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Harmonic Emission of Large PV Installations Case Study of a 1 MW Solar Campus

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Abstract. Extensive measurements were carried out at a 1 MW photovoltaic (PV) installation with focus on the analysis of harmonic emission both for classical harmonics below 2.5 kHz and higher frequency emission in the range of 2-150 kHz. The installation consists of multiple inverters with different rated power. Beside the measurement of total emission of all inverters, in one part of the measurement the inverters were switched off and on stepwise following a predefined schedule. This provides a comprehensive basis for a detailed characterisation of the interactions between the inverters in terms of harmonic emission. After a description of the measurement setup the paper discusses the total emission of the installation, the dependency of the emission on the supply voltage distortion and the potential of harmonic cancellation due to phase angle diversity between the different inverters. The results enable a better understanding of the harmonic emission behaviour of large PV installations. The paper is intended to be an contribution to the development and improvement of respective harmonic models.

Key words

Photovoltaic inverter, Harmonics, cancellation effect, Higher frequency emission

1. Measurement Setup

The PV installation comprises of nine large inverters with rated power of 100 kVA and eleven small inverters with rated power in the range between 1 kVA and 10 kVA (total output of nearly 50 kVA). All large inverters are three phase while all small inverters are single phase.

For the measurement of low order harmonics, eleven PQ instruments complying with IEC 61000-4-30 Class A were used. The voltage and current spectra (magnitude and phase angle related to voltage fundamental) were measured with each instrument for almost two days using an averaging interval of 150 periods (three seconds). Each of the large inverters, the sum of all small inverters and the total sum of the installation were monitored. Calibration measurements were carried out to assess the accuracy of the PQ instruments. For voltage harmonics larger than 0.2% and current harmonics larger than 0.2 A the error for magnitude is smaller than ±2% and the error for phase angle is smaller than ±1°.

Voltages and currents in the higher frequency range (2 – 150 kHz) were measured at one large inverter (three phases) and four small inverters (each single phase). Two specific network analysers with a sampling rate of 1 MS/s and a resolution of 16 bits were used. The current was measured using current clamps. During the switching of inverters raw data in time-domain was stored continuously. Otherwise three seconds every minute were stored to reduce the data size. Afterwards, a high pass filter (elliptic, 3rd order, 2 kHz passband) was applied to the measured data. Subsequently it was split in 200-ms-blocks (5-Hz-resolution) and for each block a discrete Fourier transformation was performed. All values are presented in the logarithmic unit $dB_{\mu V}$, where 120 $dB_{\mu V}$ corresponds to 1 V and 0 $dB_{\mu V}$ to 1 µV. For currents the unit $dB_{\mu A}$ is used respectively. The network analysers have accuracy better than ±5% for currents larger than 30 $dB_{\mu A}$ and ±2% for voltages larger than 40 $dB_{\mu V}$.

In order to obtain comprehensive data for a systematic analysis of harmonic emission of a different number of inverters and the interaction among them, a coordinated switching of the inverters was performed in one part of the measurement. The inverters were switched off sequentially in a predetermined order (Table I) and with a defined time delay. A part of small inverters were turned off in the beginning followed by the large inverters and the remaining small inverters. Figure 1 illustrates the switch-off procedure by means of active power. Power Line Communication (PLC) is used in the network for meter reading but was switched off during this experiment.

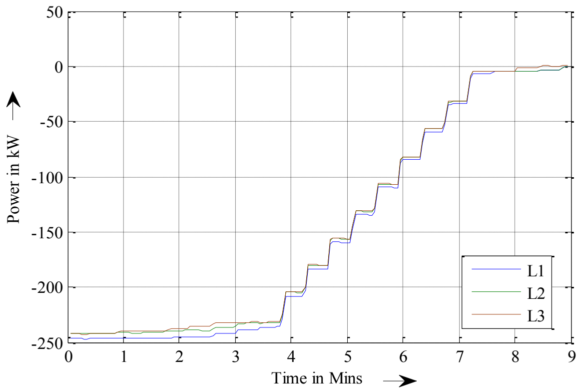

Fig. 1 Total power during coordinated switching OFF

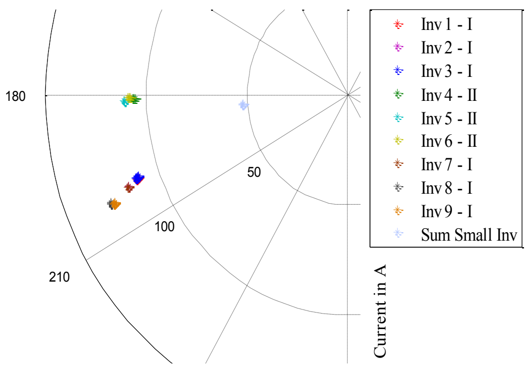

Fig. 2 Fundamental currents of all inverters

While almost all of the small inverters are of different brand and type, the nine large inverters are of same brand and type, but with two different settings for their cosφ(P)-control:

