POWER QUALITY ASPECTS OF SOLAR POWER – RESULTS FROM CIGRE JWG C4/C6.29

Jeff SMITH
EPRI – USA

Sarah RÖNNBERG
Luleå University of Technology – Sweden

Math BOLLEN
Luleå University of Technology – Sweden

Jan MEYER
TU Dresden – Germany

AnaMaria BLANCO
TU Dresden – Germany

Kah-Leong KOO
PB World – UK

Daudi MUSHAMALIRWA
Alstom – France

ABSTRACT

The increasing use of solar power connected to the public grid and the associated concern for deteriorating power quality triggered the formation of a joint working group with the aim to describe and quantify this impact.
The WG formed in 2012 as a joint C4/C6 effort, formed to examine the power quality aspects of solar power, specifically addressing a number of phenomena, all which will be discussed in this paper.

INTRODUCTION

There has recently been a massive increase in the amount of PV installations connected to the grid, and this trend is expected to continue during the coming years. Not only are the numbers of PV installations increasing but also the sizes of the installations. PV installations can be from a few kW to tens of MW. With large numbers of PV plants under construction and being planned in many countries, their impact on power quality in the network is becoming of concern to grid operators. The following power-quality disturbances have been covered by this working group:

- Characteristic harmonics as well as low-order non-characteristic harmonics,
- Supraharmonics (any type of waveform distortion of voltage and current between 2 and 150 kHz),
- Fast voltage variations (time interval of less than 10 minutes) induced by variations in power production.
- Slow voltage variations (time interval of 10 minutes and longer) induced by variations in production,
- Overvoltages induced by PV power production,
- Flicker performance from various PV installations,
- Voltage unbalance due to single-phase connected PV installations,
- Sudden disconnection and reconnection of PV, particularly transient overvoltages, temporary overvoltage, steady-state overvoltage and inrush currents

HARMONICS

PV inverters, which are available on the market today, utilize power electronics based on self-commutating techniques at high switching frequencies (supraharmonics). Consequently, the harmonic emission at frequencies below 2 kHz is usually low compared to other equipment using line-commutating circuit topologies. However, measurements have shown that harmonic emission is still a significant issue for individual inverters and PV installations.

Findings

The harmonic current characteristic of individual PV inverters (all with a power rating below 10 kW) varies between different models and manufacturers as can be seen in Figure 1.

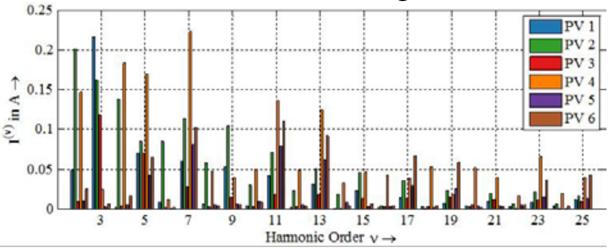

Figure 1 Current harmonic magnitudes of six different PV inverters operating at rated power under sinusoidal grid voltage

Magnitude and phase angle of the harmonic currents depend on many factors, like supply voltage distortion, output power and harmonic network impedance. In most cases, highest harmonic currents (in absolute value) are observed at 100% output power. Consequently neither general models, nor simplified constant current source approaches are sufficient for realistic simulation studies. This issue is also addressed by the CIGRE/CIRED working group C4/B4.38 on network modeling for harmonic studies.
Harmonic magnitudes and phase angles are important for realistic studies of cancellation effects between PV inverters / PV installations and other installations. If larger PV plants are built using multiple PV inverters of the same model, the harmonic currents of individual inverters can add up almost arithmetically [1], even at higher harmonic orders. The standard summation exponents (e.g. according to IEC 61000-3-6) are not suitable in such cases.
PV inverters impact harmonic network impedance. Particularly in larger PV installations the grid-side filter circuits can cause significant resonances at low frequencies. The resonant frequency decreases with increasing number of inverters. Consequently, input impedances of PV inverters should be considered in

harmonic studies.
Under specific circumstances PV inverters can get unstable and trip. This has been observed along with high voltage distortion due to network resonances, which are usually accompanied by high source impedances.
The analysis of network measurements has shown that particular harmonic voltages at orders higher than 25 can be significantly attenuated by the distribution transformers. In case of distributed PV inverters in LV networks the impact on the harmonic voltage in the network (decrease, increase or no impact) is usually not consistent and differs between harmonic orders. It is determined by the existing potential of cancellation with other equipment and a possible filter effect of the grid-side circuit of the PV inverters.

