HARMONIC CURRENT EMISSION OF PHOTOVOLTAIC INVERTERS

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ABSTRACT

Measurements of harmonic currents were carried out in LV-systems and under laboratory test conditions with adjustable harmonic content of the AC-voltage. Two PV-inverters of different type were tested. The results indicated that the emitted harmonic currents depend strongly on the harmonic voltages prevailing in the AC-voltage. PV-inverters without transformer show significant lower harmonic currents than inverters with coupling transformer. The standard test conditions as defined in international standards does not consider real system conditions with respect to the harmonics in system voltage. The measured currents as documented in data sheets are therefore comparatively lower than under the condition of real system operation. It is recommended to reconsider the test standards.

INTRODUCTION

Grid-connected photovoltaic systems (PV-systems) with DC/AC-converters are subject to harmonic current emission which depends on the type of technology used, on the control strategy of the DC/AC-inverter, on the existence of high- or low-frequency coupling transformer and on the harmonic voltages prevailing in the AC-power system. A dominant role on the harmonic current emission is also given by the performance of the AC/DC-inverter under partial loading (generating) conditions [1].

Fig. 1 indicates the total harmonic current THD_I of a PV-generator (P_n=3kW; PWM-frequency 16 kHz; with coupling transformer) under different generating condition (ratio P/P_n), measured for the period of one week. The shape of the THD_I is characterised by a comparative high value under low generating conditions with a sharp decay for increased generation; the THD_I will remain below 10% in case the loading of the inverter exceeds approx. 18% of the rated power [2], [3]. Some measurements are significantly lower for low load conditions, which is the effect of the ENS-signal generated by the inverter to detect and to prevent island operation of the PV-generator [4]. The variety of the THD_I due to the ENS-signal is increasing only to a comparatively small extend for increasing generating conditions, as can be seen in Fig. 1. International standards [5] and [6] define standard test conditions with respect to the harmonic voltages of the voltage source, in order to measure the emitted harmonic currents of any equipment; the standards have to be applied to PV-inverters as well.

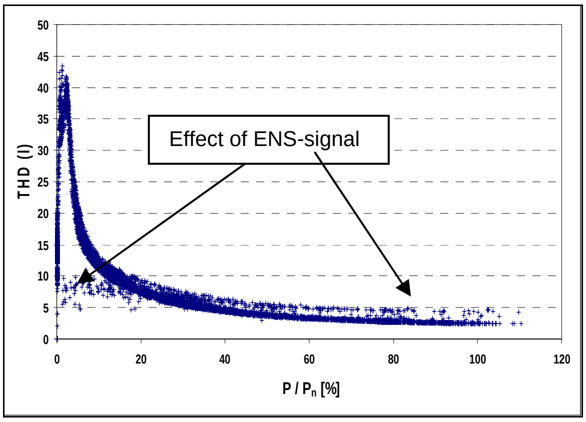

Figure 1. Total harmonic distortion of a 3-kW-PV-inverter without transformer for different generating conditions

The defined maximal harmonic voltages (e.g. the maximal permissible 5th harmonic voltage for testing is 0.4%, whereas the compatibility level and the maximal expected value in LV-systems is 6%) are comparatively lower than the expected values of harmonic voltages of power systems, outlined in [7].

MEASUREMENTS IN POWER SYSTEMS

Harmonic currents and generated power

Measurements of harmonic currents and voltages in a LV-power system have been carried out for periods between four days and one week. The system consists of cables and overhead-lines supplying mainly domestic load and small industry. Some agricultural load is also supplied. The system is fed from the local 20-kV-system (S_k”=46MVA) through a 630-kVA-transformer. Different types of PV-generators with rated power of the DC/AC-inverter between 2.1kW and 5kW are installed in the system.

The measured data were evaluated with statistical program giving the statistical distribution function of the 95%-probability of the individual harmonics and the relation between the emitted harmonic current and the generated power. Fig. 2 outlines the relative values of the major odd harmonic currents for different loading condition of a 3-kW-inverter (with coupling transformer). The individual classes for the partial power were set to be P/P_r = <5% - 10% - 15% - 20% - 40% - 60% - 100 % > 100%.