I) cosφ(P)-control enabled (1, 2, 3, 7, 8, 9)
II) cosφ(P)-control disabled (4, 5, 6)

The different behaviour of inverters for fundamental current is depicted in Figure 2.

2. Analysis of low order harmonics

A. Emission of the installation

The analysis is focused on the time span of the coordinated inverter switch-off. The current spectrum in L1 (all inverters ON) is shown in Figure 3a, while the voltage harmonics for both states (all inverters ON and OFF) are presented in Figure 3b. Both plots are limited to the order 25 as the harmonics beyond are insignificant and non-informative. 99th percentiles of the data are shown (cf. IEC 61000-3-14). Considerable current is observed for harmonic orders 5, 7, 9, 11, and 13. 5th and 7th harmonic current are predominant and hence emphasis is laid on these harmonics in the later analysis. The voltage spectrum is evaluated for before and after the switching process to analyse the impact of the inverters. The profile of voltage spectrum in the ON state is similar to the current spectrum implying a strong correlation between the voltage and current harmonics. The 9th harmonic voltage is dominated by the inverters. The cause for the reduced 11th harmonic can either be a possible cancellation effect or a variation in the level in the upstream grid, because the spectra correspond to different instants of time. The other phases have similar properties. L3 shows slightly different values, which may be caused by different impedance of the phases. This is not further considered in this paper.

Table I Switch off sequence of inverters

Time (mm:ss)	Inverter	Setting	Time (mm:ss)	Inverter	Setting
0:00	*Measurement Begin*		5:30	Inv 4	II
0:30	*PLC system OFF*		5:55	Inv 3	I
0:55-3:20	7 Small Inverters		6:20	Inv 2	I
3:50	Inv 8	I	6:45	Inv 1	I
4:15	Inv 7	I	7:10	Inv 9	I
4:40	Inv 6	II	7:35-8:50	4 small inverters	
5:05	Inv 5	II	9:00	*Measurement End*	

The Total Harmonic Distortion (THD) in voltage is evaluated by the following equation:

$$THD_V = \frac{\sqrt{\sum_{i=2}^{50} V_i^2}}{V_1} \cdot 100\% \qquad (1)$$

The time plot of THD_V (Figure 4a) at the busbar decreases by nearly 45% when switching off the inverters. The THD in current calculated in similar way can be misleading if the fundamental component is low

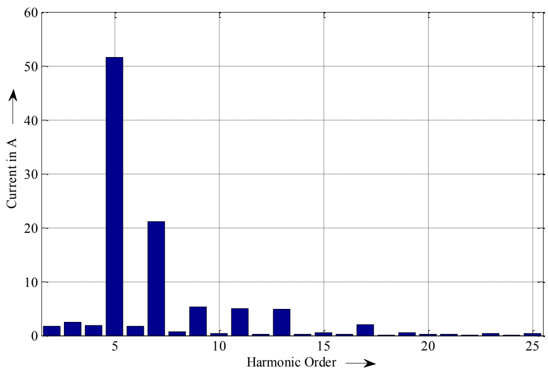

Fig. 3a Spectrum of Harmonic Currents (total)

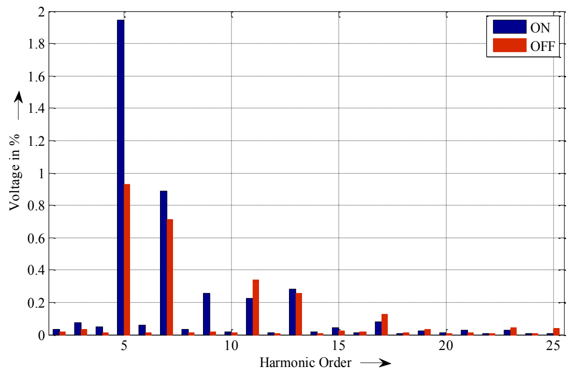

Fig. 3b Spectrum of Harmonic Voltage (Busbar)

