and 10 MVA, resulting in more than 100% penetration levels on some distribution feeders. These distribution network impacts are discussed and mitigation solutions are provided. A highly distributed PV solution with a unique advanced generator emulation control is presented to mitigate these grid impacts.

INTRODUCTION

Utilities world-wide are confronted with high penetration levels on distribution feeders at levels of 30 – 100% based on distribution feeder loads and substation transformer ratings. In the US the Renewable Portfolio Standards (RPS) proposed by the different states requires renewable energy production to levels of 15 – 30% by 2020. To avoid large expansions, permitting and associated time delays to build new transmission, there is a large likelihood that a large percentage of the renewable portfolio will be connected as distributed renewable energy resources (DRER) on the existing distribution networks. Large penetration levels of solar photovoltaic (PV) systems are currently located on utility customers' roofs, utility poles and other assets [2],[3].

Large-scale distributed PV generation impacts several aspects of the distribution system. Some of the most noticeable effects concern voltage, current profiles, power quality, protection, electric losses, reactive power management, power balancing, regulation, protection and operability of the system. Solar PV generation impacts can be steady state or dynamic (transient) nature. These impacts vary in severity as a function of the degree of penetration and location of solar PV distributed generation on the distribution feeder.

For instance, since traditional feeders are commonly designed for radial-unidirectional power flows, some of the most significant impacts occur for large solar PV penetration levels, which lead feeders to become active circuits and inject power back through the sub-stations to the transmission system. Under this condition, voltage profiles, sub-station protection schemes, and capacitor bank and voltage regulator operations are evidently affected.

On the other hand, large penetration of distributed PV generation can be used to alleviate overloads and release capacity of feeders and substation transformers. Furthermore in most cases no new transmission facilities need to be added and less permitting is required. These DRER features are important benefits from a grid impact and RPS fulfillment point of view, since it allows utilities to get to the integration targets quickly, defer capital investments and have fewer impacts on the distribution networks if the DRER systems are planned correctly. The more the generation is distributed across the distribution feeder, the better the system impacts can be managed.

Mitigation solutions to some of the expected interconnection issues include a highly distributed PV generation solution, improved PV inverter controls, distributed energy storage and dynamic distributed reactive power support [8]. Voltage profiles and reactive power management can actually be improved if highly distributed generation is integrated using improved inverter controls.

Embedded voltage regulation support algorithms for PV inverters can help alleviate some of the problems encountered with the integration of intermittent PV power plants. At the same time, they can make PV power plants more cost effective and even more dispatchable in virtual power plants (VPP).

CHARACTERISTICS OF PV SOLAR SYSTEMS

In most urban regions PV flat-plate collectors are predominately used for solar generation and can produce power production fluctuations with a sudden (seconds time-scale) loss of complete power output. PV generation penetration within residential and commercial feeders approaches 4 – 8 MW per feeder. With partial PV array clouding, large power fluctuations result at the output of the PV solar facility due to blocking of complete array strings if one module is shaded [2].

Some practical measurement data of the power output from utility scale PV solar farms are presented below. It is clear that these types of power variations on large-scale penetration levels can produce several power quality and power balancing problems. Recently a US utility installed large 2 MW utility scale power plants on warehouse roofs [3]. The power output from such a 2 MW utility scale PV power plant, which was monitored over several months and certain individual days is presented in Figure 1. The solar power generation profiles are based on actual measurements, one sample per 5 minutes.

In coastal and urban areas cloud cover and fog may provide large power fluctuations with associated energy production loss, grid stability concerns, power quality, low capacity factors and power balancing problems.

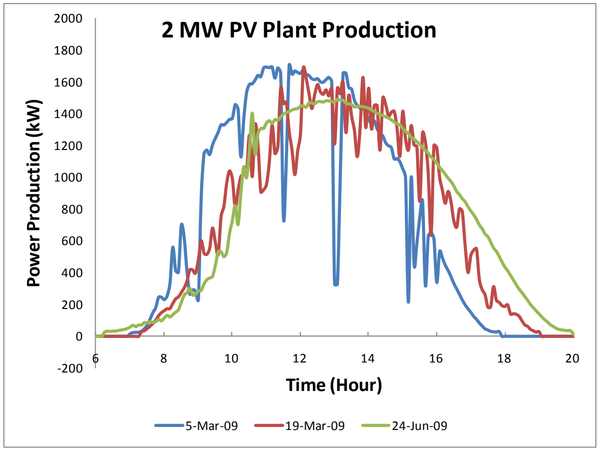

Figure 1: 2 MW PV Solar generation profiles during 3 days in southern California.

Studies and actual operating experience indicate that it is easier to integrate PV solar energy into a power system where other generators are available to provide balancing power, regulation and precise load-following capabilities. The higher the degree of distributed generation of solar farms operating in a given area, the less their aggregate production will be variable. A summary is provided followed by a more in-depth description [8].