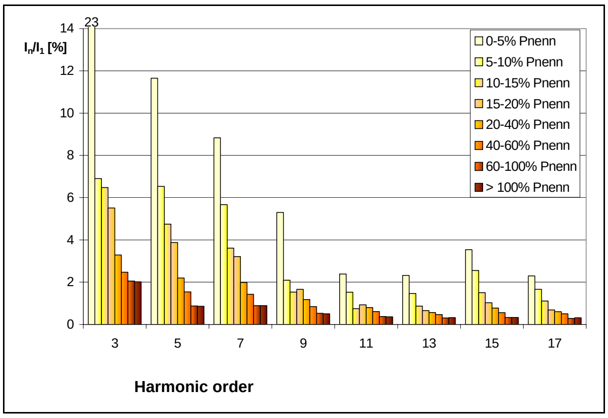

Figure 2. Relative harmonic currents of a 3-kW-inverter of a PV-generator for different loading conditions (Pnenn: nominal power P_n) measured during four days

As can be seen, the relative harmonic current, indicated by the 95%-probability-value, are decaying with increasing loading of the converter, whereas the absolute current values are increasing. The even harmonic currents were measured and assessed as well, but are not shown in Fig. 2.

Harmonic currents and harmonic voltages

Further evaluation of the measurement results was carried out to indicate the relation between harmonic current emission of the inverter and harmonic voltages prevailing in the LV-system. As the harmonic current emission depends on the partial loading conditions, as can be seen from Fig. 2, the assessment was carried out for different classes of the generated power. Fig. 3 and Fig. 4 indicate the results of this assessment obtained for an inverter loading of appr. 47% of the rated power for two types of inverters, one having rated power 3kW (with coupling transformer) and the other with rated power 5kW (without transformer).

By means of the least-square-error method the average increase of the emitted harmonic currents for increasing harmonic voltage was calculated. The results are outlined by the straight lines in Fig. 3 and Fig. 4.

The power ranges (1.38kW-1.43kW and 2.35W-2.45kW resp.) as mentioned in Fig. 3 and Fig. 4 were selected due to the availability of a sufficient high number of data (n≥50) of measured harmonic voltages and currents. As can be seen from the figures, the emitted harmonic current increases for higher harmonic voltages, whereas the differences between the two inverters are comparatively small in terms of absolute values of harmonic currents, however significant in terms of relative values of the harmonic currents. The dependency of the 3rd harmonic current on the harmonic voltage is different for the two different inverters. This effect is seen to result from the presence of the coupling transformer, which is not installed in the 5kW-inverter. Furthermore is may result from a different design of the EMC-filter on the AC-side.

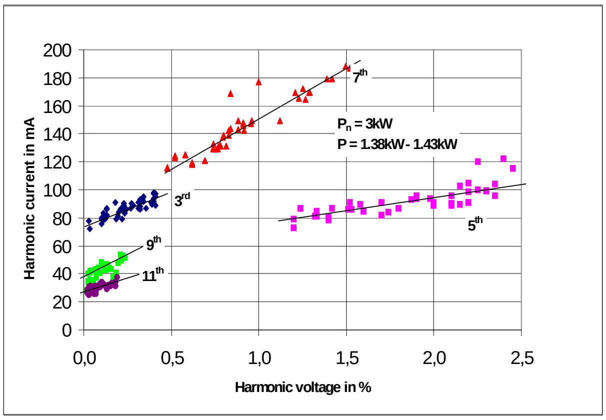

Figure 3. Emitted harmonic currents of a 3-kW-inverter (with coupling transformer) for different harmonic voltages, generated power: 1.38kW – 1.43kW

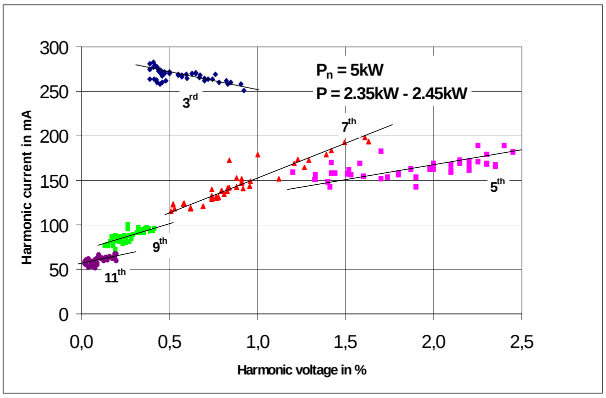

Figure 4. Emitted harmonic currents of a 5-kW-inverter (without coupling transformer) for different harmonic voltages, generated power: 2.35kW – 2.45kW

Table I shows the parameter "increase of harmonic current related to the percentage harmonic voltage" obtained from Fig. 3 and Fig. 4. The results as per Table I indicate that the emitted harmonic currents are depending on the prevailing harmonic voltages in the system, the harmonic currents are increasing with increasing harmonic voltages except in case of the 3-kW-inverter, which shows a decreasing 3rd harmonic current with increasing harmonic voltage. Furthermore it can be noticed that the increase is nearly identical for harmonics of the 7th and higher order for both inverter concepts.

