Key Needs and Solutions for Solar Power Monitoring

Why Solar Power?

As pointed out in the article "The History of Solar," published by the U.S. Department of Energy, solar power is not new. It has been in use since the 7th century B.C. Originally the power of the sun was magnified using glass and mirrors to make fire and light torches. The article dates the first modern use of solar power to 1767, when Horace de Saussure, a Swiss scientist, built the first solar collector.(United States Department of Energy)[i]

MarketWatch Guides points out that the U.S., "nationwide solar capacity exceeded 135,700 megawatts (MW) as of late 2022" and predicts that "more than 1 in 7 U.S. homeowners will have solar panels on their roofs by 2030." (David and Addison, 2023)[ii] A major advantage of using solar energy is that it is a freely available, renewable resource. It is speculated that we will have a steady, limitless supply of sunlight for another five billion years. In fact, every 60 seconds the earth's atmosphere receives enough sunlight to power the electricity needs of every human being on earth for a year.

Solar energy is clean. After the solar photovoltaic (SPV) technology equipment is constructed and put in place, solar energy does not need fuel to operate. It also does not emit greenhouse gases or toxic materials. When solar panels eventually break down (they have a projected lifespan of over 20 years), most of their materials can be recycled and used again. Using solar energy can drastically reduce the negative impact we have on the environment.

How Well Does Solar Power Integrate Into the Utility Grid?

Small-scale SPV systems that are used to power one or more buildings may not be connected to an electrical utility. Larger residential and commercial locations with SPV systems may act as both a load and a source, depending on whether they are supplying excess energy to the grid (at the substation level) or drawing energy from the grid. Large scale solar farms and utility grade SPV systems supply their solar-generated power into the existing electrical grid at the transmission level. There are several considerations when solar-generated power is connected to the traditional electrical grid. Among other things, solar power's unique voltage profile and frequency can have effects on the utility power supply's quality and reliability.

Power Quality Challenges in SPV Systems

Power quality (PQ), the consistency, stability, and reliability of electrical power**,** is essential for utilities and consumers alike. All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems. The electrical device might be an electric motor, a transformer, a generator, a computer, a printer, communication equipment, or a household appliance. All these devices and others react adversely to power quality issues, depending on the severity of PQ problems. Good power quality allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy.

Since these power quality issues can decrease the efficiency and longevity of the distribution transformers, voltage regulators, capacitors, and other power distribution equipment, they must be addressed. Any integration of renewable energy sources to the grid must meet standard power quality requirements. (Central Electricity Authority, 2018)[iii] The following sections explore some of the SPV power quality challenges, from the standpoint of both residential/commercial systems and large-scale SPV systems.

Residential and Commercial SPV System Challenges

<u>Waveform Distortion (Harmonics and Interharmonics)</u>

The main PQ challenge for residential/commercial SPV systems is harmonics and interharmonics. The IEEE 1159 – 2009 standard defines harmonics as "sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency; usually 50 Hz or 60 Hz). Combined with the fundamental voltage or current, harmonics produce waveform distortion. Harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system." (IEEE 1159, 2009)[iv] High harmonic currents can cause premature failures in motors and transformers as well as sensitive electronics.(Sagl, 2019)[v]

SPV systems have inverters, which are power electronic equipment that uses pulse width modulation (PWM) switching to convert the direct current (DC) generated by the SPV system into alternating current (AC), which is used in the electrical grid. The process used for conversion from DC to AC is one of the main causes of harmonics in SPV systems. To convert a DC current to an AC current with the strength and frequency needed for utility use, PWM switching regulates the on/off status of semiconductor switches, such as insulated-gate bipolar transistors (IGBTs). Due to the rapid changes in voltage and current, PWM switching introduces high-frequency noise and harmonics into the current.

The main problem with harmonics generated by the inverters is the high frequency electromagnetic noise they generate around cables. When solar power is being introduced into the electrical grid, it must be as close to the utilities' power quality as possible. IEEE 1547, which outlines the rules for the connectivity of distributed energy resources with electric power systems, is one of the standards that defines the acceptable harmonic content of SPV inverters. This standard restricts the output current's total harmonic distortion (THD) to 8% for all harmonics up to the 50th order and 5% for individual harmonics. Additionally, IEEE 1547 mandates that the SPV inverters cannot introduce any DC current into the grid.