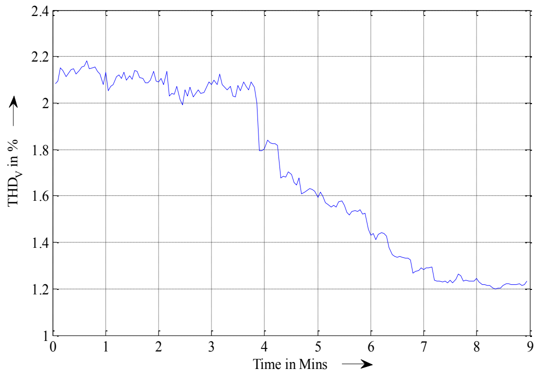

Fig. 4a Time Characteristic of Voltage THD$_V$

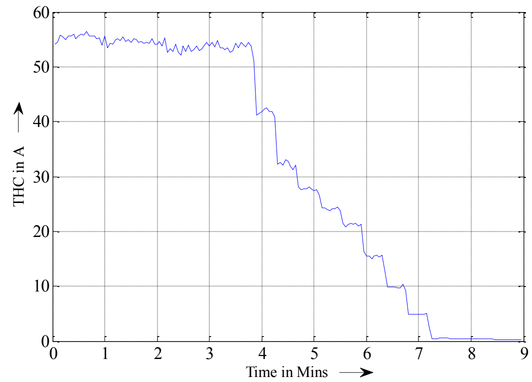

Fig. 4b Time Characteristic of THC (total current)

or strongly varying. In order to meet this shortcoming, total harmonic current (THC) is defined as absolute value as follows:

$$THC = \sqrt{\sum_{i=2}^{50} I_i^2} \qquad (1)$$

The time plot of the THC (Figure 4b) shows the dominating impact of the nine large inverters on the current distortion.

B. Emission of individual inverters

An extensive analysis of all relevant harmonics was carried out. For space reason the paper presents a detailed study of 5th harmonic and discusses only additional findings for the other harmonics. The 99th percentile values of the 5th harmonic current of individual inverters before switch-off are shown in Figure 5. The slightly higher

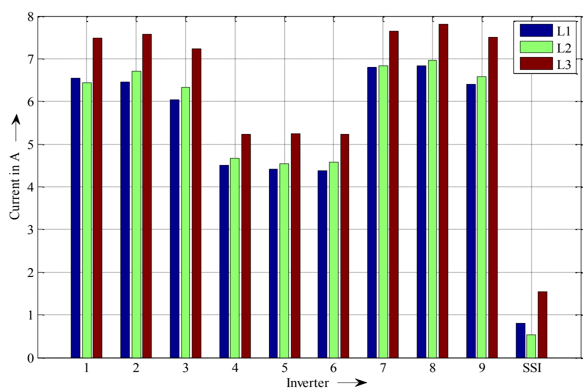

Fig. 5 5th Harmonic Current (all phases)

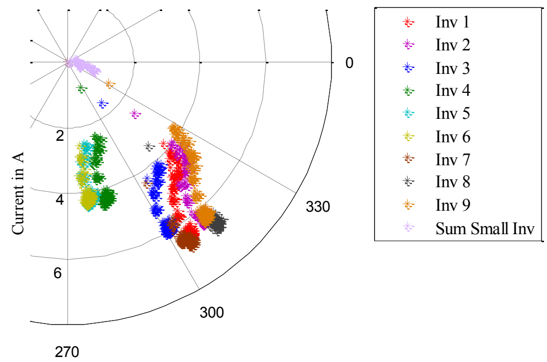

Fig 6 5th Harmonic Current Clusters (L1)

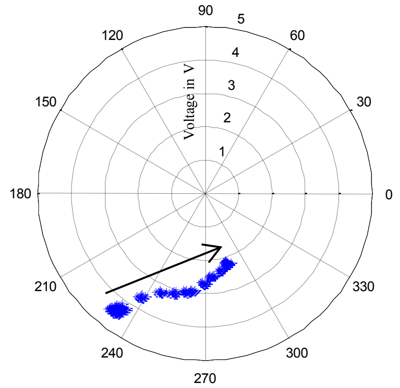

Fig 7 5th Harmonic Voltage (L1)

current in L3 is due to a possible impedance variation of the phases. The setting II inverters have a smaller magnitude. The total harmonic current of all small inverters (SSI) is very low and therefore not further considered.

