Integration of Photovoltaic Solar Power – The Quest towards Dispatchability

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Existing photovoltaic (PV) power plants impact the power grid in a negative way due to a lack of voltage regulation, energy storage, forecasting and wide-area communications, measurement, and control. Currently utility-scale distributed solar PV plants on distribution networks have nominal capacities that are compatible with distribution substation MVA ratings e.g., between 5 and 30 MW. Furthermore, PV plants in the 30 to 100 MW power range are currently integrated in transmission networks. The system impacts are discussed, and mitigation solutions are proposed using advanced power converters, energy storage systems, as well as local and remote measurements and forecasting options. Case studies are provided.

Introduction

USA electric utilities embraced the Renewable Portfolio Standards (RPS) proposed by different states a few years ago. RPS penetration levels of 10 to 33% are required in most US states by 2020. Due to the fast developing penetration expansions and associated time lags to build new transmission, most of the existing projects are connected as distributed renewable energy resources (DRER). Large penetration levels of solar photovoltaic (PV) systems will be located on customers' premises across the United States within the next two to three years in the race for receiving federal and state tax incentives before they expire. In the coming years, we could see major changes to the current energy business model due to the rise of large-scale DRER. Electric utilities need to evaluate both the technical and business models to mitigate these impacts.

Potential PV power generation stress to the grid coincides with pressures from other rapidly developing technologies such as electric vehicles, which may call for grid upgrades. At high penetration levels of PV power production, feeders are becoming active circuits and can inject power back to the transmission system. Under this condition, voltage profiles, overcurrent protection, frequency variations, and capacitor bank and voltage regulator operation may evidently be affected. These problems have been reported over the last decade or more in [1], [4], [7], [9], [10], and [12].

Mitigation solutions to some of the expected problems include distributed energy storage, intelligent inverter control, dynamic reactive power support, and coordinated control of fast acting natural gas peaker generating plants. A well-engineered energy storage plant can help alleviate the problems encountered with the integration of intermittent PV power plants. At the same time, it can make PV power plants more cost effective and dispatchable so that they can participate in the energy markets as regular dispatched power plants, including providing ancillary services like frequency regulation and spinning reserves.

Large penetration levels of distributed solar PV generation can be used to alleviate overloads and release capacity of feeders and substation transformers. In a well-designed and operated microgrid that includes distributed PV, system reliability, power quality and grid resiliency can be improved [2].

Characteristics of PV Solar Farm Production

Taking the low capacity factors of solar generation in the existing generation pools into account, the installed capacity of these renewable resources and transmission and distribution (T&D) infrastructure need to increase by 50-100% for the same energy delivery, if no mitigation is included. Furthermore, existing transmission capacity has to be increased by 100% to transport the renewable generation to the load centers without mitigation measures.

Southern California Edison (SCE) and other U.S. west-coast electric utilities now have several years of operational data on large distributed PV generating arrays. For example, SCE installed large 2 MW electric utility scale rooftop PV plants on distribution feeders [4]. The power output from a 2 MW rooftop PV power plant is presented in Fig. 1. The solar power generation profiles are based on actual measurements, one sample per five minutes.

The measurements are performed using local high bandwidth voltage and current transformers, triggered and collected through the Digital Fault Recorder (DFR) and integrated into the electric utility's SCADA network and fed into the PI historian

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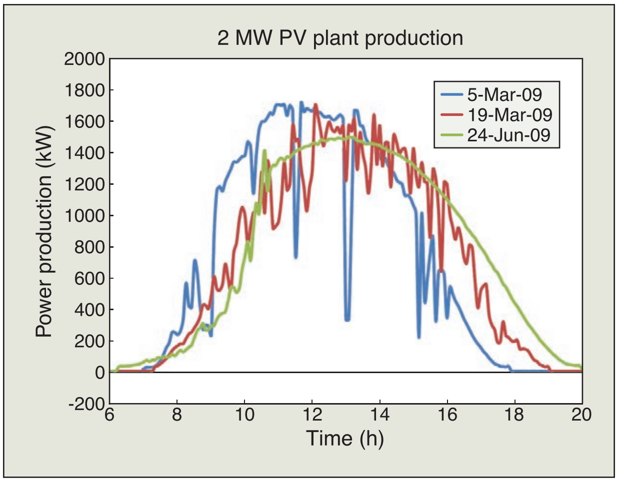

Fig. 1. Two MW PV Solar generation profiles during 3 days in Southern California.

for remote retrieval. Voltage, active and reactive power profiles are collected. Current technologies are able to provide five-second historical data on these PV power plant output profiles.