External filtering, often with an LC filter, is typically used to reduce the harmonics and noise produced by inverters. "The LC filter is used to limit the rate of rise of the inverter output voltage and reduce common mode noise to the motor."(Habetler, Naik, and Nondahi, 2002) [vi] The LC filter is made up of an inductor (L) and a capacitor (C) that are linked in series or parallel. The LC filter produces a resonance at a particular frequency, which can reduce the PWM modulation frequency and its harmonics. The system's power factor can also be increased, and the output voltage waveform can be rounded off by the LC filter.

High Voltages and Phase Imbalance

Many residential and most commercial SPV systems generate single phase electricity, which is connected to the utility's secondary voltage. The single phase voltage from the SPV system can cause high voltages for other customers connected to the same secondary voltage. If voltages from the SPV system are high enough and the single phase loads are not evenly distributed, the result can be phase imbalance, which can damage three phase motor loads. Unbalance in a motor causes it to overheat, which can break down the oil and grease in the motor bearing and cause the motor windings to be derated or to fail.

Intermittent Nature of Solar Power

As more SPV systems are integrated into the electrical grid, operators will need to be aware of, and able to respond quickly to, changing SPV system capability due to weather changes, i.e., cloud cover. "Since weather can change quickly and unpredictably, high penetration requires grid operators to be flexible and quickly react to new conditions and production patterns using additional energy to balance supply and supportive actions such as frequency regulation and voltage support. Failure to do so potentially results in power shortages and blackouts."(Min, 2022)[vii]

Transients in Solar Equipment Voltage

Transients are bursts of energy in an electrical distribution system. Transients have very high voltages and generate extremely high current in the electrical circuit for the short time they occur (which can be as short as several millionths of a second). A major source of transients in SPV systems is lightning strikes. High speed transients can have adverse impacts on the SPV system itself, as well as electronic devices.

Utility Grade SPV Challenges

Utility grade SPV systems are typically connected to the utility distribution system’s primary and usually produce 1-15 MW, depending on the distribution voltage. Its voltage is always three phase and therefore doesn’t create an imbalance, but it can create voltage rise. Large scale solar farms are connected to the utility’s transmission system.

VARs (Reactive Power)
The main power quality challenge for utilities is the effect SPV systems can have on reactive power (VARs). “Reactive power…is needed to maintain the voltage in the system, provide magnetizing power to motors and facilitate the transmission of the active power through the AC circuit.” (GSES,2015)[viii] The primary disruption to the grid from SPV systems is a loss of VARs. Inverters that cause a voltage rise can act as a motor and consume VARs to bring the voltage back down (through fixing power factor or volt/VAR curves). The voltage rise caused by the injection of real power can also turn off voltage controlled utility capacitor banks, causing a shortage of VARs.

Reactive power is essential to the smooth running of the grid. “Electrical power is maximized when voltage and current are synchronized. However, there may be times when the voltage and current have delays between their two alternating patterns like when a motor is running. If they are out of sync, some of the power flowing through the circuit cannot be absorbed by connected devices, resulting in a loss of efficiency…utilities supply reactive power, which brings the voltage and current back in sync and makes the electricity easier to consume.” (Solar Energy Technologies Office)[ix] When not enough reactive power is being supplied by the SPV system, the utility must supply it from its transmission system. This causes a voltage drop on the low side of the substation transformer, leading to poor efficiency and wasted energy.

For solar farms, utilities may require the solar farm’s inverters to perform ride through functions during faults, i.e., inject VARs when the voltage gets too high or low.

Potential Loss of Revenue through Utility Conditions

Solar farms make their revenue from selling energy to the utility. If the voltage rise in the grid is too high, solar farms must trip off or curtail their output, causing them to lose revenue.

Islanding

If the utility trips the line, the solar farm needs to disconnect and wait until good voltage has been restored for five minutes. If the solar farm does not disconnect when they should, a dangerous islanding condition can take place, in which the solar farm "is still supplying power to the grid while the electric utility is down." (De Rooij)[x]

Strategies for Combating SPV System PQ Challenges

- Waveform distortion (harmonics and interharmonics): The method of measuring and analyzing the system's harmonic distortion is known as harmonic analysis. Harmonic analysis can assist operators to pinpoint the causes and consequences of harmonics as well as identifying the best methods for mitigating them. Power quality monitoring conducted by Class A power quality meters is necessary for the electrical grid, and specifically for power quality issues that can arise with renewables such as solar power. The Nexus® 1500+ and Nexus® 1450 power quality meters provide magnitude and angle up to the 127th order harmonics in real time and 511th order post-processing. All known harmonics orders are easily captured and analyzed by the Nexus® meters. And the EnergyPQA.com® AI based energy management system provides PQ and harmonic direction, so operators can determine if the harmonics are due to source or load.