Typical distribution impacts of PV systems include [1]:

- Capacity factors in the range of 10 – 20 %
- No dispatch capability of PV solar farms without storage.
- Ultra-fast ramping requirements (400 – 1000 MW/min)
- Most existing PV inverters do not provide reactive power and voltage support capability.
- Most existing PV inverters do not have Low-Voltage-Ride-Through (LVRT) capability [7].
- Most PV plants are non-compliant with FERC – Large Generator Interconnection Procedure (LGIP).
- IEEE-1574 provides contradicting guidance with LVRT and non-islanding requirements.
- Reactive power management of feeders are not designed with high PV production in mind
- Power Quality, especially voltage fluctuations, flicker and harmonics may be out of IEEE-519 and other standards.
- Lack of coordination control of existing reactive power support

There are also several technical benefits having PV generation especially on the distribution feeders as distributed generation resources. When designed correctly, large penetration of distributed PV solar generation can be used to alleviate overloads on highly loaded distribution feeders and release capacity on these feeders and substation transformers. This allows distribution planners to defer capital investments to other areas. More detailed analysis can be found in ref. [8].

HIGHLY DISTRIBUTED PV GENERATION INTO A SMARTER GRID INTERCONNECTION

Petra Solar [10] has pioneered a new highly distributed renewable energy technology that efficiently generates power through PV solar modules on utility, streetlight poles, or other highly distributed assets that can hold one or more PV modules such as rooftops. Petra Solar's SunWave™ photovoltaic (PV) systems not only feed distributed renewable energy into the electric grid, but also introduced a smarter grid connection with associated communications, remote sensing, grid management and control. These Smart Grid features improve grid operation efficiency with very limited grid impacts due to the highly distributed nature of the generation and intelligent inverter control. The grid-tie distributed nature of the SunWave™ systems also reduces the cost of interconnecting PV on the utility grids. The AC module with micro-inverters furthermore increase the energy harvesting compared to a string inverter design by approximately 20 - 30% as independently measured by Berkeley [11].

Distributed PV and Smart Grid Implementation

An existing distributed PV project is underway at PSE&G 0 integrating 40 MW of Distributed Solar PV Power installed on up to 200,000 poles in NJ using a 200 W, or larger, PV panel per installation. This is the largest distributed solar electric project currently being deployed in the world. This project has the following available sub-systems as shown in Figure 2.

The following sub-systems are identified below:

- Solar PV power production by SunWave™ Smart Energy Module (SEM) from a 200 W solar PV panel through a maximum power production (MPPT) controller directly on 120 V_{ac} secondaries of distribution transformers.
- Reactive power production by Smart Energy Module as priority on 120 V_{ac} secondaries of the transformers.
- Energy and electrical grid data collection through the re-configurable Communicator Access Points (AP).
- Web-based Energy Portal located at a centrally hosted server for energy production measurement, grid data access, and system diagnostics.
- Petra Solar Support Server for System Management.

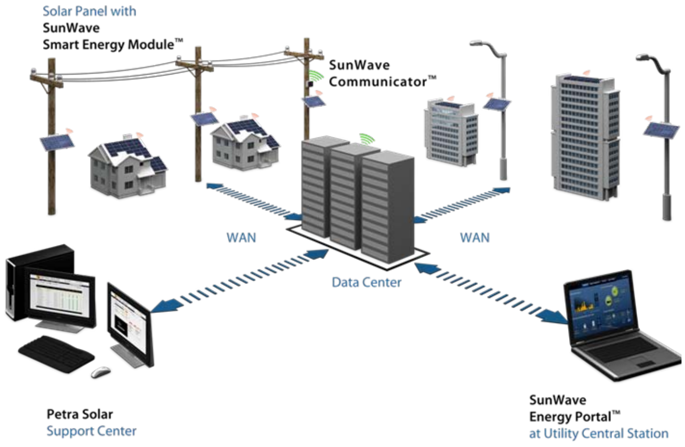

Figure 2: Petra Solar's Approach to Integrate Distributed PV within a Smart Grid network [10]

In this application energy production, voltage profiles and other electrical grid data are available on an individual SEM level for integrating into the utilities Smart Grid program. These parameters can be used for Smart Grid applications, such as Outage Management, Volt-VAR optimization, voltage regulation, transformer monitoring, etc. All the individual SEM units are commanded, individually, regionally, or collectively with the following control functions in an open-loop mode:

- Command reactive power output (VAR).
- Command PV energy production limits and curtailment
- On-line diagnostics per SEM
- On-line firmware and software upgrades.

Application of Advanced Inverter Controls

Some of the main problems of integrating PV plants are dynamic reactive power requirements and power output smoothing during partially cloudy days, as shown in the previous figures.