As Fig. 1 shows, cloud cover and morning fog require fast ramping and fast power balancing. Furthermore, several other solar production facilities are normally planned in close proximity on the same electrical distribution feeder that can result in high levels of voltage fluctuations and even flicker on the feeder. Reactive power and voltage profile management on these feeders are common problems in areas where high penetration levels are experienced.

Characterization of PV Solar Energy Integration Issues

A general description of the integration issues that need to be addressed in regions with high levels of PV solar production is provided in references [1], [7], [9], and [10] and are summarized. Typical transmission and distribution system related problems include:

- Capacity factors in the range of 10 to 20 %;
- Limited firm dispatch capacity of PV solar farms without storage;
- Ultra-fast ramping requirements (400 to 1000 MW/min);
- Most existing PV inverters are not allowed to provide reactive power and voltage support capability;
- Limited PV inverters provide Voltage-Ride-Through (VRT) capability;
- Most PV plants are non-compliant with US Federal Energy Regulatory Commission (FERC) Large Generator Interconnection Procedure (LGIP) and do not provide any ancillary services;
- IEEE-1547 provides incomplete or contradicting guidance in terms of voltage regulation and reactive power support. No VRT and islanding requirements are provided [3];
- Reactive power management and coordination along feeders are not taking high PV production into account/consideration [9],
- Power Quality, especially voltage fluctuations, flicker and harmonics may be outside of the requirements of IEEE Std 519 – 1992 and other standards;
- Increased frequency variations due to the intermittency in weak systems and microgrids;
- Islanding and protection coordination. In feeders where load power consumption is closely matched with PV solar production, islanding is difficult to detect and protection devices do not operate correctly;
- Lack of coordination control of existing reactive power and voltage regulating devices on feeders. Especially capacitor bank controllers and voltage regulator operations are affected; and
- Loss of spinning reserves and system inertia. With increased levels of PV power penetration and retirement of traditional generation, electric utilities are losing spinning reserves and system inertia.

Characterization of Expected Benefits from PV Solar Energy Production

There are also several technical benefits in 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.

Total distribution losses and reactive power requirements can also be optimized through the feeder. An example of such a case is shown in [7], where a total of eight distributed PV plants are installed on a feeder with a combined load of 10 MW distributed throughout the feeder. From the results, at levels of 2 to 3 MW of PV generators, the plants will provide optimized losses and minimize reactive power requirements. Losses are measured across the complete feeder.

The real limit in this case is actually during low loading and high PV production conditions. The PV plants do provide voltage support for the feeder and less capacitor banks are required. In summary, the PV power plants release feeder capacity.

Advanced PV Inverter Controls

To facilitate large-scale integration of distributed renewable energy sources into the grid, it is critical for such generation to perform load-following functions and be more dispatchable. 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 with other distributed resources like energy storage.

Generator Emulation Controls (GEC) [2], [8], is a control scheme under which the grid-tied PV inverter is controlled to mimic the behavior and dynamics of synchronous machine-based generation. The objective of GEC is to allow the PV inverters to: supply reactive power and harmonic currents to

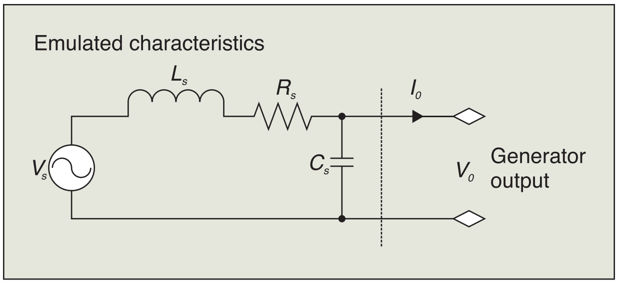

Fig. 2. Emulated characteristics of a GEC PV inverter.

local loads, support local voltage stability through Volt/VAr control, and perform frequency regulation with Hertz/Watt control.