Recommendations

For realistic harmonic studies the dependency of harmonic currents of PV inverters on supply voltage distortion and network impedance as well as the input impedance characteristic, which can cause resonances in the networks, has to be considered.
In case of centrally located PV inverters (e.g. in large PV plants), particularly in case of similar inverter models, harmonic currents should be added arithmetically independent of the harmonic order. For distributed PV inverters (e.g. in residential areas) the aggregation with residential equipment should be taken into account.
Particularly in case of a high share of PV inverters in a network or in case of large PV plants the risk of high harmonic voltages due to instabilities with multiple controllers should be considered.
Standardization testing conditions and emission limits, especially for the small-sized PV inverters for mass-market applications, should be revised. Setups using only sinusoidal test voltage and no reference impedance (like in IEC 61000-3-2) do not reflect the real behavior of the inverter in the network and do not consider the different sensitivities of the PV inverters to supply voltage distortion or network impedance at all. Even the specification of a defined input impedance characteristic of PV inverters for certain frequency ranges could be considered for future revisions of the respective standards.
Measurements of PV inverters or PV plants in laboratory or field should include harmonic magnitudes and phase angles. Knowledge about complex harmonic currents can significantly improve studies of cancellation effects or the separation between customer-side and network-side contributions to the harmonic emission levels.

Open Issues

More comprehensive knowledge about the harmonic current characteristic of medium-sized and large-sized PV inverters is needed, particularly in order to improve the accuracy of respective harmonic studies.
Suitable, manufacturer-specific harmonic models capable to be used for studies of harmonic emission, harmonic instabilities or harmonic resonance are still missing. This includes also aggregated harmonic models, e.g. for representing a PV plant consisting of multiple PV inverters. Measurement-based models are a possible approach to improve the model accuracy compared to the simple models based on constant current sources. However, the superposition of the different impact factors, like supply voltage distortion, network impedance, magnitude of supply voltage and output power of the PV-inverter is still not validated.
Comprehensive knowledge about the possible impact of PV inverters on the harmonic network impedance, particularly their contribution to harmonic resonances in public LV grids, is still lacking.
General conclusions about the impact of PV power on the harmonic levels are not known and might even not be possible. It strongly depends on the size of PV installation, harmonic impedance at the connection point and the inverter models. A significant increase of harmonic levels on a large scale has not been observed.

SUPRAHARMONICS

The term “supraharmonics” is used to refer to any type of waveform distortion of voltage and current in the frequency range between 2 and 150 kHz. Supraharmonics related to PV inverters consists of residues from the switching and are present as long as the PV is producing power.
From a large number of measurements done mainly in Sweden and Germany it is seen that the emission from single phase PV inverters (installed power below 4.6 kW) occurs at frequencies between 15 kHz and 20 kHz. For three phase inverters used for high power units the switching often takes place at a lower frequency starting at around 2 kHz [2][3]. More recently smaller three phase inverters started to appear at the market with switching frequencies around 20 kHz.

Findings

PV inverters are a source of supraharmonics. Measurements show that the emissions can be found at frequencies up to 20 kHz. The emission from PV inverters (as well as for other low voltage devices) is greatly affected by neighboring devices; this has been shown for inverters connected at the low voltage network in the following ways:

- The presence of neighboring supraharmonic sources can cause secondary emission at the PV inverter.
- Changes in source impedance due to connection and disconnection of neighboring devices will impact the primary emission from a PV inverter.
- Voltage harmonics (3rd, 5th and 7th) have shown strong correlations with the supraharmonic emission from a PV inverter.

