ABSTRACT

This paper deals with the characterisation of the waveform distortion in the operation of grid-connected photovoltaic (PV) inverters. The PV system assessment is based on experimental results. The data elaborated are taken from the measurements gathered at the terminals of individual PV inverters and at the point of common coupling (PCC) between the PV plant and the grid. For the connection of multiple PV inverters to the grid, the peculiar characteristics of the PV plants, allowing for their distinction with respect to the harmonic loads addressed in the literature, are identified and discussed. Specific harmonic and interharmonic models are constructed on the basis of experimental data, indicating the different ways in which low-order and high-order harmonics sum up at the PCC.

1. INTRODUCTION

During the last years, a significantly high increase of Photovoltaic (PV) installations has been recognized in some European countries like Germany and Spain [1, 2]. PV plants are a relevant example of distributed generation [3, 4], and their installation is often encouraged by specific incentives provided by the legislation and/or the regulation of various countries. In particular, most of these incentives are provided as feed-in tariffs [5, 6] or refer to the integration of PV plants into buildings [7, 8].

The main aspects concerning grid-connected PV inverter operation refer to their impact on the distribution system voltage profile and losses, and to the voltage and current waveform distortion [9, 10, 11]. Concerning voltage profile and losses, the specific contribution of PV systems is often relatively limited, since the rated power of the PV systems are much smaller than the short-circuit power of the distribution systems at the Point of Common Coupling (PCC) [11]. Taking into account waveform distortion, the relevant issues are harmonics and interharmonics [12] depending on the interaction between PV systems and the grid at the PCC. In the presence of multiple inverters connected to the grid [13][14], it becomes relevant to characterise the sum of the harmonic and interharmonic components. For this purpose, the summation of harmonic vectors has been addressed in the literature by taking into account the cancellation effect that may arise in distribution networks at different harmonic orders, depending on the phase angles of the harmonic vectors. Both analytical [15, 16] and semi-empirical [17] approaches have been proposed to deal with statistically independent random vectors.

In principle, the analysis of harmonic distortion in PV plants with multiple inverters could be seen as similar to the one carried out for other inverter-interfaced systems, thus applying the above indicated concepts and approaches. However, these concepts cannot be directly extended to address the grid connection of multiple PV inverters. In fact, in the PV inverter operation:

a) the assumption of statistically independent harmonic vectors is not reasonable, since the PV systems operation depends on external variables such as climatic conditions (solar irradiance and temperature), that act as strong linking factors impacting on the operational characteristics of the PV inverter units located in close geographical positions [18][19];

b) the PV inverters installed at a specific site are in many cases of the same manufacturer and characteristics, and could even be of equal size, thus they can exhibit similar harmonic behaviour;

c) in many cases, the PV inverter control adopts techniques like pulse width modulation with high frequency switching, in which most harmonics are moved to harmonic orders higher than the ones typically considered in the power quality standards (i.e., 40) [20][21];

d) all PV inverters are located relatively close to the PCC, so that the supply voltage waveform at the PV inverter terminals exhibits relatively similar shape;

e) the PV inverters are subject to the action of control systems aimed at maximum power point tracking and at providing zero reactive power at fundamental frequency [22]; these characteristics could even successfully reduce the harmonic distortion at the PCC with respect to the one appearing without the PV plant connection;

f) the actual operating conditions are highly variable, making it difficult to draw generalised conclusions and to set up suitable specifications to carry out laboratory tests [23].

The above observations clarify that a specific methodology has to be developed for addressing the case of multiple PV inverters connected to the grid.

In this paper, some harmonic analysis results obtained by using experimental data and by applying dedicated indicators formulated by the authors are illustrated and discussed. Section 2 presents the harmonic and interharmonic indicators and applies them to the measured data. Section 3 contains the concluding remarks.
2. MULTIPLE INVERTERS OPERATION IN PV PLANTS