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.
- Distributed intelligence: Decision-making, V-VAR, and frequency regulation are done at the interconnection point. This approach minimizes the need for fast and wide-area communication networks and control centers. It also promotes reconfiguration and self-healing functions with localized measurements.

GEC features support and improve voltage stability within systems of different sizes, both in microgrid and integrated distributed generation. The per-phase characteristics of GEC are shown in Fig. 2. The voltage source V_s and synchronous 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 [8].

In both steady-state and dynamic conditions, a GEC-controlled PV inverter exhibits Volt-VAr, Volt-Watt or Hz-Watt droop characteristics outlined for example in references [8], [12]. GEC controls directly 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 due to over-generation or loss of load. Similarly, the real power can be increased with the drop of frequency due to loss of generation and increased load [8].

Dynamic reactive power can also be provided outside the PV inverter in a dedicated distributed, dynamic VAR controlled device on the low-voltage distribution networks. This approach provides increased performance with GEC-like control modes, as described in the referenced solution [17].

The analysis results to show the impacts of using a Smart GEC type Inverter is illustrated below in Fig. 3 [12]. It is clear that much higher penetration levels are possible on feeders with Volt-VAr regulation before voltage violations become unacceptable as depicted in Fig. 3 (b) compared to (a).

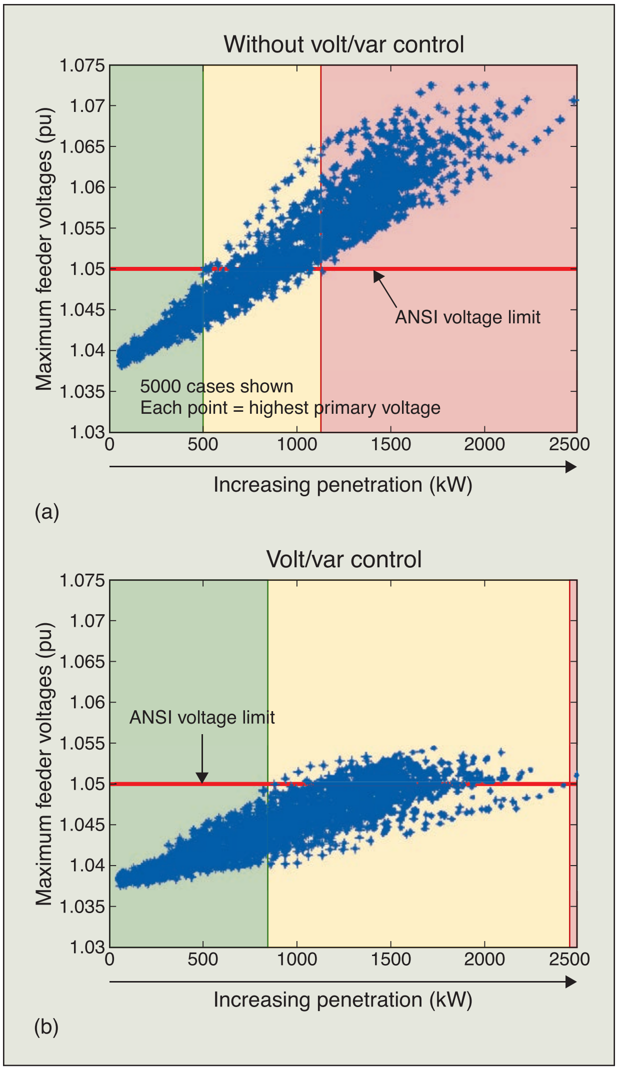

Fig. 3. Impact of using Smart Inverters.