Figure 6 shows the 5th harmonic current in phase L1 during the whole switching interval in the complex plane. The phases L2 and L3 show similar behaviour. All large inverters except Inv 8 show a significant change in magnitude in the range of 30% to 50%. The level of variation is directly related to the switching order. Inv 8 was switched off first and does not show any “variation trail”. Inv 9 was turned off last and has the highest variation (longest trail). The 5th harmonic current emission of the inverters strongly depends on the voltage distortion (cf. Figure 8). As soon as the 5th voltage harmonic decreases due to switching off the other inverters (4th to 7th minute in Figure 8), the 5th current harmonic drops considerably in magnitude until the inverter is turned off. In case of sinusoidal supply voltage conditions the current magnitude would become a minimum. Due to the existing background distortion this value can however not be obtained from the measurements. A similar behaviour has been observed for other types of PV inverters as well as for car charging rectifiers or switched mode power supplies with active power factor correction. Therefore a simple constant current source is not sufficient to model these inverters in terms of harmonics.

The impact of switching off inverters on the grid voltage is depicted in Figure 7. The 5th harmonic voltage is observed to drop by nearly 50%. The 5th harmonic

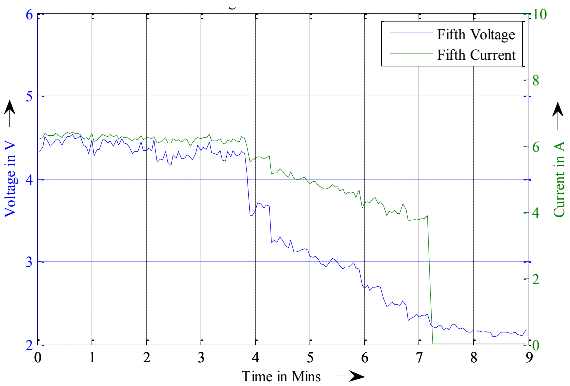

Fig. 8 Time plot of 5th voltage and current harmonic of an individual inverter

current with a prevailing phase angle of 300° in combination with the inductive grid impedance causes the voltage to shift from 290° to 230°.

The relationship between the current and voltage harmonics is studied with scatter plots of Inv 9 (Figure 9). It provides valuable information for development of harmonic models. A linear relation is observed in magnitude and phase angle between voltage and current for 5th harmonics. The slope of the curve is determined not only by the sensitivity of emission of the inverter to the voltage variations but also by the impedance of the upstream grid. However, as far as an individual inverter is concerned as in the Figure 9, the inverter characteristics are dominant and the grid impedance plays a minor role.

For 7th harmonic currents the setting I inverters have nearly six times higher emission than setting II inverters. Moreover setting II inverters are observed to have a higher phase angle variation. The scatter plots between the voltage and current shows linear relationship only for setting I inverters. Figure 10 exemplarily shows the total 9th harmonic current and voltage at the busbar as the inverters are switched off. Similar curves are also observed for 11th and 13th harmonics.

C. Phase Angle Diversity

Figure 6 gives a qualitative perspective of the phase diversity of 5th harmonics. Unlike magnitude, the phase angle of the current harmonics does not vary largely under the changing voltage harmonics during switching period. Therefore a weak phase cancellation effect is expected.

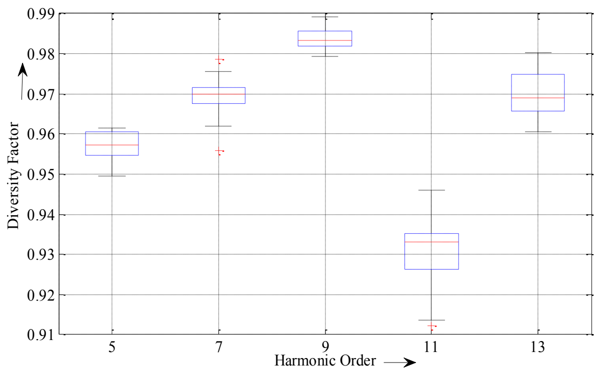

Fig. 11 Diversity Factor

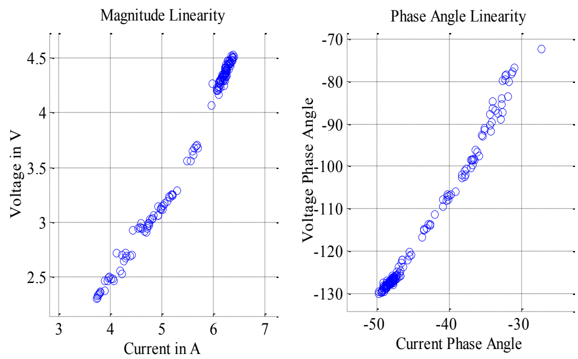

Fig. 9 5th Harmonic Voltage – Current Relationship (Inv 9)