In order to facilitate large-scale integration of distributed renewable energy sources into the grid, it is critical for such generation to perform load-following functions. Some load-following functions such as voltage support and reactive power supply can be achieved by appropriate control of PV inverters. Other functions, such as frequency regulation support and spinning reserve can be addressed by coupling PV and other DRER with energy storage capabilities. In micro-grid applications these advanced PV inverter contol features are very important to get stable system control.

This section presents the concept of Generator Emulation Controls (GEC). GEC is a control scheme under which grid-tied inverter-based DRER is controlled to mimic the behavior and inertial dynamics of synchronous machine-based generation. The objective of GEC is to allow DRER inverters to:

- Supply reactive and harmonic currents to local loads
- Support local voltage stability through Volt/VAr control
- Perform low-voltage ride-through (LVRT)

The GEC concept presents a paradigm shift for PV inverters as it allows:

- Capacity firming: the coordination of renewable energy resources, energy storage, and demand response to create truly dispatchable generation and/or load centers.
- Distributed intelligence and decision making in the grid system. Such distribution minimizes the need for vast communication networks and control centers. It also promotes reconfiguration and self-healing functions.

The basic concept behind GEC is to control DRER inverters in a manner that emulates the characteristics and behavior of traditional generators. GEC features support voltage stability within systems of different sizes: as small as a residential microgrid in intentional islanding mode, and as large as the national grid. Characteristics targeted by GEC are shown in Figure 3. The voltage source, V_s, and inductor, L_s, are the fundamental components of the model, and govern the basic power relationships of the model. The series resistance, R_s, is used to limit dc-current buildup, while the capacitor, C_s, helps absorb load current harmonics.

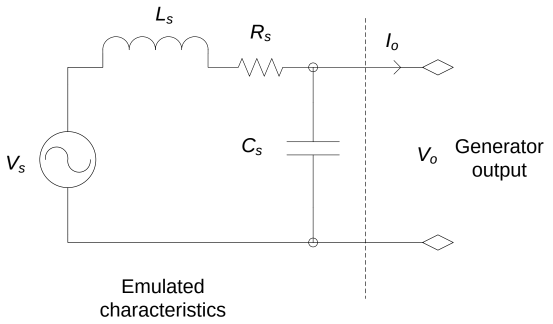

Figure 3 Emulated output characteristics of a GEC-controlled inverter

In steady-state, a GEC-controlled exhibits Volt-VAr and Hz-Watt droop characteristics as outlined in Figure 4 and Figure 5 below. GEC controls direct the inverter to source an increasing amount of reactive power as the line voltage drops. Similarly, GEC directs the inverter to reduce real power output as the line frequency increases. Power output is derated based on the maximum availability of the PV resources, and line frequency. The nominal frequency setpoint of a battery inverter is chosen to cause the battery system to source power when the frequency drops below nominal, and to sink power when the frequency is too high. The frequency setting can also be adjusted during operation to induce battery charging/discharging per system requirements.

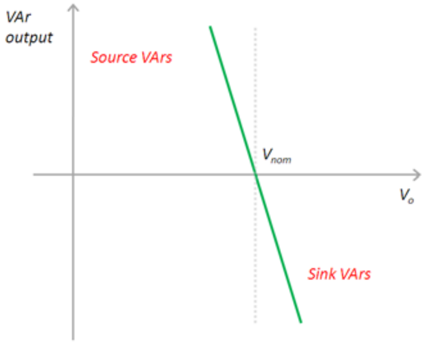

Figure 4 Volt-VAr droop characteristics of the GEC inverter

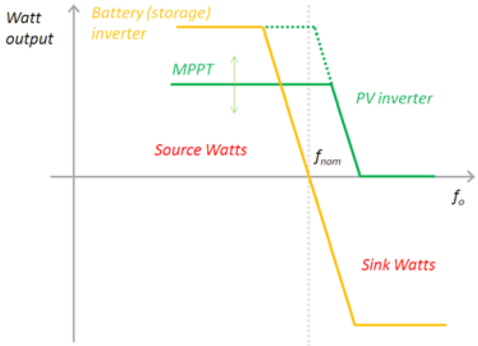

Figure 5 Hz-Watt characteristics of the GEC inverter

Careful design of GEC modules is critical for obtaining stable output of the inverter, and a positive impact on static and dynamic grid stability. Sub-synchronous stability is largely determined by the dynamics of the bus-voltage controller, dynamics of the phase-locked loop (PLL) following the line voltage, slope of droop characteristics, and amount of short-term energy storage and power balancing in the system.

This GEC PV controller is currently tested by Petra Solar under a DOE program as part of the SEGIS program at utilities in the US.

CONCLUSIONS

This paper has presented some of the challenges and benefits of integrating large-scale distributed PV power plants. To mitigate the negative aspects, highly distributed PV generation with Smart Grid features are proposed and implemented. The advanced control of the PV micro-inverters is included where reactive power, LVRT and voltage regulation is available at the micro-inverter level.

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