Application of D-STATCOM with Energy Storage

Recently, California passed the United States' first energy storage mandate [5]. This mandate commits all investor-owned electric utilities in the state to collectively buy what the mandate refers to as "1325 megawatts of energy storage" by 2020. This is surprisingly only a power mandate and not an energy mandate. The required power rating provides short-term power balance and grid support, but energy is required to do peak shaving and energy related ancillary services. Ownership, operation, and cost allocation of these energy storage devices are still unclear and should be addressed and supports the need for accurate measurements.

One of the most promising solutions to mitigate these integration issues is by implementing a hybrid fast-acting energy storage and dynamic reactive power device (i.e., Distribution-level Static COMpensator (STATCOM) solution [6]). Several fast energy storage solutions are currently available and the price-points are continuously falling. These include NaS, Li-Ion, Sodium-Ni, VRB, and other battery technologies as well

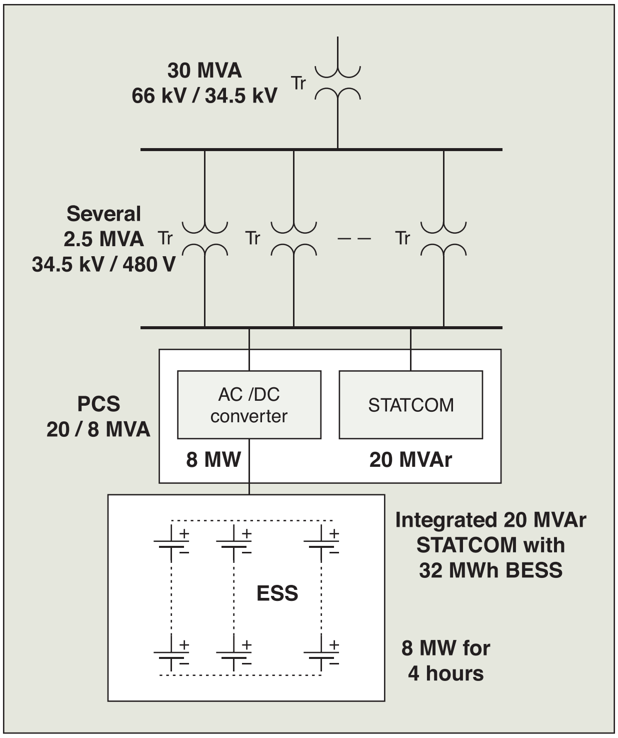

Fig. 4. Basic Schematic of the STATCOM – BESS.

as compressed air (CAES) energy storage solutions [13]. For mitigating the mentioned PV solar integration problems, the energy storage device needs to be fast acting (<1 sec power response time). Furthermore the storage solution needs a storage capability of typically 15 min to one hour. For dynamic reactive power and voltage support, the STATCOM capacity needs to be 20 to 50 % larger than the battery power rating.

Fig. 4 shows an implementation of a STATCOM with battery energy storage system (BESS) application for mitigating the PV integration issues [6]. The BESS consists of a Power Converter System (PCS) and an Energy Storage System (ESS).

The technical characteristics of the main components are described in Fig. 4. This design will be adequate for providing dispatch and PV smoothing support for a 50 to 100 MW PV power plant [6]. The key functionality and possible revenue streams are calculated for the following mitigation solutions:

- Contingency support in terms of MW and MVAr. The STATCOM-BESS system prevents the system from collapsing for the critical contingencies.
- Voltage regulation support. With the STATCOM-BESS system the voltage recovery after a contingency is improved by 10 to 15 %.
- Improved fault voltage ride-through (VRT) support on PV inverters.
- A 75 MW PV Power plant can be dispatched an hour ahead.
- Regulation ancillary services, like spinning reserves can be provided.
- Large T&D upgrades to the PV facility can be postponed for several years.
- Curtailments of a remote PV solar farm are minimized up to four hours.