Recommendations

More efforts from network operators as well as from the research community should be put towards harmonic studies covering the whole frequency range up to 150 kHz. Small installations at LV (i.e. roof top installations) and larger installations at higher voltage levels (i.e. solar plants) need to be treated differently with regards to supraharmonic interaction. Solar plants are often connected to medium voltage with few other loads connected and any interaction will likely take place within the plant between inverters. Roof top installations are connected at the customer side of the meter and therewith close to other LV devices. Possible interaction between the inverter and other devices is hence more likely to occur for small installations.

Open Issues

The lack of a good method to distinguish between primary and secondary emission [4] is a serious barrier when studying emission from PV installations and other modern types of devices or installations.

It is unclear if the impact from neighbouring devices shown for PV inverters connected at the low voltage network will be the same within large solar plants.

FAST VOLTAGE VARIATIONS

This section will address fast voltage variations which are variations in the rms voltage with a duration of less than 10 minutes. The connection of PV installations on a distribution network will result in a voltage rise at the generator terminals. The change in voltage magnitude is determined by the active and reactive power injections as well as the equivalent short-circuit impedance at the terminals of the PV installation. A number of factors contribute to the variability of PV power production, including

- Size and layout of PV plant,
- Cloud enhancement
- Fixed-axis versus tracking systems,
- Climate characteristics,

And next to this, fast voltage variations can also be due to variations in reactive power.

Findings

Geographic size and layout have the greatest impact on output variability from a PV installation. The larger installations (in terms of capacity and geographic footprint) exhibit slower ramping compared to their smaller-sized counterparts.

Relating the PV installation ramping characteristics to voltage fluctuations is dependent on the grid-connection point and the associated grid impedance (especially the resistance). Simple calculation methods for determining impact of PV installations at a single point of connection are provided in the WG brochure [6]. Distributed PV installations across a network require more detailed network modeling.

Recommendations

When examining voltage impacts due to output variability of a PV installation, realistic variation data with respect to the size of the installation has to be used. For example, utilizing measurement data from a 1 kW system and scaling the output to a much larger 1 MW system will result in overestimation of PV ramping impacts.

The output distribution characteristics provided for various sized PV installations in [6] can be used for examining the impact of sudden changes in PV output on voltage.

Open Issues

There are no general aggregation rules for multiple PV systems connected to the same distribution grid.

SLOW VOLTAGE VARIATIONS

Slow voltage variations are variations in the rms voltage with a duration of 10 minutes and longer. The effect of these is relevant to voltage control strategies – highly affected by changes in power flow from medium to low-voltage substations where load and generation are installed. At a time interval of 10 minutes and longer, the impact of PV installations on voltage variations is due to

- The daily movement of the sun over the sky;
- Changes in amount of cloud cover
- Shading by fixed objects

Findings

The presence of PV installations in distribution networks will result in additional contribution to the variations of voltage magnitude at time interval of 10 minutes and longer. The average voltage magnitude will increase, but the voltage magnitude will also show more variations. This includes daily variations, annual variations and intra-hour variations due to passing clouds. Also rare but predictable solar eclipses will result in additional variations in voltage magnitude.

The presence of PV may also lead to an increase or decrease in operations of mechanically-switched regulation equipment (OLTCs, regulators, switched capacitor banks) depending upon coincidence of solar production and load.

Recommendations

Studies are needed to quantify the consequences of coincident and non-coincident solar production and load profiles on voltage-magnitude variations. A good starting point will be the gathering of long-term data on voltage-magnitude variations at locations with and without solar power, as well as the analysis of historical data.

Open Issues

The net impact of solar and load coincidence or non-coincidence on voltage regulation equipment is not understood in a quantitative way yet.

OVERVOLTAGE

The connection of a PV installation (or any type of distributed generation) to the distribution network will result in a voltage rise at the terminals of the generator and elsewhere in the distribution grid. The voltage when the PV produces power is higher than when the PV does not produce power.