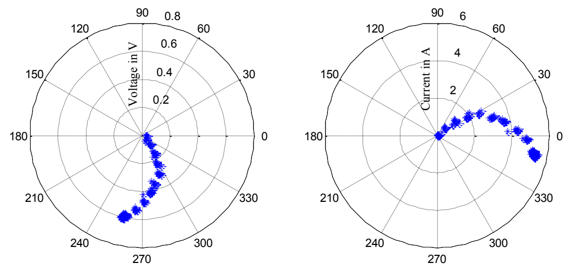

Fig. 10 9th Harmonics a) Voltage; b) Current

In order to validate the reliability of the data, the measured sum at the busbar is compared with the calculated vectorial summation of individual inverters and the percentage error is calculated. For all considered harmonics the error is smaller than 5% for 95% of the measurement data, which means a reliable data set for further diversity calculations.

Two indices are commonly used to quantify the phase cancellation effect: diversity factor and summation exponent. The diversity factor is determined by

$$k_p^{(h)} = \frac{Vector\ sum}{Arithmetic\ sum} = \frac{I_{VEC}^{(h)}}{I_{ARI}^{(h)}} = \frac{\left|\sum_{i=1}^{n} \underline{I}_i^{(h)}\right|}{\sum_{i=1}^{n} \left|\underline{I}_i^{(h)}\right|} \qquad (3)$$

where $\underline{I}_i$ is the current vector of device i (in this case a particular inverter), h the order of harmonic and n the number of devices (in this case inverters). The diversity factor directly presents, how much the absolute value of the vector sum is smaller than the algebraic sum. The value ranges from $0 \le k_p^{(h)} \le 1$, where $k_p^{(h)} = 0$ means perfect cancellation and $k_p^{(h)} = 1$ no cancellation at all.

The diversity factor is evaluated for all considered harmonics and the time when all inverters are connected. The measurements at the individual inverters are simply added algebraically and are divided by the corresponding measurement value at the transformer. Figure 11 plots the diversity factors for phase L1. Similar results are observed for the other phases. With values higher than 0.9 all considered harmonics have a high diversity factor and consequently a weak phase cancellation.

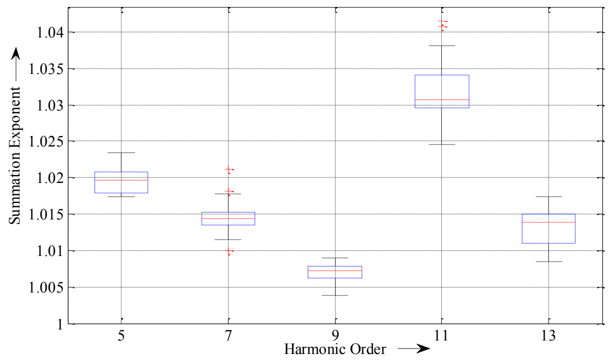

Fig. 12 Summation Exponent for Current Harmonics

The summation exponent $\alpha^{(h)}$ is determined by solving the following non-linear equation iteratively:

$$I_{VEC}^{(h)} = \sqrt[\alpha^{(h)}]{\sum_{i=1}^{n} \left| \underline{I}_i^{(h)} \right|^{\alpha^{(h)}}} \tag{4}$$

A summation exponent $\alpha^{(h)} = 1$ corresponds to a diversity factor of $k_p^{(h)} = 1$ and represents no cancellation. In case of perfect cancellation ($k_p^{(h)} = 0$) the summation exponent becomes infinite.

Figure 12 shows the distribution of summation exponent calculated for the time span when all inverters were connected. With values almost equal to $\alpha^{(h)} = 1$ the weak phase cancellation effect is confirmed. In case of multiple inverters with similar behaviour a summation exponent of $\alpha^{(h)} = 1$ should be used for all harmonics instead of the recommended values e.g. in IEC 61000-3-14.