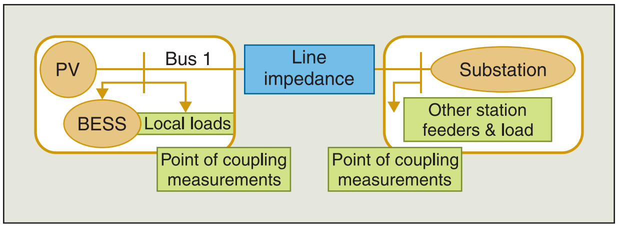

Fig. 5. Integrated BESS and PV Array on Rural Distribution.

It is important to use the BESS system to provide several value streams, like frequency regulation, delayed capital investments, minimizing resource curtailment and reactive power support, to make the PV power plant more cost effective. This includes the net present value (NPV) of the avoided cost in the delay of upgrading the transmission line. Having totaled the yearly-avoided cost for the investment of the different value streams with respect to a possible $25 M investment in a hybrid BESS / STATCOM application can provide a return on investment (ROI) of about 13%. Other additional valuable features not included in the ROI, include voltage support, improved voltage ride through (VRT) and reduction of peaker generator plant maintenance costs. The BESS helps to minimize start-and-stop operations of these peaker plants during regulation services.

PV with BESS Integration Case Study

In an electric utility demonstration installation, on a rural feeder the total connected feeder capacity is 30.5 MVA at 12.47 kV [9]. The system level impacts at different PV penetration levels are investigated with some recommended mitigation measures in the referenced paper. On this feeder, there is also a 1 MW PV array installed, a 1 MWh / 250 kW Energy Storage System (ESS) with a 1.2 MVA Power Converter System (PCS) that form the complete Battery Energy Storage System (BESS) (Fig. 5). The BESS system is installed at the same location as the 1 MW PV array.

The practical Point of Common Coupling (PCC) and substation measurements include voltage, power and recently time-synchronized phasors or Synchro-Phasors, where added to provide real-time phasor information to mitigate, among others unintended islanding of the distributed PV generation. The goal for the BESS is to mitigate any voltage profile and intermittency issues back to the substation, but also help to mitigate unnecessary voltage regulator operations along the feeder. Different ancillary services are investigated for the BESS, including energy arbitrage (to buy and store energy at low prices and discharge and sell back at higher prices), PV smoothing, voltage regulation and frequency regulation.

The PCS is oversized to perform the charging-discharging as well as reactive power support at the PCC. Local and remote measurement signals, at the PV source, substation and along the feeder is used to minimize system impacts and coordinate reactive power resources. Results for the active and reactive power control options are shown in Fig. 6 and Fig. 7 to mitigate the fast PV power ramp rates and provide voltage regulation at the same time.

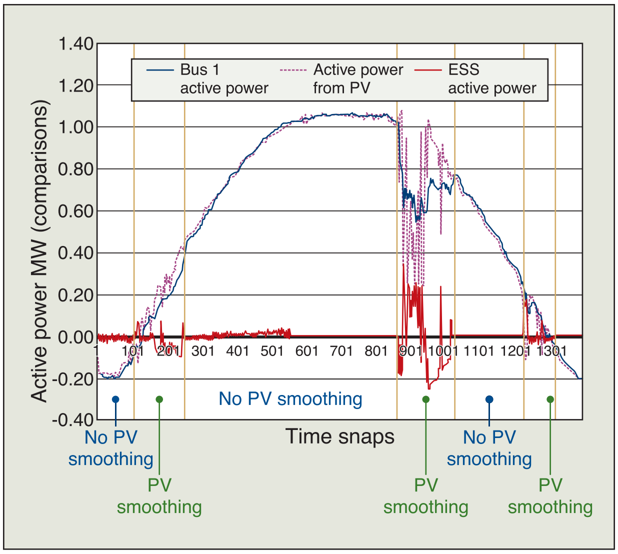

Fig. 6. Mitigating PV intermittence and limit fast ramp rates.