TABLE I. PARAMETER FOR THE INCREASE OF EMITTED HARMONIC CURRENTS RELATED TO PERCENTAGE HARMONIC VOLTAGE (DATA IN 10^{-3}A/% OF VOLTAGE)

HARMONIC ORDER	INVERTER 3KW	INVERTER 5KW
3RD	53.0	-20.2
5TH	18.7	35.0
7TH	74.2	79.3
9TH	66.6	62.3
11TH	42.0	42.7

This effect of increasing resp. decreasing harmonic current with increasing harmonic voltage can be interpreted either originating from the PV-inverter itself, from the EMC-filter on AC-side or from the power system. The EMC-filter reduces the emitted harmonic currents and also extracts harmonic currents from the power system depending on the impedance-frequency characteristic of the filter. It is obvious that a measurement of harmonic currents at the connection point of the converter, will measure the summation of the emitted harmonic currents from the inverter into the system and the harmonic current from the power system into the AC-filter. The individual effects cannot be measured separately in this case.

It is therefore essential to measure the emitted harmonic currents of the inverter under defined conditions in laboratory tests with a voltage source having adjustable harmonic voltages in a suitable range that coincide with harmonic voltages in real power systems.

LABORATORY MEASUREMENTS

General

Due to the results of field measurements, as mentioned in the previous chapter, measurements in laboratory have been carried with controlled harmonic voltages in the AC-voltage. Equipment for the test circuits as mentioned below was used.

- Waveform-generator: Elgar 5250 AE, harmonics to be programmable individually up to the 40th order, minimal source impedance Z=(0,03+j0,03) Ω,
- Voltage-constant: Delta Elektronika SM300-10D, maximal output voltage 300V, maximal output current up to 10A,
- AC-load: Small electrical heating appliances, different power between 200W and 2kW,
- Harmonic measurement: Haag Euro-Quant with assessment software DAMON EWS 130.

During the tests the harmonic voltages of the AC-source have been modified one by one to different values starting from zero up to some percent in 10 steps. The maximal value of the individual harmonic voltages was taken as per DIN EN 50160 [7], e.g.: u_3=5%; u_5=6%; u_7=5%; u_9=1.5%, see Table II. The test voltage, e.g. for the 5th harmonic, was adjusted between 0% and 6% in steps of 0.6%. The power of the inverter was set for all tests to 50% of the rated power by adjusting the voltage-constant DC-source to compare the result with those from the power system measurements.

Results of measurements

The tests were carried out for several minutes for each individual harmonic and adjustment, leading to a set of 15 measured data per harmonic.

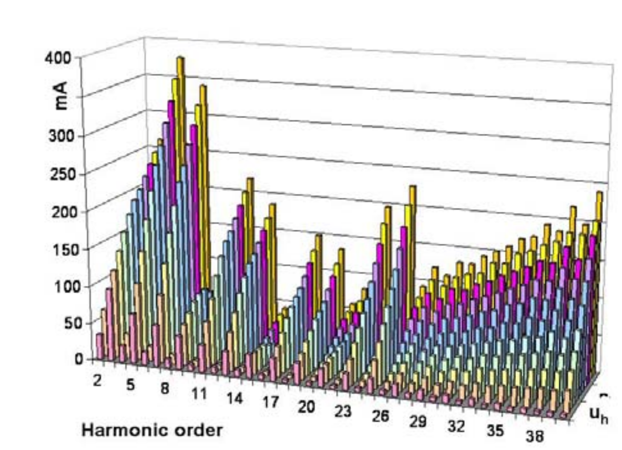

Figure 5. Emitted harmonic currents of 3kW-inverter (without coupling transformer) for increasing harmonic voltage during laboratory tests

To assess the results, the average value of each individual harmonic was calculated. The variety between the individual measurements for the same harmonic was negligible small. The results are outlined in Fig. 5 and Fig. 6 for the two types of inverter.

3-kW-inverter

The harmonic currents are increasing with increasing harmonic voltage. Especially the harmonics of the 3rd and 5th order reaches high values for the maximal value of the harmonic voltage (u_3=5%; u_5=6%). Harmonics of the odd order in general have a lower increment than harmonics of even order. This is valid up to the 25th order. The higher order harmonics show a comparative high increment for even and odd order harmonics characterized by a continuously increasing current for increasing harmonic voltage and increasing order reaching for the 40th order nearly i_{40}=4% of the rated fundamental current and a harmonic voltage of u_{40}=0.5%.