3. Analysis of higher frequency emission

All following plots are limited to 100 kHz, because the frequency range above 100 kHz doesn't contain any considerable emission. Figure 13 presents the 5-Hz-spectrum of the busbar voltage in phase L1. The other phases show a similar behaviour. Several peaks indicate the switching frequencies of the inverters and their respective harmonics. All large inverters of the installation have a similar switching frequency of 3 kHz. The 2nd emission band at 6 kHz and the 3rd emission band at 9 kHz are also clearly visible. The peaks at 10 kHz, 16 kHz and 25 kHz are caused by the small inverters. This confirms the common manufacturer practice to use higher switching frequencies in case of smaller rated power of the inverter.

The "hills" between 40 kHz and 80 kHz were caused by a narrow band power-line-communication-system (PLC) with eight channels for transmitting metering information. This emission is called intentional, because it is intentionally injected by the network operator. Compared to other narrow band PLC systems with less channels (down to two) the system in this case is more robust, because if one or more channels are disturbed, the system can still switch to another channel for communication. Especially for environments, where other disturbances in this frequency range has to be expected, a more robust

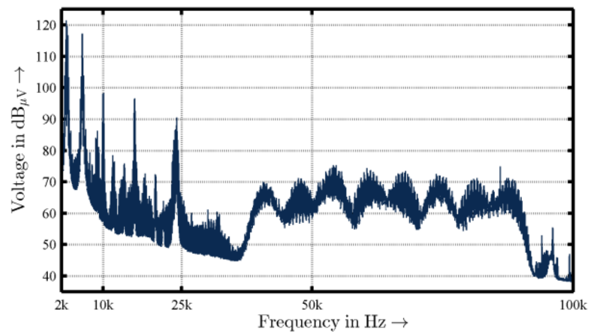

Fig. 13 Voltage spectrum at busbar in phase L1

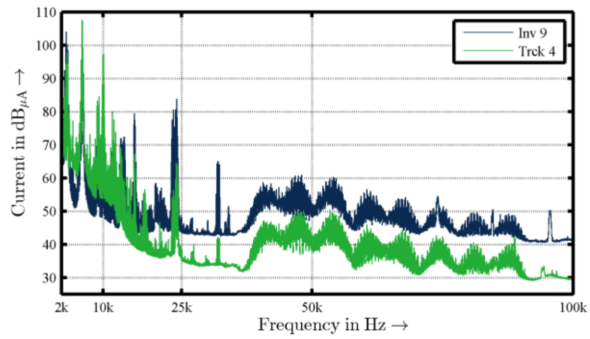

Fig. 14 Current spectrum for individual large inverter (Inv 9) and small inverter (Trck 4) both in L1

PLC system with a larger number of channels should be used. Nevertheless ensuring a proper operation of the widely used narrow-band PLC communication systems should be carefully considered in the current standardization work in IEC SC77A in terms of compatibility levels and emission limits for the frequency range 2 – 150 kHz. Further details on those issues can be found in [5].

Figure 14 shows the current-spectrum of a large inverter (Inv 9) and a small inverter (Trck 4). Even though both inverters emit at different frequencies (large inverter at 3 kHz, 6 kHz and 9 kHz; small inverter at 10 kHz, 16 kHz or 25 kHz) both spectra show current components at all higher frequencies which exist in the voltage spectrum (Figure 13). This means a significant interaction between all inverters, which is caused by the relatively small input impedance of inverters. At higher frequencies (usually above 3 - 5 kHz) the total impedance is more and more dominated by the input circuits of the inverters (usually the EMC filters) that subsequently act more and more as sink for the higher frequency emission.

Figure 15 shows the voltage level depending on time and frequency as spectrogram for the time interval of coordinated inverter switching (cf. Table I). Every switch-off of an inverter decreases the emission level of the corresponding switching frequency and their harmonics. The emission of the large inverters disappears completely after switching off Inv 9 (7:10 min). Especially the switch-off at 7:35 min results in a significant decrease of emission in a wide range. This particular small inverter has a switching frequency of 24 kHz including a sub-harmonic at 12 kHz. Moreover also the 2nd emission band at 48 kHz and the 3rd emission