Findings

The presence of PV installations in distribution networks will increase the probability of overvoltages. The setting of the overvoltage protection, as part of the anti-islanding protection, has played an important role in preventing sustained overvoltages which could lead to damaged equipment. In many countries, the required settings require that the PV inverters trips before the regulatory overvoltage limits are exceeded. However, use of anti-islanding protection for voltage control could lead to nuisance tripping of PV generation.

Recommendations

The overvoltage settings, as part of the anti-islanding protection should consider the impact on the operation of the PV installations during periods with high production and low consumption. Network planning methodologies for control of voltage levels that consider hosting capacity for PV generation based on relative voltage margins as well as advanced voltage control from inverters which reduces output before overvoltage occur should be considered.

Open Issues

Should the regulatory limits be based on 100% values or are there arguments to allow the overvoltage limits to be exceeded during a certain percentage of the time?

FLICKER

One area of concern with regards to PV production is the potential to cause flicker due to the variations in output of the generation. Experience from high-penetration PV neighborhoods are discussed in [5] and note that flicker has not been an issue in these installations. Figure 2 shows the P_{st} for a 20 kW installation in Northern Sweden, with the PV system scaled to 6 kW, during a day with varying cloud cover in June [7]. The maximum value of the P_{lt} calculated in this case was 0.036.

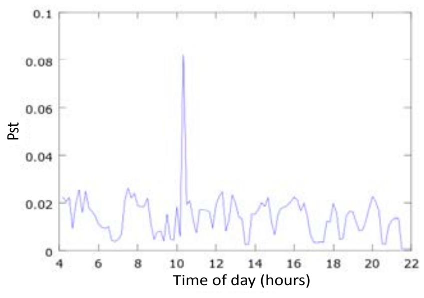

Figure 2 P_{st} for a PV installation in Northern Sweden during a day with varying cloud cover

Findings

Results from literature as well as from analyses of measurements indicate that low levels of flicker can be contributed to the active power production from PV installations. While this increase in flicker is measurable it is not expected to reach unacceptable levels.

Recommendations

While unacceptable flicker levels are not found to be contributable to the changes in active power from PV installations, the results have shown that some installations can in fact cause unacceptable changes in voltage if the capacity of the PV installation exceeds the local hosting capacity of the grid. This change in voltage is slower by nature due to the slow-response time of PV installations relative to frequencies of concern in relation to flicker. This phenomenon is appropriately identified in [6] as slow and fast voltage variations.

Open Issues

Flicker contribution from changes in reactive power has been observed in some PV installations. Analysis should be performed using measurements from additional installations to determine the extent of this phenomenon.

VOLTAGE UNBALANCE

The primary source of voltage unbalance at the distribution voltage level is unbalanced load due to uneven spread of single-phase low-voltage customers to the three phases. The connection of single-phase PV installations will result in an increase of the voltage unbalance. Single-phase units can only be expected in low-voltage networks, most likely with domestic and small commercial customers.

Findings

The hosting capacity for voltage unbalance is only relevant for single-phase units. Large individual PV installations and large numbers of small installations should be treated differently. For large individual units the hosting capacity is obtained from the source impedance at the point of connection (point of common coupling), the existing (pre-connection) unbalance, and the acceptable voltage unbalance.

For small units, calculation of the hosting capacity requires knowledge on their spread to the phases and to the locations. A simple relation has been obtained between voltage unbalance and number of units [5].

Voltage unbalance may be an issue when single-phase units are used. For three-phase units, unbalance should not be an issue. However, it has been mentioned that certain older types of three-phase inverters also exhibit a large unbalance in current. No further information on this has been obtained.

Recommendations

To be able to estimate the hosting capacity, it is important to obtain background measurements of voltage unbalance at many locations including information on the phase angle of the voltage unbalance.

Open issues

Some countries have put requirements on inverters, requiring them to be three-phase above a certain size. Other countries even consider this requirement to cover all inverter sizes. It remains unclear to which extent such requirements are needed.

Single-phase inverters can be connected to the phase in which they give the smallest increase in voltage unbalance. It may even be possible to use PV inverters to compensate the background unbalance. It is however unclear to which extend this is practically possible.