5-kW-inverter

The harmonic current of the 3rd order is decreasing with increasing harmonic voltage; the 5th harmonic current is decreasing up to a harmonic voltage of 2.4% and than increases linear with increasing harmonic voltage. Harmonic currents of higher order are increasing with increasing harmonic voltage. Harmonics of the odd order in general have a lower increment than harmonics of even order up to the 25th order. The higher order harmonics show a comparative moderate increment for even and odd order harmonics, whereas the even order harmonic have a lower increment than the odd order ones.

The maximal value is reached for the 26th order having i_{26}=0.67% of the rated fundamental current in case the harmonic voltage is u_{26}=0.5%.

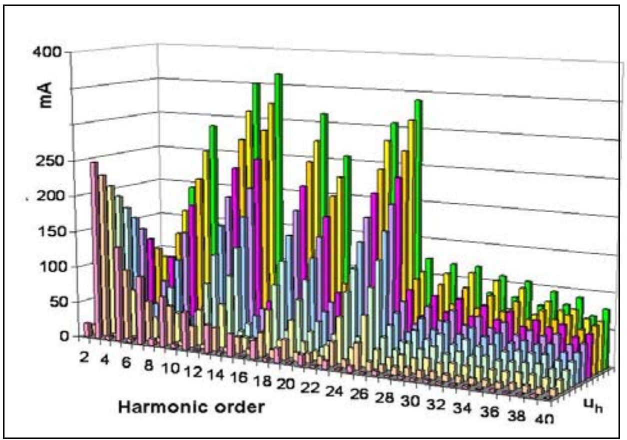

Figure 6. Emitted harmonic currents of 5kW-inverter (without coupling transformer) for increasing harmonic voltage during laboratory tests

STANDARD TEST CONDITIONS

International standards [5] and [6] define voltage test conditions to carry out measurements of harmonics emitted by equipment. These standards have to be applied to PV-inverters as well. Both standards apply for low-voltage systems, PV-inverters with low rating ($P_r \leq 3.68$kW; $I_r \leq 16$A) are allowed to be tested under more restricted conditions than inverters with high rated power ($P_r < 17.25$kW per phase connection; $I_r < 75$A). Table II outlines the maximal values of the harmonic voltages for standard test conditions and the maximal expected values in power systems as per DIN EN 50160 [7], identical to the compatibility levels as per [8].

The values in Table II indicate that the standards test conditions define only a small part of the range of harmonic voltages that might be expected in power systems. As the emitted harmonic currents depend on the harmonic voltages prevailing in the AC-system, the measurements under standard test conditions will obtain harmonic currents which are lower than those emitted by the inverter under real power system conditions.

TABLE II. PERMISSIBLE HARMONIC VOLTAGES AS PER EN 61000-3-2 AND EN 61000-3-12, EXPECTATION VALUES AS PER DIN EN 50160

Harmonic order	Voltage in % of nominal voltage		
	61000-3-2	61000-3-12	50160
3	0.9	1.25	5.0
5	0.4	1.5	6.0
7	0.3	1.25	5.0
9	0.2	0.6	1.5
11	---	0.7	3.5
13	---	0.6	3.0
Even (2 … 10)	0.2	0.4	2.0 … 0.5
Other (odd order) (even order)	0.1	--- 0.3	3.5 … 1.5

As the measurements under standard test conditions are the basis to assess the suitability for the connection of PV-installations to the power system, the results are not on the safe side. The emitted harmonic currents of PV-inverters will be higher than expected and might cause impermissible high harmonic voltages and thus endangering the electromagnetic compatibility in power systems.

CONCLUSION AND OUTLOOK

The comparison of the site measurements and the laboratory tests with controlled harmonic voltage conditions indicated that the emitted harmonic currents depend strongly on the harmonic voltages in the AC-voltage. Standard test conditions do not take account of this characteristic of the PV-inverter. The harmonic voltages to be allowed for the standard test voltage do not reflect the expected harmonic voltages in AC-systems. In order to avoid impermissible high harmonics in power systems due to the operation of PV-generators, realistic test conditions have to be established and applied during laboratory tests. Furthermore the typical operation sequence of PV-installations and the typical daily variation of the harmonic voltage level need to be taken into account.

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[6] EN 61000-3-12: Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current <75A per phase….

[7] DIN EN 50160: Voltage characteristic of electricity supplied by public distribution systems.

[8] DIN EN 61000-2-2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.