2.1. Harmonic and interharmonic summation

PV plants of low power rating may be installed in large number in LV distribution systems. In these systems, the PV inverters can be located relatively close to the PCC. The impedance between the PCC and the different PV inverters is relatively small. However, it is not viable to measure simultaneously the currents of all individual PV inverters and the total current seen from the PCC. PV plants in MV and HV systems are characterized by a large number of inverters operated at the same PCC. The total current of the PV plant can also be measured, as well as the current of one individual inverter. However, again a full simultaneous measurement of all the currents of the individual inverters and the total current seen from the PCC is generally not feasible. Thus, it could be useful to characterize the harmonic and interharmonic behaviour of a generic number $N$ of PV inverters connected to the PCC through a simplified but meaningful approach. For this purpose, the approach described in the sequel is based on measuring the current waveforms $i_{h}(t)$ of one of the PV inverters and $i_{hN}(t)$ due to the contribution of all inverters seen from the PCC. Then, the current waveforms are subject to the Fourier transformation to obtain the currents in the frequency domain, for all the harmonic orders $h = 1, \ldots, H$ (with $H = 40$). The resulting currents are $I_{h}$ for one of the PV inverters and $I_{hN}$ due to the contribution of all inverters seen from the PCC. This extends the formulation shown in [19] and [24], in which all inverters are assumed to be of equal type and size, to the case in which different inverters could be installed. The choice of the individual inverter to monitor is arbitrary. More generally, it can be possible to try and monitor different individual PV inverters, if easily accessible together with the total contribution, in order to check the consistency of the results for different monitored cases.

Let us consider the rated power $P_{rIN,AC}$ of the inverters $i = 1, \ldots, N$, where in particular $P_{rIN,AC}$ is the rated power of the individual inverter monitored.

The effect of the presence of $N$ inverters connected to the PCC is represented by calculating, for each harmonic order $h = 1, \ldots, H$, the harmonic summation ratio

$$
\zeta_{h}^{(x)} = \frac{I_{h}^{(x)}}{N I_{hN}^{(x)}}
$$

(1)

The last ratio at the right-hand side in (1) takes into account that the inverters could be different, and its value is $1/N$ if all inverters are equal in type and size, leading to the reduced formulation:

$$
\zeta_{h}^{(x)} = \frac{I_{h}^{(x)}}{N I_{hN}^{(x)}}
$$

(2)

In the definitions (1) and (2), the harmonic summation ratio should belong to the range $0 \leq \zeta_{h}^{(x)} \leq 1$, for $h = 1, \ldots, H$. Conceptually, when the harmonic summation ratio is equal to unity, the harmonic contributions sum up arithmetically, that is, the corresponding current phasors of the various PV inverters at the harmonic order considered are in phase, so that:

$$
I_{h}^{(x)} = \sum_{i=1}^{N} I_{h}^{(x)}
$$

(3)

Conversely, when the harmonic summation ratio is equal to zero, there is a cancellation effect among the whole set of phasors at the corresponding harmonic order. For equal PV inverters, assuming current phasors with the same amplitude, this happens if the current phasors are regularly distributed in the complex plane (with regular phase shifts of $2\pi/N$). However, in practical calculations it could also happen that one or more values of $\zeta_{h}^{(x)}$ are higher than unity. This can be due to the effects of measurement uncertainty, or to the fact that the characteristics of the monitored PV inverter do not correspond to the expected ones.

In addition to these limit conditions, it is possible to identify another condition, according to which the current phasors sum up in an Euclidean way. In this case, the magnitude of the total current is equal to the square root of the sum of squares of the magnitudes of the individual currents, that is:

$$
I_{h}^{(x)} = \sqrt{\sum_{i=1}^{N} (I_{h}^{(x)})^2}
$$

(4)

If all PV inverters are equal, this corresponds to the harmonic summation ratio value

$$
\zeta_{h}^{(x)} = \frac{1}{\sqrt{N}}
$$

(5)

The same considerations used for the formulation of the harmonic summation ratio are used to define the interharmonic summation ratio $\zeta_{\mu}^{(x)}$, referred to the interharmonic order $\mu = h + 0.5$, for $h = 0, 1, \ldots, H$:

$$
\zeta_{\mu}^{(x)} = \frac{I_{\mu}^{(x)}}{\sum_{i=1}^{N} P_{rIN,AC}^{(x)}}
$$

(6)

Considering all PV inverters of equal type and size, the condition (6) becomes:

$$
\zeta_{\mu}^{(x)} = \frac{I_{\mu}^{(x)}}{N I_{\mu}^{(x)}}
$$

(7)
2.2. Experimental assessment of the harmonic and interharmonic summation ratios

The investigation on the harmonic distortion due to the operation of multiple PV inverters connected to the grid has been carried out for three PV systems, here denoted as Plant A, Plant B, and Plant C. The characteristics and data of these systems are listed in Table 1.

The plants are connected through MV/LV transformers to the respective MV distribution system. Plant A and Plant B are connected to the LV system. Plant C is directly connected to the MV system. In each PV system, all PV inverters are of equal type and size.