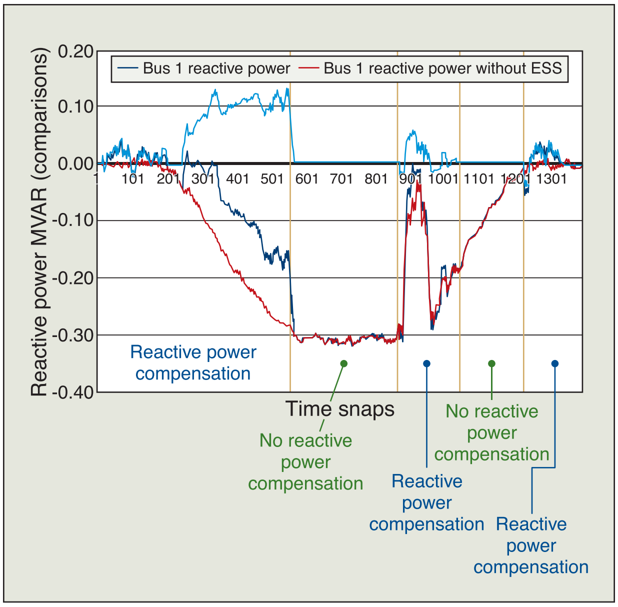

Fig. 7. Reactive power injection to mitigate voltage profiles. (Light blue line is the injected reactive power.)

It is clear that the BESS system provides PV smoothing and limits the fast acting ramps from the PV power plant, as shown in Fig. 6. The BESS uses the reactive power generated, shown in Fig. 7, to mitigate voltage profiles.

PV Inverter Smart-Islanding

Distributed Generation islanding detection and control are particularly important in the measurement and control of PV inverters. For most of the existing approaches, PV inverters make islanding decisions using local data, such as frequency and voltage, without using wide-area information. Wide-area information is however available from synchrophasors and provides the measurements needed to improve these methods [15].

Synchrophasors improve islanding detection methods because wide-area information is available to each inverter. Using information obtained from a larger area results in better control decisions. The communications requirements are simplified because, within the wide area, only a few selected signals need to be monitored. Similar to the anti-islanding case, providing the PV inverter with time-aligned, wide-area information opens new opportunities to use this information for improved control algorithms. This is a very important area in instrumentation, measurement, communications, and control of PV systems.

Solar Resource and Load Forecasting

With higher penetration levels of distributed PV generation and the quest to make PV power plants behave similarly to traditional generating plants and participate in the energy markets, forecasting is becoming critical to the operations of an electric utility [14]. Previously forecasting was mainly related to load electricity demand since most generation was fully dispatchable.

As an example, a feeder-level virtual power plant (VPP) that leverages innovative smart GEC type PV inverters and an innovative energy-management and trading solution need fast PV resource forecasting (15 to 30 min) to participate in transactional energy markets and operate in a microgrid. Such a system will combine these resources with an advanced distributed control framework as well as energy-storage and volt-VAr optimization technologies that will jointly allow distributed photovoltaic (PV) assets to intermittently and locally communicate with each other and their distribution and transmission networks.

Neural Network based forecasting and measurement techniques show a promising approach to derive sub-hourly site-specific irradiance forecast as a basis to predict PV power output [16]. Hourly forecasts can be generated from web-based weather forecasts. Moreover, localized insolation measurements and using data analytics with pattern reconditioning algorithms can forecast sudden cloud cover impacts on power production.

Accurate and fast solar forecasting will also help to minimize expensive energy storage requirements and can improve the performance of smart GEC-type inverters and VAR devices with a coordinated P-Q control approach. Currently, accurate and fast irradiance measurements and pattern reconditioning algorithms are of key importance.

Conclusions

This paper has presented some of the integration challenges and benefits of integrating large-scale PV power plants. The value of dynamic reactive power support, fast acting energy storage and PV resource forecasting help to alleviate some of the problems encountered with integrating intermittent solar power plants on T&D systems. Local and remote measurements, including synchro-phasor measurement units, irradiance-forecasting measurements, together with robust and secure communication networks are required to minimize system-wide impacts of PV solar power generation and make PV power generation more dispatchable.

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