- High voltages and phase imbalance: The Nexus® 1500+ and Nexus® 1450 meters provide unprecedented accuracy for providing voltage unbalance readings, resulting in immediate understanding of voltage unbalance issues. This understanding leads to the appropriate steps to balance voltage and prevent damage to motors and other vulnerable equipment.

- Intermittent nature of solar power: The Shark® series of multifunction power and energy meters have multiple options for communication of real time readings and limit alarms directly, through SCADA, via the Internet, or viewing in the Cloud. This information enables operators to respond quickly to changing SPV-grid conditions.

- Transients in solar equipment voltage: The Nexus® 1500+ power quality meter has a 50 MHz high-speed transient capture rate, which lets it capture events other meters miss. Being able to view and understand the transient event helps SPV and grid operators respond correctly.

- VARs (reactive power): The CommunicatorPQA® energy management application used with any of EIG's power quality meters gives you real time readings for real power, reactive power, and active power. Using this information, operators can manage real and reactive power to maintain a reliable and efficient electrical grid. For solar farms, waveform capture performed by power quality meters and analyzed by EIG's energy management software can verify that the solar farm is injecting VARs correctly.

- Need for revenue accuracy: Solar farms can use EIG's revenue accurate meters to document their loads and prove their loss of revenue to the utility. The utility can also benefit from having a revenue accurate meter at the solar farm. In addition, the solar farm can use the waveform recording capability of the meter to prove that high voltage under normal conditions is limiting their output and their revenue.

- Islanding: EIG's PQ meters can record waveforms of events so that the solar farm is aware of the grid conditions and able to respond to them appropriately, e.g., disconnecting when the line is tripped.

Conclusion

Solar power is a rapidly growing energy resource. It has multiple advantages for both the consumer and producer/distributor of electricity. It also presents unique challenges, especially for maintaining the reliability and quality of power in the electricity grid. Using advanced PQ meters and energy management software, SPV and grid operators can view real time readings, receive limit alarms, monitor trends in the data collected, identify weak points in the system, and plan equipment service and replacement, rather than dealing with costly and interruptive downtime in the event of a failure.

Notes

[i] "The History of Solar," U.S. Department of Energy, accessed 6/21/2023, https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf.
[ii] "Top Solar Energy Facts and Statistics of 2023," *MarketWatch Guides,* Leonardo David, Tori Addison, accessed 6/21/2023, https://www.marketwatch.com/guides/home-improvement/solar-energy-statistics/.
[iii] "Solar PV (SPV) System for Power Quality and Safety Issues," Central Electricity Authority, 2018.
[iv] "IEEE Recommended Practice for Monitoring Electric Power Quality," IEEE Std. 1159™-2009, IEEE Power & Energy Society.
[v] "Recognizing and Combating Power Quality Issues in Solar Power Systems," "PV Magazine," Andrew Sagl, September 5, 2019.
[vi] "Design and Implementation of an inverter output LC filter used for dv/dt reduction," *IEEE Transactions on Power Electronics*, Volume 17, Issue 3, May 2002, T.G. Habetler, R. Naik, T.A. Nondahi.
[vii] "Integrating Solar Energy into the Grid Challenges and Remedies," January 13, 2022, Ye Min, accessed 6/21/2023, https://www.linkedin.com/pulse/integrating-solar-energy-grid-challenges-remedies-ye-min/.
[viii] "Power Factor and Grid-Connected Photovoltaics," Global Sustainable Energy Solutions, 2015.
[ix] "Solar Integration: Inverters and Grid Services Basics," Solar Energy Technologies Office, accessed 6/28/2023 from https://www.energy.gov/eere/solar/solar-integration-inverters-and-grid-services-basics.
[x] "Islanding: what is it and how to protect from it," Dricus De Rooij, accessed 6/30/2023, https://sinovoltaics.com/learning-center/system-design/islanding-protection.