In each system it has been possible to measure the current waveforms at one of the PV inverters and the total current contribution simultaneously, due to the close connection of the individual plant terminals and the PCC. The current harmonics and interharmonics have been evaluated according to the IEC Std. 61000-4-7 [25] for frequencies up to 2 kHz.

Table 1 Data of the PV Systems

<table>
<thead>
<tr>
<th>System</th>
<th>unit</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed PV power $P_{PV,plant}$</td>
<td>MW</td>
<td>2</td>
<td>1.94</td>
<td>1.06</td>
</tr>
<tr>
<td>Rated voltage at the MV side</td>
<td>kV</td>
<td>20</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Rated voltage at the LV side</td>
<td>kV</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Number of PV modules</td>
<td>--</td>
<td>7046</td>
<td>6528</td>
<td>3200</td>
</tr>
<tr>
<td>Single module rated power $P_{PV,mod}$</td>
<td>W</td>
<td>283</td>
<td>297</td>
<td>330</td>
</tr>
<tr>
<td>Number of inverters</td>
<td>--</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Single inverter rated power $P_{INV,AC}$</td>
<td>kW</td>
<td>250</td>
<td>260</td>
<td>250</td>
</tr>
<tr>
<td>Rated voltage of the single inverter</td>
<td>V</td>
<td>405</td>
<td>405</td>
<td>405</td>
</tr>
<tr>
<td>Number of strings for each inverter</td>
<td>--</td>
<td>84</td>
<td>102</td>
<td>50</td>
</tr>
<tr>
<td>Number of modules for each string</td>
<td>--</td>
<td>12</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Installed power $P_{INV,DC,ins}$</td>
<td>kW</td>
<td>283</td>
<td>300</td>
<td>264</td>
</tr>
<tr>
<td>Max. generated power $P_{AC,max}$</td>
<td>MW</td>
<td>1.75</td>
<td>1.72</td>
<td>0.93</td>
</tr>
<tr>
<td>Short-circuit power (MV) $S_{e,MV}$</td>
<td>MVA</td>
<td>112</td>
<td>142</td>
<td>76.73</td>
</tr>
<tr>
<td>Short-circuit power (LV) $S_{e,LV}$</td>
<td>MVA</td>
<td>21.63</td>
<td>38.2</td>
<td>---</td>
</tr>
<tr>
<td>Voltage level at PCC</td>
<td>--</td>
<td>LV</td>
<td>LV</td>
<td>MV</td>
</tr>
</tbody>
</table>

The harmonic summation ratio for the various harmonic orders considered is shown in Fig. 1. The behaviour of the three PV inverters is consistent. For the lower harmonic orders, the harmonic summation ratio is close to unity, that is, the corresponding harmonics are approximately added arithmetically. For higher harmonic orders, the currents are approximately added in the Euclidean way. The corresponding levels of harmonic summation ratio given by $1/\sqrt{N}$ (that is, 0.378 for the PV System A with 7 inverters, and 0.5 for the PV systems B and C with 4 inverters) are indicated in Fig. 1.

The measurement results of the interharmonics are reported in Fig. 2 for the PV System C (with 4 inverters). In this case, the interharmonic summation ratio is slightly higher than 0.5, so that at first approximation it is possible to apply the Euclidean model (7) to the interharmonics with frequencies below 2 kHz. As a relevant result, the behaviour is similar for all interharmonic orders, differently to what happens to the PV inverter harmonics.

3. CONCLUDING REMARKS

The waveform distortion in grid-connected PV plants has been assessed on the basis of experimental data. The reasons why the aggregated harmonic behaviour from renewable generation is different with respect to the applications with loads generating harmonics (such as personal computers or fluorescent lamps in LV systems, or other equipment with power electronics) have been listed and briefly discussed. The correlated behaviour of the PV inverters depends on the similar impact that the external variables have on PV inverters located in relatively close positions. The investigations indicated that, in the presence of multiple PV systems connected to the PCC, the low-order harmonic currents tend to sum up arithmetically, whereas the higher-order harmonics (indicatively over the 17th harmonic order) and the interharmonics tend to sum up in an
almost Euclidean way. For the harmonics, this result is verified in a similar way both for odd and even harmonics. The harmonic summation properties are relevant to assess the harmonic behaviour of an arbitrary number of PV inverters connected to the PCC by avoiding gathering large amounts of data from the field. In any case, these properties have to be verified in a more general context, on systems with PV inverters of different manufacturers.

REFERENCES