CONNECT AND DISCONNECT

Large PV installations are generally connected to the grid via LV/MV power transformers. In order to compensate the reactive power generated by the network cable capacitance, shunt reactors may be needed at the point of common coupling on the MV system. The connecting transformers, the compensating reactor or the entire PV installation can be switched on and off because of intermittent power output of the source or due to faults. The switching of the PV plant for either normal scheduled operation or for a fault can lead to undesirable overvoltages and currents.

Findings

Transient overvoltages and currents due to sudden connection and disconnection of a PV installation have been documented. Energizing the PV installation MV/LV transformer can result in inrush currents up to 10 times rated current.

Laboratory tests have been performed to assess the duration and magnitude of transient overvoltages created by PV inverters during load-rejection conditions. These tests have shown that the measured maximum load rejection overvoltage did not exceed 2 pu of nominal peak voltage.

Laboratory tests have been performed in order to assess the inverter behaviour during the presence of ground faults once the breaker is opened. Ground fault overvoltages up to 1.6 pu have been observed.

Recommendations

The test results available at this time are based upon single and three-phase inverters of 20 kW and below. Additional testing of larger sized inverters is recommended to determine the full extent of load rejection and ground fault overvoltages.

Additional testing is recommended to consider additional fault conditions, inverter vendor technologies, load levels, and load compositions (e.g, motor loads).

Open Issues

Although different tests on PV inverters are performed by laboratories, there is an absence of acceptance criteria to characterize load rejection and ground faults overvoltages. The tests themselves are not yet standardized.

CONCLUSIONS

A concern with the connection of PV installations is their potential impact on the voltage and current quality in the grid. The creation of this working group should not be seen as a confirmation of any negative impact of PV installations on the grid. Instead, the principal aim of this working group is a mapping and quantification of that impact where it concerns power quality disturbances. Key findings from each of the power quality phenomena have been summarized here. More details can be found in [6]. For each of the disturbances, the emission by PV installations is characterized, as much as possible, based on existing installations. A decision about possible negative impacts can be made most likely only on a case by case basis.

REFERENCES

[1] A. Varatharajan, S. Schoettke, J. Meyer, A. Abart: “Harmonic Emission of Large PV Installations - Case study of a 1 MW Solar Campus”, International Conference on Renewable Energies and Power Quality (ICREPQ), April 2014, Cordoba, Spain.

[2] S. K. Rönnberg, A. G. Castro, M. H. J. Bollen, A. Moreno-Munoz, E. Romero-Cadaval, "Supraharmonics from power electronics converters," in *Proc. of 9th Int. Conf. on Compatibility and Power Electronics (CPE)*, Costa da Caparica, 2015, pp. 539-544.

[3] M. Klatt, J. Meyer, P. Schegner, A. Koch, J. Myrzik, C. Korner, T. Darda and G. Eberl, "Emission levels above 2 kHz—Laboratory results and survey measurements in public low voltage grids," in *Proc of.* (CIRED 2013), *22nd Int. Conf. and Exhibition on Electricity Distr., Stockholm, 2013*

[4] M. Bollen, S. Rönnberg, “Primary and Secondary Harmonics Emission; Harmonic Interaction – a Set of Definitions“, In *Proc. of Int. Conf. on Harmonics and Quality of Power* (ICHQP), Belo Horizonte, Oct 2016

[5] F. Katiraei, M. Konrad, L. Dignard-Bailey, “Integration of Photovoltaic Power Systems in High-Penetration Clusters for Distribution Networks and Mini-Grids.” *Int. Journal of Distributed Energy Resources.* Vol 3 No 3 July - Sep 2007 ISSN 1614-7138.

[6] JWG C4/C6.29 Power Quality Aspects of Solar Power, Technical Brochure 672, Cigre 2016

[7] O. Lennerhag, M. Bollen, S. Ackeby, S. Rönnnberg, "Spänningsvariationer och intermittent produktion“ (Voltage variations and intermittent production, in Swedish), report 14:42, Elforsk, Stockholm, July 2014.