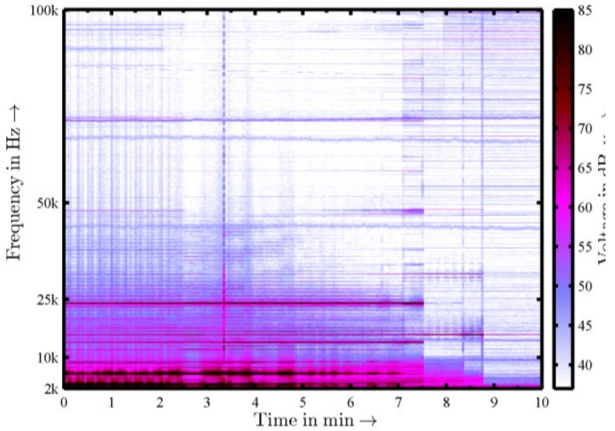

Fig. 15 Spectrogram of the voltage in L1 during coordinated switching (cf. to table I)

band at 72 kHz can be clearly identified. This example shows how coordinated switching can help to identify the individual emission for a particular inverter. The spectrogram also shows that every single switching operation leads to a short, momentary increase of emission in the voltage.

The collective behaviour of the large inverters at their switching frequency is analysed in detail by means of the time characteristic of busbar voltage and current of Inv 9 at 3 kHz (Figure 16). A 600-Hz-band is used, because it reflects almost the total signal energy for PV inverters at switching frequency. The voltage decreases stepwise with each switch-off, while the current increases in a comparable way. After the last inverter (Inv 9; 7:10 min) has been switched off, the levels of both voltage and current suddenly drop to background noise levels. Figure 14b illustrates that Inv 9 can be characterized in terms of its emission at switching frequency as power source. Looking on the emission at same operating states before (0:00 min) and after (35:00 min) switching, the relation of voltage and current at 3 kHz behaves different. After complete switching on, the voltage is considerably smaller, while current is significantly higher than before switching inverters off. This behaviour is not yet fully explainable, but may increase complexity of modelling approaches.

4. Conclusion and Outlook

The paper studies the characteristics of low order harmonics and higher frequency emission of a large photovoltaic installation, consisting of multiple small and large sized inverters.

The low order harmonics have a predominant 5^{th} and 7^{th} harmonics, both in current and voltage. Current harmonics strongly depend on the voltage distortion, but also on the setting of the cosφ(P)-control. Diversity factor and summation exponent indicate a weak phase cancellation effect for large inverters, which consequently means that a summation exponent $\alpha^{(h)} = 1$ should be used for all harmonics in such installations. All inverters have a significant emission at their respective switching frequencies. The highest emission is caused by the large

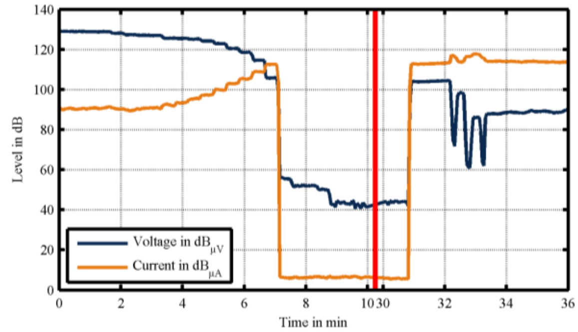

Fig. 16a Voltage and current of Inv 9 at 3 kHz during switching off and on all inverters (L1)

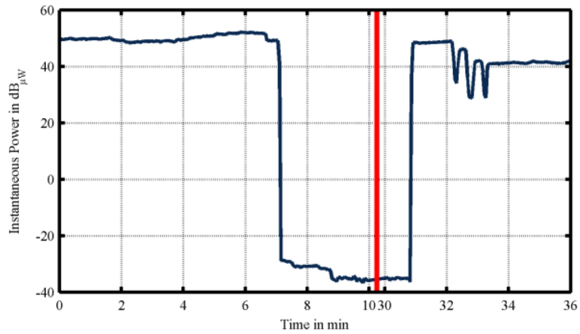

Fig. 16b Instaneous power of Inv 9 at 3 kHz during switching off and on all inverters (L1)

inverters at 3 kHz and levels about 130 $dB_{\mu V}$ (ca. 3 V) in voltage. At higher frequencies a set of inverters (same and different types) at one connection point shows a large interaction. Most of the emitted currents will stay within the installation and doesn't propagate into the grid. Coordinated switching can be a useful tool to identify emission of individual inverters.

The paper is limited to a few aspects of the work only. Many more experiments were carried out in order to analyse e.g. the impact of PV inverters on the PLC signal characteristics (damping effects) or the transfer characteristic of a cable for higher frequency emission.

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